LIMIT CYCLE REPRESENTATION OF THE GYMNASTICS LONGSWING

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Human movement science is searching for ways to capture global dynamics of our complex multi-segment system. The aim of this study was to explore differences in a limit cycle representation of longswings on high bar as a function of skill level. One elite international, one collegiate, and one novice gymnast performed four consecutive longswings on high bar. Through the novel representation of the longswing as a limit cycle, and exploration of the limit cycle characteristics, it is shown that higher frequency, more phase coherent oscillations, and lower limit cycle variability occurs as a function of skill level. It is suggested that this candidate collective variable be explored as a global indicator of skill level and learning that can provide insight into the efficiency of the mechanical system.

KEY WORDS: dynamical systems, variability, frequency, collective variable

INTRODUCTION: Human movement science is searching for ways to capture global dynamics of our complex multi-segment system. Measures of coordination used in motor control and biomechanics often consider phase relations between two oscillators, for example measures of Relative Phase, Vector Coding and Continuous Relative Phase (van Emmerik et al., 2016). However, Bernstein's (1967) problem was to understand how the many degrees of freedom of the system are organised so as to master the redundancy of the system. To date, order parameters for complex multi-variable human movements have been proposed by two key approaches; statistical approaches and global variables. For example, statistical methods such as Principal Component Analysis (Daffertshofer et al., 2004; Lamoth et al., 2009) use the components level of data as an input to the resulting 'nodes' or models that characterise the coordination of the system and to reduce the dimensionality of multiple degrees of freedom of the system. While data reduction and statistical methods are introduced, these techniques preserve knowledge of individual mechanical degrees of freedom in the dynamic. Alternatively, authors have described the state of the entire system through a biomechanically relevant global variable, and its relationship to another global variable. It is suggested then, mechanical degrees of freedom are working to preserve characteristics biomechanically related to the successful performance of the action (Williams et al. 2015). For example, Ko and Newell (2015) suggested that the order parameter for postural control was the phase relation between the centre of mass and the centre of pressure, while Segers, Aerts, Lenoir, De Clercq (2007) suggested that for gait transitions, the order parameter was the phase relation between the potential and kinetic energy of the centre of mass. Similarly, the structure of a single global variable such as the centre of pressure during standing, has been analysed in line with Lipzits and Goldberger's loss of complexity hypothesis (Scholz, Kelso and Schöner, 1987; Costa et al., 2005, van Emmerik et al., 2016).
A variable capturing the biomechanically relevant global state of the system could be a good candidate collective variable to capture the system dynamics and understand motor control and motor learning. Therefore, the aim of this study was to investigate a limit cycle representation of the longswing on high bar (a global variable) as a function of performers' skill level.

METHODS: Prior to the onset of the study, approval was gained from the University's Ethics committee. Three male participants; one elite international GB Squad gymnast, one collegiate level gymnast, and one novice gymnast (mean age 22 ± 1 years, mass 69 ± 2 kg, height 1.74 ± 0.08 m), gave voluntary informed consent to take part in this study.
Anthropometric data were obtained using the digital image technique facilitating the calculation of individual-specific body segment masses. Each participant performed a series of four longswings while looped to the high bar. Unilateral kinematic data were collected using an automated 3D motion capture system (CODA) sampling at 200 Hz. Two CX1 CODA scanners (Charnwood Dynamics Ltd, UK) provided a field of view exceeding 2.5 m around the centre of the bar. Active markers were placed on the lateral aspect of each participant's right side at the estimated centre of rotation of the shoulder and the elbow, at the mid forearm, greater trochanter femoral condyle, lateral malleolus, fifth metatarsophalageal and the centre of the underside of the bar.
Data Processing: The angle between the vertical and the centre of mass defined the gymnast's position about the bar, where 0 and 360 º saw the gymnasts in handstand above the bar. Angular velocity of the centre of mass (ωCM) was interpolated in 1° increments of rotation about the bar and plotted as a phase space (Figure 1). Variability between ωCM of each of the four swings at each degree in the circle was calculated based on the standard deviation (SD). Average variability in each quartile of the swing (90 º) portions was calculated, as well as the average variability across the whole swing. A frequency analysis was performed on the raw (not interpolated) ωCM data in R (http://www.r-project.org) using the seewave package (http://rug.mnhn.fr/seewave/) to perform Fast Fourier Transform (FFT) with 216 point moving Hanning window with no overlap. The harmonicity index is a quantitative description of how a certain spectrum was deviating from a perfectly harmonic one and was calculated by first normalizing the spectrum to their base frequency (swing frequency), then as the average of the exponential of the deviation of a peak from a perfectly harmonic spectrum. A purely harmonic spectrum where all the overtones are integer multiples of a fundamental frequency has a harmonicity index equal to 1, a less harmonic spectrum is >1. The Q Factor is the resonance quality factor of a frequency spectrum determined using the Q function in seewave at a specific dB level -3 dB.

