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Evaluation of coordination hysteresis in a multidimensional movement task with continuous relative phase and Self-Organizing Maps

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ABSTRACT

Hysteresis in the coordination of movement can be described in the language of coordination dynamics as an asymmetrical response of a system's order parameter with respect to opposite changes in a control parameter. For movement tasks involving a large number of active degrees-of-freedom, the order parameter can be modelled with a pattern recognition approach like Self-Organizing Maps (SOM). This study explored this method in a rope-skipping task, which involves the coordinated oscillation of several segments in the lower and upper limb and trunk and we compared the results to a classical order parameter like continuous relative phase. Five rope skippers completed a task which involved 30 s continuous forward rope-skipping during which the frequency (set by a metronome) increased linearly, immediately followed by 30 s during which the frequency decreased linearly. CRP was analyzed with statistical parametric mapping and a hysteresis measure for the SOM was calculated based on inter-trial variability. Both the CRP and the SOMs showed that the coordination patterns changed differently during the two conditions, signifying hysteresis. While the CRP captures only the relative coordination of two segments, the SOM is able to accommodate the whole-body multidimensional coordination. Hysteresis is often used as proxy for higher-order information about the movement system. While the low sample size in this study does not allow us to generalize the results, the present methodology can be used in further studies to advance our theoretical understanding of dynamical systems in complex whole-body movements.

1. Introduction

Hysteresis is defined as the history-dependence of the state of a system. In biological non-linear systems, this phenomenon is associated with irreversible thermodynamic changes such as non-equilibrium phase transitions (Kelso, 1995; Prigogine, 1997). Classical examples at the cellular and tissue levels include the refractory period of neurons and elastic hysteresis in the musculo-tendinous unit. In the language of coordination dynamics (Kelso & Engstrom, 2006), it is characterized by an asymmetrical response of a system's order parameter with respect to opposite changes in a control parameter. Hysteresis effects demonstrate that for a

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certain range of a control parameter, bi- or multi-stable coordination states exist and that switching between these states is history-dependent, i.e. the switching occurs at different points of the control parameter when it is manipulated in opposite directions. Switching between stable states (phase transitions) are often initiated through an increase in variability (Kelso, 1995). Hysteresis is a consequence of the non-linearity of the biological systems that contribute to the task. Non-linear equations allow different solutions according to the history of the system.

In motor control experiments, hysteresis has been demonstrated numerous times in rhythmical (e.g. Adhikari, Quinn, & Dhamala, 2013; Bartlett, Lamb, O'Donovan, & Kennedy, 2014; Buchanan & Kelso, 1993; Van Emmerik & Wagenaar, 1996), discrete (e.g. Kelso, Buchanan, & Murata, 1994; Rein, Davids, & Button, 2010; Schütz, Weigelt, & Schack, 2016; Sørensen, Ingvaldsen, & Whiting, 2001) and static (e.g. Orizio, Baruzzi, Gaffurini, Diemont, & Gobbo, 2010) motor tasks. The previous citations also serve to illustrate the different levels of the human movement system on which hysteresis has been examined (brain activity, muscle activity, relative phase between segments, range of motion, multi-dimensional coordination). Hysteresis in motor behavior can be seen as a marker for underlying complexity and can be used as a proxy to examine potential influences thereon. In a grasping task, hysteresis in the order parameter (one- or two-handed grasping) with respect to object size (control parameter) was always present in typically developing children, whereas children with autism spectrum disorder showed no hysteresis when social cues were present (Amaral, Romero, Kloos, & Richardson, 2017). Also in a grasping and pointing task, Schütz, Weigelt, and Schack (2017) used hysteresis as a proxy for the construct of cognitive cost for motor planning and have shown how the movement system differentiates hysteresis effects between joints according to their role in the movement. They showed that hysteresis was only present in joints that did not critically interfere with task execution. Miura, Kudo, and Nakazawa (2013) demonstrated larger hysteresis and transition points in street-dancers compared to novices in a knee flexion/extension motion to the beat (control parameter). These examples illustrate that measuring hysteresis can be informative for how our movement systems operate and what factors influence it on a global scale. However, it is not always clear to choose an appropriate order parameter for an arbitrary task when multiple degrees-of-freedom are highly relevant for the execution.

