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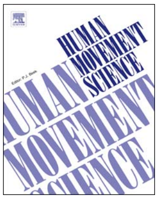

Full Length Article

Limit cycle dynamics of the gymnastics longswing

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ABSTRACT

The purpose of the study was to examine the macroscopic dynamics of the longswing through a limit cycle analysis of the motion of the center of mass (CM) as a function of skill level. One elite international, five gymnasts able to perform release and regrasp skills, five gymnasts unable to perform release and regrasp skills, and five novice gymnasts each performed four consecutive longswings on a high bar. Kinematic data were collected to facilitate the calculation of the center of mass position of the performer during swinging. Poincare plots were used to explore the limit cycle dynamics of the center of mass movement. The attractor dynamic was very close to a one-dimensional limit cycle for the elite ($D = 1.18$) but higher for the release and regrasp group ($D = 1.35 \pm 0.06$) and non-release and regrasp group ($D = 1.37 \pm 0.07$). The novice dynamic was characterized by a two-dimensional limit cycle ($D = 2.49 \pm 0.28$) that also had more variability and lower determinism. In the frequency domain, Inharmonicity was lower and the Q factor higher as a function of increased skill level. The findings show that the dynamical degrees of freedom of the CM in the skilled performance were reduced compared to those of novices and represented a more efficient and predictive, rather than exploratory, technique.

1. Introduction

The concepts of thermodynamics and self-organization have underpinned the introduction of dynamical systems approaches to further the understanding of movement coordination, control and skill (Kelso, 1995; Kugler, Kelso, & Turvey, 1980; Kugler & Turvey, 1987; Lipsitz & Goldberger, 1992). Dynamical approaches seek low dimensional solutions, such as limit cycles and other attractors, to capture the global macroscopic movement dynamics of the complex multi-segment musculoskeletal system in action. Macroscopic coordination dynamics in motor control has typically been limited to the consideration of relations between two limb segment oscillators through measures of relative phase and vector coding (Haken, Kelso, & Bunz, 1985; van Emmerik, Ducharme, Amanda, & Hamill, 2016). However, Bernstein's (1967) problem was to understand how the many degrees of freedom (DF) of the system are organized so as to master the redundancy of the system: a multivariate challenge that requires a theoretical and experimental strategy to decompose the contribution to system control of the many degrees of freedom (DF) in whole-body action.

Gel'fand and Tsetlin (1962), in an early systems approach, sought a determination of the qualitative structural relations by

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distinguishing essential variables from the nonessential variables, where the latter were hypothesized to play primarily a scaling role in a movement coordination pattern (see Kugler et al., 1980). In the coordination dynamics framework, it is assumed that mechanical DF of joint space are working to preserve (and are reciprocally preserved by) the dynamic characteristics of the collective variable in the context of a successful performance of the action (Kelso, 1995; Mitra, Amazeen, & Turvey, 1998; Schöner, Zanone, & Kelso, 1992). To date, investigation of the construct of collective variables for complex multi-variable human movement has been largely limited to the 2 DF bimanual task. The unpacking of the collective variable in whole-body motion DF tasks is a more difficult challenge. It has been approached through post hoc decomposition of a set of movement variables through principal component analysis (PCA; Daffertshofer, Lamoth, Meyer, et al., 2004; Haken, Peper, Beek, & Daffertshofer, 1996; Huys, Daffertshofer, & Beek, 2004) to derive coordinated components, reduce dimensionality, and interpreted as providing a characterization of the functional or dynamical DF of the movement coordination pattern (Haken, 1995). In addition, multivariate techniques have been demonstrated by Delignières et al. (1998), Latash (2010a, 2010b), Nourrit, Delignières, Caillou, Deschamps, and Lauriot (2003), and Vereijken, van Emmerik, Whiting, and Newell (1992). Alternatively, the macroscopic state of the system has been investigated through the guess of a biomechanically relevant global dynamical variable. For example, Ko and Newell (2016) provided evidence that the collective variable for postural control was the phase relation between CM and the center of pressure (CP). Segers, Lenoir, Aerts, and De Clercq (2007) suggested that for gait transitions, the order parameter was the phase relation between the potential and kinetic energy of the center of mass.

For the purpose of this paper, a macroscopic variable is a global variable, biomechanically associated with the performance of the skill (such as the CM which is the key outcome measure of the longswing (Hiley & Yeadon, 2016)), while a collective variable is a way to describe the relative motions of mechanical degrees of freedom, as demonstrated by relative phase measure or PCA techniques (Daffertshofer et al., 2004; Haken et al., 1985).

Several studies have provided experimental support for the freezing and freeing of the joint space degrees of freedom with learning, as proposed by Bernstein (1967) (Newell, 1991; Newell, Broderick, Deutsch, & Slifkin, 2003; Vereijken et al., 1992). However, there does not appear to be a single strategy to change in learning, as the emergent pathway in the adaptive organization of the torso and limbs in action is strongly influenced by the particulars of the task constraints (Newell & McDonald, 1994). In addition, research has shown that depending on the task constraints and intrinsic dynamics, the functional dynamical DF of the attractor dynamic can either increase or decrease with learning (Newell & Vaillancourt, 2001; Newell et al., 2003). The confluence of these approaches has resulted in much debate as to what the DF of movement organization represent in motor control, for example mechanical or dynamical variables (Latash, 2010a, 2010b; Newell & Vaillancourt, 2001).

The longswing on the high bar (Fig. 1; also referred to as the "horizontal bar") involves the rotation of the performer about the high bar in the sagittal plane. The longswing is a fundamental skill that underpins the development of more complex high bar skills. The biomechanics of the joint motions, as well as the inter-joint/segment couplings, in the longswing as a function of skill level has been extensively studied (Busquets, Marina, & Angulo-Barroso, 2013; Busquets, Marina, & Irurtia, & Angulo-Barroso, 2013; Busquets, Marina, Irurtia, Ranz, & Angulo-Barroso, 2011; Busquets, Marina, Davids, and Angulo-Barroso, 2016; Williams, Irwin, Kerwin, & Newell, 2012, 2015a, 2015b; Williams et al., 2016). However, from a dynamical perspective, the longswing has an implicit limit cycle demand in the task constraints, where consecutive rotations are sustained via the input of energy in each cycle. Specifically, a limit cycle is defined as an attractor with a closed trajectory in phase space. Defining the overarching mechanics of the system, further evidence to support the use of an angular position-angular velocity (phase space) representation of the skill is found in forward dynamics models. These consider the angular velocity of the center of mass (CM) of the performer about the bar as the key outcome measure (Hiley & Yeadon, 2014; Hiley & Yeadon, 2016): suggesting that it is a macroscopic dynamical variable. Therefore, the dynamics of the CM could provide evidence of skill level in line with the dimensionality and deterministic properties of that limit cycle dynamic (see Goldfield, Kay, and Warren (1993) for a related developmental oscillatory movement example).

Fig. 1. Representation of a performer completing a longswing on high bar. The performer is at 0 and 360° when in handstand above the bar.