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The changes in classical and nonlinear parameters after a maximal bout to elicit fatigue in competitive swimming

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ABSTRACT

The aim was to assess the effect of fatigue on linear and nonlinear parameters in swimming. Twenty-four fitness-oriented swimmers performed a maximal bout of 100 m at front-crawl to elicit fatigue. Before (pre-) and immediately after (post-test) the bout, participants swam an all-out 25 m to derive the speed fluctuation (dv), approximate entropy (ApEn) and fractal dimension (FD) from the speed-time series collected by a speedo-meter. Swim speed was 10.85% slower in the post-test than in the pre-test ($p < .001$, $\eta^2 = 0.72$). There was an effect of the fatigue on the dv with a moderate effect size. The dv increased shifting the 95CI band from 0.116–0.134 to 0.140–0.161. The ApEn showed non-significant variations between the pre- and post-test having the 95CI of pre- and post-test overlapped (pre: 0.659–0.700; post: 0.641–0.682). The FD showed as well a significant variation (the 95CI moved from 1.954–1.965 to 1.933–1.951). It can be concluded that in swimming there are changes in classical and nonlinear parameters under fatigue.

1. Introduction

In some sports settings, high-level performers (the athlete) are no longer able to elicit significant improvements of the performance determinants. The margins to improve the performance and/or its determinants are rather small (Allen, Vandenbogaerde, & Hopkins, 2014). In such event, an extra challenge is that the mainstream variables selected to monitor the athletes are not sensitive enough to trivial variations of the motor behaviour. For instance, it was reported that the performance of elite swimmers improved less than 1% by season (Costa et al., 2012). Therefore, the assessment of the sports performance as a linear system may not be insightful enough. A linear system is characterised by proportionality between inputs (in this case, the performance determinants) and the output (the sports performance). The alternative is to consider the relationship between sports performance and its determinants as a nonlinear and complex system (Komar, Seifert, & Thouvarecq, 2015).

A nonlinear and complex system features several components. These components interact among each other's direct and/or indirectly, having an effect ultimately on the output (Abarbanel, Rabinovich, & Sushchik, 1993). In sports settings one may argue that different determinants will interact among them, having an effect on the sports performance. A nonlinear complex system is

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characterized by interaction-dominant dynamics. Another main feature of these systems is that there is no proportionality between the changes in inputs and output (Bravi, Longtin, & Seely, 2011; Komar et al., 2015; Preatoni, Ferrario, Donà, Hamill, & Rodano, 2010). Trivial changes in one input can have a meaningful effect on the output. So, an alternative to tackle the concern reported early on about the lack of sensitivity of classical variables might be monitoring nonlinear parameters. Nonlinear parameters can be more sensitive to trivial changes in the performance and the motor behaviour of the performer than classical parameters (Bravi et al., 2011). However, there is scarce research in sports performance underpinned by nonlinear dynamics. In time-based sports, such as competitive swimming, the performance is measured with a 0.01 s of accuracy. Therefore, the follow-up question is how insightful nonlinear parameters can be in assessing the athletes' motor behaviour. On top of that, it has also been noted that in competitive swimming there are several interplaying factors that ultimately affect performance (Barbosa et al., 2010). Altogether, for such narrow margin of improvement, nonlinear parameters might be very insightful of the performance delivered.

On land walking, the magnitude of the stride-to-stride fluctuations and their changes over time helps to understand the motor control of gait (Hausdorff, 2007). The assessment of the fluctuations within the stride cycle by nonlinear parameters can provide insight into the organization, regulation, interactions and stability of the entire locomotor system. If on land it is assessed the stride-to-stride fluctuations, in water it is monitored the arm-stroke to arm-stroke fluctuations, being this known as speed fluctuation (dv). The dv quantifies the amount of variation of the time-series in reference to its mean value (Barbosa et al., 2005). This is a dimensionless measure that ranges between 0 (no fluctuation) and 1 (high fluctuation). There are several parameters that can be selected under complex science as well. The approximate entropy (ApEn) and fractal dimension (FD) are the most common ones. The ApEn describes the degree of irregularity and complexity over the time-series (Bravi et al., 2011). The ApEn ranges between 0 (repeatability over the time-series) and 2 (randomness over the time-series) (Pincus, 1991). The FD provides insight on the level of complexity of a time-series (Higuchi, 1988). The FD ranges between 0 (the motor behaviour is less complex) and 3 (the motor behaviour is more complex).