Arguably the most commonly used measure to define coordination is the continuous relative phase (CRP) between two oscillating segments (Hamill, Haddad, & Mcdermott, 2000; Lamb & Stöckl, 2014; Peters, Haddad, Heiderscheit, Van Emmerik, & Hamill, 2003). However, for whole-body movements, part of the attractiveness of the relative phase is lost, because it represents only the coordination between two oscillating segments (Lamb & Bartlett, 2017). Analyzing relative phase angles for all combinations of degrees of freedom soon becomes cumbersome with increasing numbers of relevant degrees of freedom. In case the research interest lies with the global whole-body coordination of both arms and legs with each three segments, six intra-limb- and nine inter-limb CRPs are needed to capture the entire pattern. Additionally, in tasks with large fluctuations of the CRP within a movement cycle, it is sometimes unclear when a new coordination mode emerges; e.g. when the CRP changes on the order of π radians within a cycle, then it is difficult to make a discrete in-phase/anti-phase description of the entire motion and the CRP-pattern becomes a time-continuous order parameter. Recent studies in motor control of high-dimensional motions have suggested Self-Organizing Maps (SOM) as a tool for visualization and analysis of coordination of systems with multiple degrees-of-freedom (Lamb, 2012; Lamb, Bartlett, & Robins, 2011; Serrien, Clijsen, Anders, Goossens, & Baeyens, 2016; Serrien, Hohenauer, et al., 2017). SOMs are a type of artificial neural network, inspired on neurobiological models of learning, that are able to reduce the complexity of multiple time series data to a trajectory on a two-dimensional plane, while still preserving the non-linear topological relations in the original data (Kohonen, 2001; Lamb et al., 2011). This trajectory through the SOM represents a collective variable of the multiple time series and can be used as an order parameter of the complete coordination state (Bartlett et al., 2014; Lamb, Bartlett, Lindinger, & Kennedy, 2014; Lamb et al., 2011; Serrien et al., 2016).

In this paper, we will present a SOM methodology to examine hysteresis in multidimensional rhythmic coordination and compare the results to a classic CRP analysis. We will use rope skipping as a paradigm task for whole-body multidimensional coordination and study how the SOM and CRP capture changes therein with respect to jumping frequency, which will act as the control parameter. Rope skipping is a fun, intensive sport characterized by sometimes difficult techniques. It demands a high degree of coordination at multiple levels: intra- and inter-limb coordination, inter-personal coordination and perceptual-motor coordination with the rhythm of the music. Already in its simplest form, rope skipping is a complex high-dimensional whole body movement that involves both jumping and upper limb joint movements to rotate the rope. It represents a paradigm skill that allows to examine possible hysteresis effects in a complex motion and to develop a method to describe this effect. Our objectives in this study were to: (1) Propose a SOM methodology to examine hysteresis and compare the results to an analysis with CRP; (2) Verify whether hysteresis is present in a continuous forward rope skipping task. For the latter objective, we hypothesized the presence of hysteresis in the coordination patterns. Based on the tenets of coordination dynamics (Kelso, 1995; Kelso & Engstrom, 2006), we assumed that the couplings between the large number of degrees-of-freedom would be non-linear and therefore probably show history-dependent effects. Because rope skippers have to scale their jumping frequency up and down multiple times to the pace of the music under various conditions and techniques, the bi/multi-stability associated with this hysteresis would be beneficial for their repertoire.

2. Methodology

2.1. Subjects

Five female rope skippers were recruited for this study (S1–S5). Two were professionally occupied with rope skipping (S1, S2). The range in age, height, weight and rope skipping experience across the five participants were respectively 17–33 years, 163–176 cm, 53–79 kg and 16–26 years. All subjects were informed about the study protocol and signed an informed consent. The study protocol was approved by the ethics committee of the university hospital Brussels.