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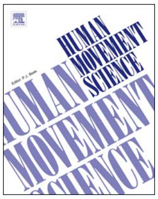

Full Length Article

Multiscale coordination between athletes: Complexity matching in ergometer rowing

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ABSTRACT

Complex systems applications in human movement sciences have increased our understanding of emergent coordination patterns between athletes. In the current study, we take a novel step and propose that movement coordination between athletes is a multiscale phenomenon. Specifically, we investigated so-called "complexity matching" of performance measured in the context of rowing. Sixteen rowers participated in two sessions on rowing ergometers: One individual session of 550 strokes and one dyadic session of 550 strokes side-by-side with a team member. We used evenly-spaced detrended fluctuation analysis (DFA) to calculate the complexity indices (DFA exponents) of the force-peak interval series for each rower in each session. The DFA exponents between team members were uncorrelated in the individual sessions ($r = 0.06$), but were strongly and significantly correlated when team members rowed together ($r = 0.87$). Furthermore, we found that complexity matching could not be attributed to the rowers mimicking or locally adapting to each other. These findings contribute to the current theoretical understanding of coordination dynamics in sports.

1. Introduction

In the past two decades, the research domain of sports has witnessed a rapid growth of complex systems applications, both in terms of theory and methodology (e.g., Davids et al., 2014; Den Hartigh, Cox, Gernigon, Van Yperen, & Van Geert, 2015; Grehaigne, Bouthier, & David, 1997; McGarry, Anderson, Wallace, Hughes, & Franks, 2002). These applications were inspired by research in human movement sciences, foundational works on coordination dynamics in particular (e.g., Haken, Kelso, & Bunz, 1985; Kugler, Kelso, & Turvey, 1982; Newell, 1986; Schmidt, Carello, & Turvey, 1990). Dynamical models of human movement coordination have been applied to study the formation of coordination patterns in sports when athletes cooperate (e.g., Cuijpers, Zaal, & de Poel, 2015; De Brouwer, de Poel, & Hofmijster, 2013; Den Hartigh, Gernigon, Van Yperen, Marin, & Van Geert, 2014), compete one-versus-one (e.g., McGarry et al., 2002; Passos et al., 2008; Varlet & Richardson, 2015), or compete team-versus-team (e.g., Bourbousson, Seve, & McGarry, 2010; Duarte et al., 2013; Frencken, Poel, Visscher, & Lemmink, 2012).

Previous studies on coordination dynamics in sports have primarily focused on global patterns as they emerge through the dynamic interactions between athletes. These global coordination patterns were typically captured by a macroscopic inter-athlete or inter-team variable at a local timescale, such as the relative phases (e.g., Bourbousson, Seve, & McGarry, 2010; De Brouwer et al., 2013; McGarry et al., 2002; Varlet & Richardson, 2015) or distances between athletes or teams at the same moments (e.g., Frencken, Poel, Visscher, & Lemmink, 2012; Passos et al., 2008). In the current article, we propose that athletes' movement coordination goes

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beyond behavioral matching or mimicry at local scales, and that athletes coordinate their movements across multiple time scales. This assumption means that the interpersonal coordination would be characterized by a correspondence between athletes' patterns of performance variability. Accordingly, the complexity indices (i.e., fractal scaling exponents) of the athletes' performance time series would align. We aim to test this "complexity matching" hypothesis (e.g., Marmelat & Delignières, 2012; West, Geneston, & Grigolini, 2008) by applying nonlinear time-series analyses to performance data in a cooperative sports task, namely team ergometer-rowing.

1.1. *Capturing complexity in sport performance*

At the level of the individual athlete, well-coordinated behavior self-organizes out of the ongoing coordination within and between components at multiple levels of the system (e.g., cell activity, muscle contractions, limb movements; see Beek, Peper, & Stegeman, 1995; Den Hartigh et al., 2015). This complexity can be detected when examining the fluctuations in time series of athletes' repeated movements, such as stride-to-stride intervals in running (Jordan, Challis, & Newell, 2006) or force peak intervals in rowing (Den Hartigh et al., 2015). Optimal complexity is reflected in a pattern of high-frequency and low-amplitude fluctuations that are nested within low-frequency and high-amplitude fluctuations (e.g., Wijnants, Cox, Hasselman, Bosman, & Van Orden, 2012). This particular pattern of fluctuations is called $1/f$ noise, or pink noise. Patterns of pink noise are assumed to be typical for healthy and well-trained behavior (e.g., Den Hartigh et al., 2015; Glass, 2001; Goldberger et al., 2002; Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009). In sports, an optimal level of complexity would allow athletes to be flexibly stable, a key property of sport expertise (Davids, Glazier, Araújo, & Bartlett, 2003; Den Hartigh et al., 2015). Indeed, studies with cyclists, long-distance runners, skiers, and rowers, have empirically demonstrated patterns close to pink noise in the athletes' performance time series (Den Hartigh et al., 2015; Hoos, Boeselt, Steiner, Hottenrott, & Beneke, 2014; Nourrit-Lucas, Tossa, Zélic, & Delignières, 2015; Tucker et al., 2006).