RESULTS: Phase space plots (Figure 1a) showed that the ωCM was smoother, more symmetrical, and more consistent for elite and collegiate gymnasts, when compared to the novice gymnast. Maximum ωCM was higher for the novice gymnast, suggesting a less efficient swing. Frequency analysis of the ωCM (Figure 1b) showed that that novice participant had a higher amplitude of frequencies between 0-6 Hz, but a lower contribution at frequencies between 6-8 Hz of the normalised frequency, compared to the elite and collegiate gymnasts (Figure 2). Harmoncity index reduced as a function of experience (Table1).
Variability of the ωCM was on average higher during the whole swing and during all quadrants of the swing for the novice, compared to the collegiate gymnast, where the elite gymnast had the lowest variability in ωCM between swings (Figure 3a, b).

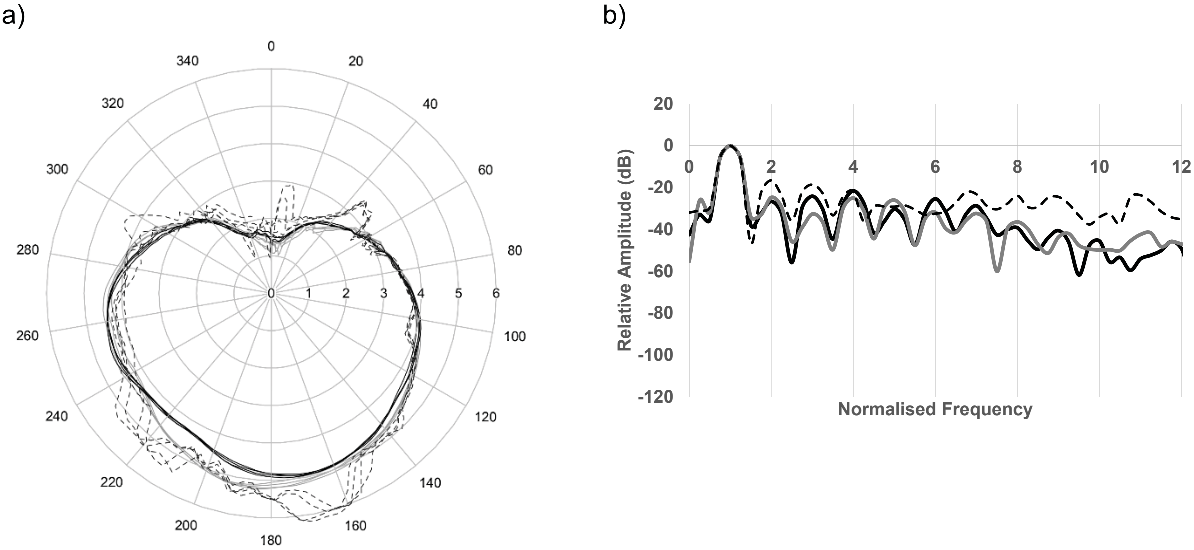

Figure 1: a) Polar plot of the centre of mass angular velocity (ωCM; x-axis) in the circle (y-axis) for four consecutive longswings by an elite gymnast (solid black line), collegiate gymnast (solid grey line) and novice (dashed black line); b) Normalised (to swing) frequency spectrum of the ωCM for an elite gymnast (solid black line), collegiate gymnast (solid grey line) and novice (dashed black line).

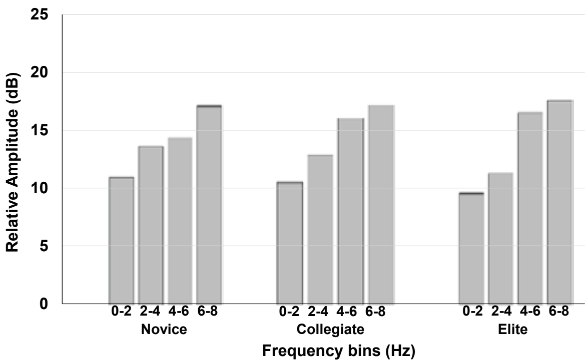

Table 1: Harmonicity index and Q Factor related to Figure 1b.

