©Journal of Sports Science and Medicine (2016) **15,** 268-276
http://www.jssm.org

Research article

Differing Roles of Functional Movement Variability as Experience Increases in Gymnastics

Albert Busquets [1]✉, Michel Marina [1], Keith Davids [2] and Rosa Angulo-Barroso [1, 3]
[1] Institut Nacional d'Educació Física de Catalunya, Universitat de Barcelona, Barcelona, Spain; [2] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, UK; [3] Kinesiology, California State University, Northridge, Northridge, CA, USA

Abstract
Current theories, like Ecological Dynamics, propose that inter-trial movement variability is functional when acquiring or refining movement coordination. Here, we examined how age-based experience levels of gymnasts constrained differences in emergent movement pattern variability during task performance. Specifically, we investigated different roles of movement pattern variability when gymnasts in different age groups performed longswings on a high bar, capturing the range of experience from beginner to advanced status. We also investigated the functionality of the relationships between levels of inter-trial variability and longswing amplitude during performance. One-hundred and thirteen male gymnasts in five age groups were observed performing longswings (with three different experience levels: beginners, intermediates and advanced performers). Performance was evaluated by analysis of key events in coordination of longswing focused on the arm-trunk and trunk-thigh segmental relations. Results revealed that 10 of 18 inter-trial variability measures changed significantly as a function of increasing task experience. Four of ten variability measures conformed to a U-shaped function with age implying exploratory strategies amongst beginners and functional adaptive variability amongst advanced performers. Inter-trial variability of arm-trunk coordination variables (6 of 10) conformed to a \-shaped curve, as values were reduced to complete the longswings. Changes in coordination variability from beginner to intermediate status were largely restrictive, with only one variability measure related to exploration. Data revealed how inter-trial movement variability in gymnastics, relative to performance outcomes, needs careful interpretation, implying different roles as task experience changes.

Key words: Task experience, inter-trial variability, performance, inter-segmental coordination, gymnastics.

Introduction

Throughout the lifespan individuals are able to achieve new task performance goals through acquiring functional coordination patterns over time, with a process of refining acquired skills continuing at advanced levels of learning. Progress towards increasingly skilled performance consists of the acquisition and stabilization of more effective movement patterns (Vereijken et al., 1997). In this dynamic process of skill acquisition, adaptation and refinement, it has been proposed that movement variability may have different roles (Davids et al., 2003; Newell, 1985). For example, within-participant variability in movement coordination, over trials, has been defined as having a functional role, providing necessary fluctuations that allow individuals to refine and adapt acquired movement patterns (Davids et al., 2003; Newell, 1985).

Inter-trial variability has previously been examined by assessing its magnitude (Barris et al., 2014; Clark and Phillips, 1993; Hamill et al., 1999; Polk et al., 2008; Williams et al., 2015a; Wilson et al., 2008). Low values of variability here is considered a behavioural state that remains stable over time, while high variability has been characterised as system exploration during transitions to new or more refined movement patterns (Clark, 1995; Clark and Phillips, 1993; Hamill et al., 1999). It is proposed that an optimal range of variability is needed to learn and adapt motor skills (Stergiou et al., 2006). Values below this optimal amount of variability could make the system too rigid and values over the optimal variability would make the system too unstable. Within the optimal range of variability, early in learning, inter-trial variability may be high due to exploration of new coordination modes during practice. But in more skilled performers, variability can also need to be high to provide flexibility in adapting and refining movements to new performance contexts or challenges (Davids et al., 2003; Hamill et al., 1999; Wilson et al., 2008). Some initial suggestions have implied that magnitude of inter-trial variability conforms to a U-shaped function with skill progression (Wilson et al., 2008). A U-shaped function characterising movement variability might indicate that stable performance outcomes can be achieved in a number of ways in sport performers, varying in skill level, because different performance conditions may require different coordination modes during task performance (Edelman and Gally, 2001; Seifert et al., 2013).

