DYNAMICS OF A CYCLIC TASK BEFORE AND AFTER A CHANGE IN TASK CONSTRAINT: HORIZONTAL BAR LONGSWING

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Returning to a consistent technique after a change in skill allows gymnasts to improve routine fluidity. This study investigates the limit cycle dynamics of the mass centre (CM) after a variation in task constraint during the horizontal bar longswing (LS). Gymnasts (n=12) from 3 different age categories completed 3 x 8 consecutive LS with LS four and five as accelerated LS. Senior gymnasts presented the most consistent limit cycle trajectory and lowest correlation dimension (CD) post- compared to pre- task constraint. Senior gymnasts displayed significantly lower CD post- constraint compared to both junior ($p = .016$) and development gymnasts ($p < .001$). The increased proficiency attributed to senior gymnasts appears to increase the stability features of the LS limit cycle of the CM angular velocity after an imposed task constraint which may indicate readiness to progress to more complex horizontal bar skills.

KEYWORDS: dynamical systems, limit cycle, correlation dimension, stability.

INTRODUCTION: Consistency in performance outcome during repetitive movements requires athletes to have the capacity to adapt to large and subtle changes in task constraints (Wilson *et al.*, 2008). Therefore, a big problem for an athlete and coach is finding a solution to producing consistent performance that encompasses optimal levels of variability and stability in the underlying redundant processes to allow for adaptability within performance. Stability of a dynamical system, distinguished by determining the response to perturbations in the system states, is a fundamental issue within system theory. In movement science, to allow for an athlete to transition to a new state and/or adapt to new constraints, Van Emmerik *et al.* (2016) note that a link between the stability and variability of movement patterns may exist. This concept has also been referred to as the ability to utilise 'functional variability' that allows a performer to ensure consistent performance outcome in the face of changing constraints and may be characteristic of the highly skilled (Wilson *et al.*, 2008). Through the application of non-linear dynamics, knowledge of variability and stability can begin to quantify the adaptability and flexibility of a system in time. From a non-linear dynamics view, the horizontal bar longswing (LS) in gymnastics has the essential features of a limit cycle attractor, with closed trajectory features in phase space whereby the gymnast's energy input sustains the required rotations (Vicinanza *et al.*, 2018). The regular longswing limit cycle has previously shown little variation and high levels of dynamical stability across age groups of high-performance gymnasts (Burton *et al.*, 2019), however how these fundamental dynamics adapt and respond to a change in task constraint is currently unknown.

In gymnastics, highly restrictive laws govern all movement patterns, therefore deviation from outlined technique is deemed negative and attracts score penalties. Should a change in task constraints occur, a rapid transition back into the required movement pattern is most desirable. The LS on horizontal bar is known as the "building material" upon which more complex elements are developed. During a horizontal bar routine, gymnasts are required to transition between LS, close bar elements, release-regrasp skills and back into the LS (Hiley *et al.*, 2013). Backward LS for which the purpose is to increase angular velocity (ω) are frequently referred to as "accelerated" LS (AccLS). Research has indicated that angular momentum essential for release-regrasp movements and dismount elements on horizontal bar are generated through the performance of the AccLS (Irwin *et al.*, 2016). For a gymnast beginning to learn more complex skills, the AccLS is an essential skill to master before progressing to a release-regrasp skill and is therefore extensively practiced ensuring safe, efficient and effective skill learning. Incorporating a change in task constraint, such as AccLS, to a series of regular LS is not essential coaching practice, however, allows investigation of LS stability characteristics and an understanding into how gymnasts respond to altering task constraints and transition back into consistent LS performance, a requirement throughout horizontal bar routines. This knowledge may inform coaches as to when gymnasts should progress onto more complex release-regrasp elements, based on the variability and stability characteristics of the LS dynamics pre- and post- change in task constraint. The faster a gymnast can return to consistent LS technique after a change in skill, the better the routine fluidity and subsequent overall execution score. Therefore, the aim of this study was to investigate limit cycle dynamics of the mass centre (CM) after a variation in task constraint during the horizontal bar longswing.

METHODS: Participants: Ethical approval was gained from the University Research Ethics Committee. Four senior (age: 19 ± 0.27 yrs, mass: 61 ± 2.66 kg, stature: 1.65 ± 0.03 m), four junior (15 ± 0.66 yrs, 50 ± 8.77 kg, 1.60 ± 0.09 m) and four development (10 ± 0.67 yrs, 27 ± 4.29 kg, 1.11 ± 0.04 m) high-performance male artistic gymnasts gave voluntary informed consent to partake in the study. A legal parent or guardian provided informed consent for participants under the age of 18 years. Each participant performed three trials of eight consecutive LS whilst looped to the horizontal bar, with the addition of AccLS during LS four and five. The three LS pre- and post- AccLS were used within the analysis. Direct anthropometric measurements were obtained in line with Yeadon's (1990) inertia model to determine CM.