	Novice	College	Elite
Harmonicity index	1.38	1.23	1.19
Q factor	4.09	4.08	2.16

Figure 2. Relative amplitude of oscillations in frequency bins 0-2:6-8 Hz.

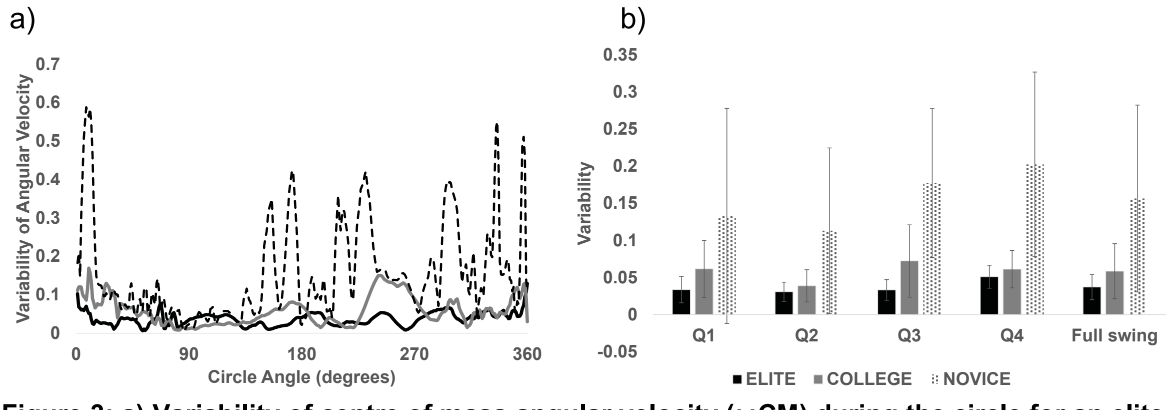

Figure 3: a) Variability of centre of mass angular velocity (ωCM) during the circle for an elite gymnast (solid black line), collegiate gymnast (solid grey line) and novice (dashed black line); Mean and standard deviation of ωCM for each quartile of the circle and the full circle for an elite gymnast (solid black bar), collegiate gymnast (solid grey bar) and novice (dashed black bar).

DISCUSSION: The aim of this study was to investigate a limit cycle representation of the longswing on high bar as a function of skill level of performers. The phase space represents the swing as a limit cycle; it is suggested that a limit cycle is a stable attractor that describes sequential longswings since energy input by the gymnast (Williams et al., 2015) creates self-sustaining oscillations.

Phase space plots (Figure 1a) showed that the ωCM was smoother for elite and collegeate gymnasts, compared to the novice gymnast. This was further explored by a frequency analysis of the ωCM, that showed the novice participant had a higher amplitude of frequencies but that they were less structured, compared to the elite and collegiate gymnasts, as demonstrated in figure 2 and through the Q Index (Table 1). The novice gymnast was adjusting the ωCM throughout the swing using lower frequency oscillations and this related to a jerkier trajectory of the limit cycle. This finding suggests that more skilled gymnasts create a smoother ωCM profile through exploiting higher frequency adjustments in ωCM. Furthermore, the smoother limit cycle provides evidence of a more efficient swing.

A novel variable, harmonicity index, is presented, which measures the deviation of overtones from integer multiples of the fundamental frequency. Harmonicity index provides an understanding of the organisation of frequencies of a signal, where a more harmonic spectrum identifies phase coherence between oscillations, likely related to a more efficient action. Harmoncity index reduced as a function of experience, suggesting that a tighter phase coherence in oscillations was present in the ωCM, and again, a more mechanically efficient swing was produced (Table1).

The consistency of sequential swings performed by the elite gymnast was high (Figure 1a). Variability in the ωCM showed that over the whole swing, and in all 4 quadrants of the swing, the elite gymnast had a more consistent profile of ωCM than the collegiate or novice gymnast (Figure 3a,b), suggesting that ωCM variability across swings decreases as a function of skill level, which could provide a metric of performance level for this skill.

CONCLUSIONS: Through the novel representation of the longswing as a limit cycle, and exploration of the limit cycle characteristics, it is shown that higher frequency, more phase coherent oscillations, and lower limit cycle variability occurs as a function of skill level. It is suggested that this candidate collective variable be explored as a global indicator of skill level and learning that can provide insight into the efficiency of the mechanical system.

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