For stationary processes, the pattern of fluctuations can tend towards disorder or randomness, called white noise (Marmelat & Delignières, 2012). Originally, deviations from pink noise have been linked with suboptimal dynamics, and the presence of (physiological) pathology or less-trained behavior (e.g., Glass, 2001; Goldberger et al., 2002; Wijnants et al., 2009). However, some researchers also suggested that imposing additional constraints on movement coordination tasks results in a different organization of the motor system, thereby shifting the pattern of variation toward more randomness (e.g., Chen, Ding, & Kelso, 2001; Den Hartigh et al., 2015; Diniz et al., 2011; Kuznetsov & Wallot, 2011; Washburn, Coey, Romero, Malone, & Richardson, 2015). In particular when adding rigid constraints (e.g., specifying a movement rhythm to be followed), shifts toward white noise are expected to occur. For example, Washburn et al. (2015) let participants perform a rhythmic arm swinging task and manipulated the environmental constraints. When participants performed their task while being exposed to a visual metronome stimulus, a shift to white noise was observed compared to a condition in which the stimulus was absent. In addition, when participants explicitly intended to time their movements with the stimulus pattern, the shift toward random variation was even more prominent.

Taken together, although external constraints can significantly impact the pattern of variation in motor behavior, under low constraints one would expect a pink noise pattern in well-trained motor behavior (Den Hartigh et al., 2015; Washburn et al., 2015). In sports, this idea was recently supported by studies with rowers and skiers (Den Hartigh et al., 2015; Nourrit-Lucas et al., 2015). In the study by Den Hartigh et al. (2015), rowers with different levels of expertise were asked to just row at their preferred rhythm on a rowing ergometer (Den Hartigh et al., 2015), whereas Nourrit-Lucas et al. (2015) asked skiers with different expertise levels to make ample and frequent cyclical sideways movements on a ski simulator. Under these low constraints, higher-skilled rowers and skiers demonstrated more prominent patterns of pink noise in their performance than their less-skilled counterparts.

1.2. *Complexity matching between athletes*

So far, research has thus provided insights into interpersonal coordination in terms of macroscopic patterns of interaction (e.g., De Brouwer et al., 2013; Passos et al., 2008; Varlet & Richardson, 2015), and more recently into intrapersonal coordination across multiple time scales (e.g., Den Hartigh et al., 2015; Nourrit-Lucas et al., 2015). It is unclear whether athletes in team sports also coordinate their joint behavior across multiple time scales, although a fundamental study on interpersonal coordination outside the domain of sports hints that this might well be the case. Marmelat and Delignières (2012) demonstrated that two people oscillating a hand-held pendulum while sitting next to each other, match the complexity indices of their individual movement time series. They also showed that this complexity matching effect could not be attributed to just copying the movements of the partner, but that it reflected a pattern of *multiscale interpersonal coordination* (for more recent demonstrations of complexity matching in simple interpersonal tasks, see also Coey, Washburn, Hassebrock, & Richardson, 2016; Delignières & Marmelat, 2014; Fine, Likens, Amazeen, & Amazeen, 2015).

Based on the study by Marmelat and Delignières (2012), it is a plausible hypothesis that athletes demonstrate complexity matching in types of sports that require absolute coordination (i.e., synchronizing movements). A typical sport in this regard is rowing, in which athletes need to synchronize their movements for optimal performance (e.g., Den Hartigh et al., 2014; Hill, 2002; Wing & Woodburn, 1995). The aim of the current research is therefore to test whether complexity matching can be detected in rowing, more specifically, in rowers performing a relatively unconstrained and steady workout together on rowing ergometers. In line with recent research on individual ergometer rowing (Den Hartigh et al., 2015), our first hypothesis was that rowers show complex intra-system coordination, reflected by patterns of performance variation that are close to pink noise. Following previous research studying the complexity matching hypothesis outside sports (Delignières & Marmelat, 2014; Marmelat & Delignières, 2012), our second hypothesis was that interpersonal coordination occurs across multiple time scales, reflected by complexity indices between rowing team members that are highly, significantly correlated when they row together. Finally, in accordance with the notion of