Data Collection and Processing: An automated 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, Leicester, UK) sampling at 100 Hz captured unilateral kinematic data. Two CX1 scanners provided a field of view exceeding 2.50 m around the centre of the bar (see Williams *et al*., 2012). Active markers were fixed laterally to each participant's right side on the fifth metatarsophalangeal joint, lateral malleolus, lateral femoral condyle, greater trochanter, estimated centre of rotation of the glenohumeral joint, lateral epicondyle, mid forearm and the underside of the centre of the horizontal bar. Data were processed using a modified code (Vicinanza *et al.,* 2018) in R (http://www.r-project.org). Circle angle (θc) was distinguished by the mass centre to bar vector with respect to the horizontal, where, a θc of 90° and 450° defined the gymnast's CM as above the bar. Data were interpolated using a cubic spline to 1° increments of overall θc about the bar.

Data Analysis: Poincaré plots (see Kantz & Schreiber, 2004) were used to denote the CM trajectory in phase space. Methods from Vicinanza *et al*. (2018) were used to calculate Takens' vectors and estimated correlation dimension (CD). A one-way analysis of variance followed by Bonferroni post-hoc tests examined differences across performance levels. Paired sample t-tests were used to examine differences between pre- AccLS and post- AccLS within groups; $\alpha < 0.05$. Hedges g calculations were used to generate 95% confidence intervals (CI) and within group effect sizes (*g*) pre- and post- AccLS with omega squared (ω^2) calculations used to generate between group effect sizes pre- and post- AccLS. Statistical tests were processed in IBM SPSS Statistics 26 Software (IBM SPSS, Inc., Chicago, IL, USA).

RESULTS & DISCUSSION: The aim of this study was to investigate limit cycle dynamics of the CM after a variation in task constraint during the horizontal bar longswing. Overall, the structure of the limit cycle displayed a more consistent ωCM trajectory in phase space and lower CD post- AccLS in comparison to pre- AccLS for senior gymnasts, whereas the opposite was apparent for junior and development gymnasts. Development gymnasts displayed significantly higher CD post- AccLS in comparison to senior gymnasts ($p<.001$) and junior gymnasts ($p = .016$) (Table 1). Poincare plots (Figure 1 and 2) denote the closed loop limit cycle trajectories in phase space pre- and post- AccLS. Topologically, minimal variation is observed for the senior and junior gymnasts limit cycle trajectory in comparison to the development gymnasts pre- AccLS. Post- AccLS little variation is observed within the senior gymnasts limit cycle trajectories, however increased variation can be observed for the junior and development gymnasts especially. The results indicate a high-level of consistency within the limit cycle trajectory for senior gymnasts. These gymnasts were able to rapidly return to the original dynamical pattern indicating that inclusion of the AccLS resulted in minimal deviation from the baseline LS limit cycle trajectory in comparison to the junior and development gymnasts. For senior gymnasts, the relatively small change in task constraint did not dislodge the system from the original state space and returned quickly to the original trajectory, indicating a high level of stability (Clark, 1995). The low levels of variation here indicates a stable behavioural state (Clark, 1995), however, it is important to note that each individual requires an optimal level of variability in order to adapt to changing constraints and ensure successful performance (Stergiou *et al*., 2006). Therefore the perfect CD of 1, which denotes perfect cyclical movement, is near impossible even for high-performance athletes.

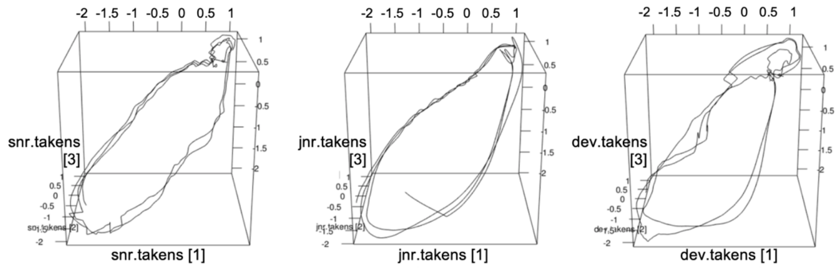

Figure 1. Poincaré plot representation of a senior (left), junior (centre) and development (right) gymnast for three LS pre- AccLS.