It was reported evidence of fractal-like fluctuations in human gait on land (Hausdorff, 2007). Over a 120-min load carriage March by servicemen, the FD decreased from 1.43 to 1.12 (Schiffman, Chelidze, Adams, Segala, & Hasselquist, 2009). Conversely, there are mixed findings on its effect in ApEn (Arif, Ohtaki, Nagatomi, Ishihara, & Inooka, 2002; Preatoni et al., 2010). In human gait on land, it was reported that the ApEn would increase by 12% to 30% between a pre- and post-test after being under a protocol that elicited fatigue (Arif et al., 2002). However, race-walkers performing a set of 40 × 20 m did not show any significant difference in the entropy between the first 20 and the last 20 trials (Preatoni et al., 2010). Altogether, there seems that fatigue has an effect on the nonlinear proprieties of human gait on land. If the same phenomenon happens in human swimming, it might help performers to excel because more insightful and sensitive details are provided to them.

In time-based sports, such as competitive swimming, the delay of the onset of the fatigue is paramount to improve performances. In alignment with this understanding, a lot of research has been carried out to understand the mechanisms of fatigue. The manifestation of fatigue can be observed by the impairment in the ability of producing mechanical force or power (Green, 1997). The mechanical output produced by the contractile properties of the skeletal muscle diminishes (Ament & Verkerke, 2009). In swimming, the fatigue will affect as well the kinetics, coordination and kinematics. Swimmers show an impairment of the swim kinetics (Toussaint, Carol, Kranenborg, & Truijens, 2006) and neuromuscular activity (Stirn, Jarm, Kapus, & Strojnik, 2011; Wakayoshi, Moritani, Mutoh, & Miyashita, 1994) under fatigue. These are coupled with a decrease in the energy expenditure of swimming (Stirn et al., 2011). The main consequence is a change in the inter-limb coordination (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005) and swim kinematics (Stirn et al., 2011; Toussaint et al., 2006). Therefore, swim speed decreases under fatigue (Aujouannet, Bonifazi, Hintzy, Vuillerme, & Rouard, 2006). The intra-cyclic variations assessed by RMS also showed a change under fatigue at front-crawl (Tella et al., 2008). Over a 200 m swim trial, the decrease in speed was coupled with an increase in the dv (Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013). Another paper noted that there is a relationship between speed and dv (Barbosa et al., 2013). A faster swim is related to lower dv. All these modifications may lead to changes in the level of predictability and complexity of the motor behaviour (in this case, the swimming technique). Nevertheless, there is no available report in the literature on the changes in nonlinear parameters due to fatigue in competitive swimming.

Recent papers reported that swimming exhibits nonlinear proprieties but its magnitude differs according to the swim stroke performed ($14.048 \leq dv \leq 39.722$; $0.682 \leq ApEn \leq 1.025$; $1.823 \leq FD \leq 1.919$) (Barbosa, Goh, Morais, Costa, & Pendergast, 2016). Of the four swim strokes, front-crawl showed the lowest dv, ApEn and FD (Barbosa et al., 2016). The complexity of the swimming technique also varies depending on the level of expertise. The dv, ApEn and FD decreases with increasing expertise (front-crawl: $15.11 \leq dv \leq 18.40$; $0.66 \leq ApEn \leq 0.73$; $1.84 \leq FD \leq 1.89$) (Barbosa, Goh, Morais, & Costa, 2017). These two papers only assessed the variations of nonlinear characteristics depending on the swim stroke performed (task constraint) and the competitive level (organismic constraint) of the performer. In both papers the participants performed all-out trials, not being under the effect of fatigue. Indeed, examining the effect of fatigue in the motor control is a popular aim for researchers in this field (Seifert & Chollet, 2008). However, it is yet to be compared in swimming (as well as, the vast majority of time-based sports) the variations of nonlinear parameters under the effect of fatigue (organismic constraint). This might provide new insights on the fatigue mechanisms in this sport and other time-based sports. Ultimately, it can also help in understanding how to delay as much as possible the onset of fatigue.

The aim was to assess the effect of an all-out bout of 100 m at front-crawl to elicit fatigue on linear and nonlinear parameters. It was hypothesized that there would be meaningful variations in classical and nonlinear parameters immediately after the maximal swim bout.