The amount of variability in the performance and coordination dimensions can change in accordance with the skill level (Schöllorn et al., 2009; Scholz et al., 2000). The Uncontrolled Manifold hypothesis proposes that the relationship between performance and coordination variability and the global performance of the task must be taken into account to interpret the functionality of the role of observed variability at different levels of motor expertise (Scholz and Schöner, 1999). Observed variability over trials can be associated with achievement of the key performance outcome in two ways: (a) low inter-trial variability would restrict variability in key performance measures (V_{REST}), yet lead to task improvements; and (b), high inter-trial variability allows individuals to explore new coordination modes (V_{EXPL}), resulting in simultane-

Received: 06 November 2015 / Accepted: 04 March 2016 / Published (online): 23 May 2016

ous improvements in key performance measures.

To elucidate these different roles of movement variability as skill level changes, in this study we investigated performance in a multi-articular gymnastic skill as a task vehicle: the ‘basic’ longswing on the high bar (Irwin and Kerwin, 2005). During the longswing, gymnasts move from handstand to handstand position (at the top of the bar) by rotating around the high bar with a relatively straight body. Full extension of the arms and legs during the whole movement are expected to reach the criteria for the quality gymnastic movements defined in the Fédération Internationale de Gymnastique (FIG) Code of Points (2015). A gymnast executes a backward swing as the body rotates to the rear with the front of the body leading throughout the movement. Individuals involved in a full gymnastics training programme successfully perform longswings after extended periods of practice, during which small longswing amplitudes of beginners increase progressively towards complete longswings from handstand to handstand in advanced performers. In addition, when gymnasts increase in competency, the longswing becomes a complementary skill to link other skills with higher difficulty levels, such as dismounts or flight elements, in a performance sequence (Arampatzis and Bruggemann, 1999; Hiley and Yeadon, 2003; Irwin and Kerwin, 2005; 2007).

Several previous studies have revealed the importance of hip and shoulder flexion and extension in successful execution of the longswing (e.g. Yeadon and Hiley, 2000). Irwin and Kerwin (2005) defined two functional mechanical phases during ‘basic’ longswing execution: (a) a rapid hyper-extension to flexion (i.e. closing angle) of the hip after the gymnast passes through the lowest part of the circle, and (b), extension to flexion (i.e. opening angle) of the shoulder joint just before reaching the highest point of the circle. Hip movements can be analyzed by observing coordination between trunk and leg segments, while the segmental arm-trunk coordination can provide insights on shoulder movements. Previous studies (e.g. Busquets et al., 2011; Williams et al., 2012; 2015a) have reported that novices, after a short period of practice (around two months), show more variability in functional phases of movement than experts. In addition, Williams et al. (2015a) found that novices who completed full longswings (360º) presented higher variability where the variability observed in expert longswings were low. They suggested that the high variability presented by the novice gymnasts allowed them to explore different motor-perceptual strategies. That is, an increase in task experience changes the coordination and performance outcomes of the longswing (Busquets et al., 2013a), and likely their variability levels.

Understanding progression in skill level of a task can be achieved by studying performance in different age groups (Fleisig et al., 1999; Streepey and Angulo-Kinzler, 2002), since older participants typically accumulate more task experience than younger groups. Performance comparisons across different age groups are a good proxy for skill level since it affords cross-sectional observations of task experience effects. Although the true process of learning cannot be characterized, this study design allows researchers to gain insights into relevant changes in task performance, from beginner status to more advanced levels. In a previous study of experience effects on longswing performance, we investigated performance and coordination across competition age groups (Busquets et al., 2013a). This work demonstrated that the younger gymnasts displayed performance and coordination of earlier key events, while more expert gymnasts also revealed later key events in longswing performance. However, the roles of movement variability in establishing and refining functional coordination modes, as age-based experience increased were not evaluated in that study. With those findings in mind, the objective of this study was to examine the relationship between movement variability and performance outcomes as a function of expertise level.

Here, we assessed changes in inter-trial variability of coordination and performance outcomes in the longswing, from beginners to more advanced performers, differing in age. Based on current theorising in Ecological Dynamics (e.g. Seifert et al., 2013), we hypothesized that a U-shaped function would be observed in movement pattern variability across groups of beginner, intermediate and advanced gymnasts. As already outlined, we expected the magnitude of inter-trial variability of performance outcome measures and relevant coordination variables to be larger in younger age groups (beginners) than in intermediate level gymnasts, and to increase again in more experienced groups. Additionally, we hypothesized that relations between inter-trial variability and a key performance outcome variable, considering individual data points for each of the three younger groups, would determine which variables revealed restrictive (V_{REST}) and exploratory constraints (V_{EXPL}) during practice. We expected that beginners would display emergent coordination modes with more exploratory variability (V_{EXPL}) than other groups, while intermediate level gymnasts would seek to stabilise emerging coordination patterns by increasing V_{REST}. From a practical perspective, results of this research study could contribute towards a more accurate focusing of the use of practice variability across competition age groups to improve performance outcomes like swing amplitude or longswing proficiency.