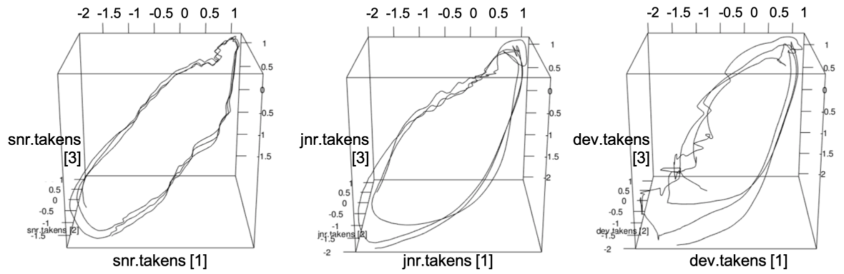

Figure 2. Poincaré plot representation of a senior (left), junior (centre) and development (right) gymnast for three LS post- AccLS.

Table 1. Comparison of CD across senior, junior and development gymnasts pre- and post- AccLS with effect sizes and confidence intervals. * denotes significant difference to senior gymnasts (α < 0.05).

Mean ± SD	Pre- AccLS	Post- AccLS	*g*	95% CI
Snr	1.40 ± 0.27	1.25 ± 0.09	0.9	[-0.02, 0.37]
Jnr	1.35 ± 0.34	1.51 ± 0.45*	0.4	[-0.53, 0.22]
Dev	1.70 ± 0.56	1.94 ± 0.41*	0.5	[-0.72, 0.24]
ω^2	0.08	0.38		

For CD of the Poincaré plot trajectory there were no significant differences between groups for the pre- AccLS ($F(2,33) = 2.595$, $p = .090$, $\omega^2 = 0.08$); however, significant differences were found for the post- AccLS (F(2,33(= 12.910, p< .001, $\omega^2 = 0.38$). Post hoc analyses revealed significantly higher CD for the development in comparison to the senior (F(2,33(= 12.910, p< .001) and junior gymnasts ($p = .016$) although no significant differences were found for senior/junior gymnasts ($p = .205$). Older gymnasts performing at the highest level often have an increased skill level, increase in practice hours and experience with fundamental gymnastics skills than high-performance development gymnasts due to the increased exposure to skills and number of training hours. Pre- AccLS CD were similar for senior and junior gymnasts which could be explained due to the differing experience levels within each chronological age group. However, post- AccLS CD presented an attractor close to a one-dimensional limit cycle for senior gymnasts whereas junior and development gymnasts presented an attractor closer to two-dimensional. The reduction in the dynamical degrees of freedom displayed by the senior gymnasts post- AccLS indicates a more predictive and

efficient limit cycle trajectory and a lower bound on the number of essential variables needed to model the dynamics (Vicinanza *et al.,* 2018), indicating that the senior gymnasts have moved more towards the control stage of learning (Newell, 1985) and therefore may be in a better position to progress to more complex skills than the junior and development groups.
No significant differences were found within participant groups pre- to post- AccLS (senior: p= .076, *g* = 0.9, junior: p= .371, *g* = 0.4, development: p= .298, *g* = 0.5). Gymnasts often begin learning and developing the demanding release-regrasps skills on the horizontal bar during their transition from junior to senior level. In comparison with these skills, the AccLS is a relatively small change in task constraint for the senior gymnasts; therefore, may be able to transition back into the more stable regular LS technique efficiently due to the small magnitude of change experienced. However, junior and development gymnasts are likely to still be familiarising with the correct movement technique for the AccLS and therefore may not be as well-rehearsed or experienced compared to the senior gymnasts, which may contribute to the increased CD post- AccLS compared to pre- AccLS for these gymnasts. The more stable movement trajectory and level of control when returning to LS post- task constraint may indicate that the senior gymnasts are in a better position to begin learning/performing the more complex release and regrasp skills. The consistency, reduced dimensionality and predictability of the limit cycle dynamics both pre- and post- task constraint may be an indicator for a coach to progress the gymnast as they may be better equipped to control the longswing in and out of other elements and maintain fluidity throughout a horizontal bar routine.

CONCLUSION: The further practice and continuing individual development that is attributed to more senior gymnasts appears to increase the stability characteristics of the LS limit cycle trajectory of the ωCM after an imposed task constraint. The ability of the senior gymnasts to display similar limit cycle dynamics before and after the task constraint is an interesting phenomenon suggesting that they possess greater ability to adapt to changing constraints and may indicate readiness to progress to more complex skills on the horizontal bar. These are desirable characteristics for gymnastics horizontal bar performance and skill learning and should be explored further.

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