Methods

Participants

The participants, age-groups and task performed in this study are the same as those presented in the previous study by Busquets et al. (2013b). Male gymnasts (n = 113), classified into five competition-age groups (G1, G2, G3, G4, and G5) participated in the study (Table 1). Gymnastic experience of participants (expressed in years) increased from younger to older individuals. All participants declared themselves to be fit and injury free, had two or more years of experience in gymnastics’ training, including experience of the longswing on the high bar, and had competed at national level for their age group. All participants older than 18 years of age, and the parent or legal guardian of participants younger than 18, signed a written consent form to participate. In addition, verbal

Table 1. Participant characteristics expresed by group means (±standard deviations).

	Group 1 (n=26)	Group 2 (n=30)	Group 3 (n=17)	Group 4 (n=18)	Group 5 (n=22)
Age (years)	8.9 (.9)	11.1 (.8)	12.9 (.5)	14.8 (.6)	20.0 (3.4)
Experience (years)	3.6 (1.3)	5.3 (1.0)	7.7 (1.4)	9.0 (1.6)	14.2 (2.6)
Height (m)	1.31 (.05)	1.39 (.07)	1.48 (.08)	1.62 (.10)	1.65 (.05)
Mass (kg)	28.6 (3.4)	34.3 (4.9)	40.3 (4.9)	53.6 (10.8)	63.4 (5.0)
Longswing amplitude (deg)	237.6 (72.5)	269.6 (80.9)	322.3 (67.6)	357.7 (.6)	357.8 (.5)

consent was also obtained from the young children. The Ethics Committee of Clinical Research of the Catalan Sport Administration approved the consent and study procedures.

Experimental protocol

A gymnasium with a regular high bar was used for the experiment. First, gymnasts performed a warm-up and practised longswings on the high bar. Each test started with participants suspended in a stable and extended position under the bar. They then performed ten consecutives 'basic' longswings to achieve and maintain maximum swing amplitude. Gymnasts were asked to execute all longswing according to the FIG Code of Points (2015) (i.e. arms and legs fully extended throughout its execution).

Data collection

Participants were filmed at 50Hz with two digital video cameras (Handycam DCR-HC23E Mini DV, SONY, Japan). Cameras were located at 1.28 m height, one on each side of the plane containing the bar, and forming a 90º angle between their optical axes. For participants who did not complete the longswings, an expert coach selected the three consecutive backwards swings with the largest amplitude for further analyses. When participants performed longswings from handstand to handstand, the second, third, and fourth longswings were selected for analysis. A trial was considered as each of three consecutive selected longswings. Space calibration was conducted following procedures of Busquets et al. (2011). Kwon3D software was used to calculate the absolute mean reconstruction error (1.67 cm) and root mean square error (RMSE) (0.67 cm) over 12 frames from images of the calibration settings.

Data reduction

Selected videotaped images were manually digitized by the first author with Kwon3D 3.00.033 (Young-Hoo Kwon and Visol, Inc). Intra-coder reliability accumulated over the entire longswing, but averaged across key action landmarks, achieved an average value of RMSE = 2.3 cm for the whole trajectory. A Butterworth Low-pass fourth order recursive filter was used to smooth the raw data. Residual analysis and qualitative evaluation of the data established a cut-off frequency of 5 Hz. Hip and shoulder angular displacements and velocities were computed in the sagittal plane. Hip angular movements were derived from the angle between the right thigh and trunk (shoulder, great trochanter and femoral condyle markers). Shoulder angular movements were obtained from the angle between the right upper arm and trunk (elbow, shoulder and great trochanter markers). Segmental angles of the arm, thigh and trunk were also calculated relative to the vertical axis (*z*-axis). To identify peaks and valleys in joint angle displacement-time traces, custom software in Matlab version 7.01 (Mathworks R14) was developed.

The angle formed by the line connecting the center of mass (CM) with the middle of the grasping hand and the vertical (*z*) axis of the coordinate system defined body position angle during longswings (Yeadon and Hiley, 2000). Location of gymnasts' CM was calculated in two ways: (a) for gymnasts younger than 20 years, we used Jensen's equations for participants between 4 and 20 years (Jensen, 1989; Jensen and Nassas, 1988), and (b), de Leva's data (de Leva, 1996) were applied for gymnasts aged 20 years or more. Body position displacements around the high bar were characterized to range the possible path from 0 degrees, when CM was at vertical over the bar before the downswing (i.e. initial handstand position), to 360 degrees, when the CM was directly over the bar, after the upswing (i.e. final handstand position).

A single parameter can be used to define the key performance outcome of a task, and in our study, the swing amplitude was the key performance outcome measure we selected for analysis (Busquets et al., 2013a; Williams et al., 2012). It was defined as the body position trajectory between the start point (Pi, defined by the maximum elevation of the CM in the downswing) and the end point (Pf, defined by the maximum elevation of the CM in the upswing) for each longswing. The task goal was defined as achieving a completed longswing when gymnasts moved from handstand to handstand, while other amplitudes were classified as non-completed longswings.

In addition to swing amplitude (i.e. the key performance output), skill performance of participants, in executing longswings, was described using performance outcomes (task events) and coordination variables (positive and negative areas in the continuous relative phase) (Busquets et al., 2013 a; 2013b). Three events of interest independently for the hip (H) and shoulder (S) angle joint movement in the sagittal plane were defined to characterize longswing performance (Yeadon and Hiley, 2000): (i) the maximum angle (i.e. opened angle) of the hip and shoulder under the bar (P2H, P2S); (ii) the minimum angle (i.e. closed angle) of the hip and shoulder before P2 (downswing, P1H and P1S), and (iii), both these key events after P2 (upswing, P3H and P3S). These task events were identified by analyzing hip and shoulder angle joint movements in each longswing trial. Longswing amplitude value and task events were expressed in degrees referenced to body position trajectory from handstand to handstand (Figure 1).

To describe the coordination mode between the actions of two limb segments at every point, we used segmental angular data from arm, trunk, and thigh to

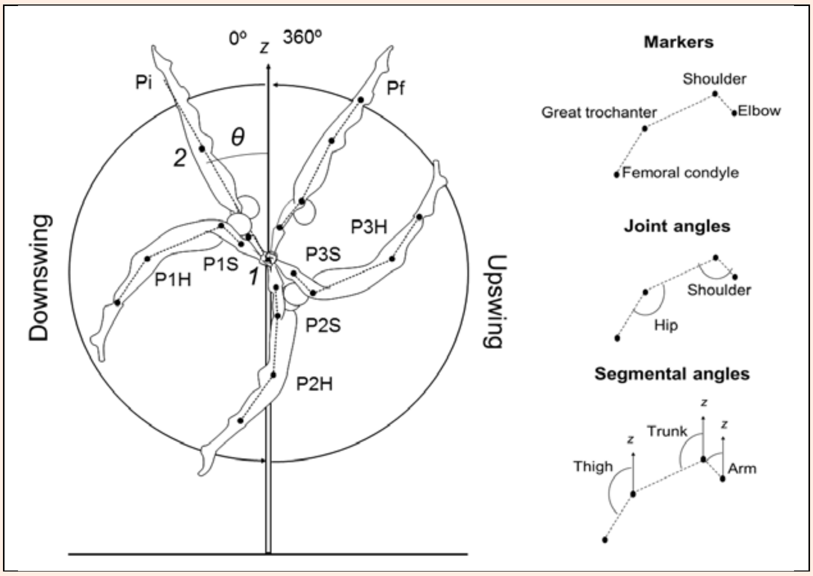

Figure 1. Graphic schema of the events during a longswing. On the left side, Middle grasping hand marker (*1*) and the center of mass (*2*) defined the body position angle (*θ*) in relation to the z axis. The illustrations shows the initial position (Pi), final position (Pf) and longswing events (P1, P2, and P3) from the hip (H) and shoulder (S) joints. Hip and shoulder events have been represented at the same instant of time for P1-P3 for simplicity. On the right side, definitions of the markers (elbow, shoulder, great trochanter and femoral condyle), joint angles (hip and shoulder), and segmental angles (arm, trunk, and thigh) are depicted.

compute the value of continuous relative phase (CRP) between arm-trunk (AT) and trunk-thigh (TT) (Clark and Phillips, 1993; Hamill et al., 1999). Continuous relative phase of each longswing was characterized examining the positive (Pos) and negative areas (Neg) (Busquets et al., 2013a; 2013b). Since all body segments move in the same direction during longswing performance, positive and negatives areas of CRP indicate changes in relative angular velocity of limb segments. Positive values in AT CRP signify that the arm moves faster than the trunk, while positive values in TT CRP indicate that movements of the trunk are faster than the thigh movements. Positive (Pos) and negative areas (Neg) were computed over intervals established by the three shoulder events for arm-trunk CRP (P1S-P2S, P2S-P3S, and P3S-Pf), and the three hip events for trunk-thigh CRP (P1H-P2H, P2H-P3H, and P3H-Pf).

Variables

We analyzed inter-trial variability by computing the standard deviation (SD) value of each performance outcome and coordination variables for each participant. Due to the enormous amount of time involved in manually digitizing the videotape images, we decided to compute inter-trial variability across three trials which has been deemed sufficient to characterize system variability in previous research (Clark and Phillips, 1993; Polk et al., 2008). Inter-trial variability in performance was assessed for P1H, P2H, P3H, P1S, P2S, and P3S; and inter-trial variability in coordination was evaluated for positive and negative areas over intervals determined by shoulder and hip events (P1S-P2S, P2S-P3S, and P3S-Pf in arm-trunk CRP and P1H-P2H, P2H-P3H, and P3H-Pf in trunk-thigh CRP).

Statistical analyses

To assess changes in variability magnitude across the competition-age groups performing longswings, we used a One-way MANOVA in which competition age group was the between-group factor. Achieving the complete longswing was expected to impact coordination modes adopted by each gymnast. In order to control this factor in the MANOVA, we included task achievement (completed longswing or non-completed longswing) as a controlling variable. A Shapiro-Wilks test was used to check distribution normality; data were transformed adequately when normality tests failed. Differences between groups were established using Tukey's HSD post hoc test. P values of subsequent One-way ANOVAs from MANOVA were adjusted using Bonferroni's correction. Effect size was measured with partial eta squared (η^2p) indicating a small effect when $\eta^2p = 0.010$, while $\eta^2p = 0.059$ and $\eta^2p = 0.138$ is medium and large respectively.

Statistically significant One-way ANOVAs were also followed up by visually checking the U-shaped graph fitting by plotting the inter-trial variability group means across age-groups (i.e. scatter plots). In addition, Pearson correlation coefficients and scatter plots were used to relate inter-trial variability variables with the selected key performance outcome measure (i.e. longswing amplitude) in each of the three youngest groups (G1, G2, and G3). Since all older gymnasts (G4 and G5) performed completed longswings (i.e. 360º), correlations between longswing amplitude and inter-trial variability were only conducted for the youngest groups.

Statistical significance levels were set at $p < 0.05$ level, and only statistically significant results reported. All tests were performed with SPSS 13.0 (SPSS Inc., Chicago, IL, USA) and Sigma Plot 9.0 (Systat Software, Inc., San José, CA, USA).

Table 2. Significant simple main effects of One-Way (Group) MANOVA.

Variable group	Variable name	*F*	*df*	*p*	η^2p	Power
Performance	P2H	2.84	4,108	.028	.095	.757
	P3S	2.92	4,108	.024	.098	.770
Coordination	AT-Pos P1S-P2S	2.58	4,108	.041	.087	.710
	AT-Neg P1S-P2S	3.35	4,108	.012	.111	.832
	AT-Neg P2S-P3S	4.73	4,108	.001	.149	.945
	TT-Pos P1H-P2H	3.56	4,108	.009	.116	.856
	TT-Pos P2H-P3H	3.03	4,108	.021	.101	.787
	TT-Neg P1H-P2H	3.01	4,108	.021	.100	.784
	TT-Neg P2H-P3H	4.47	4,108	.002	.142	.930
	TT-Neg P3H-Pf	6.64	4,108	.001	.197	.990

P1, P2, and P3 represent hip (H) and shoulder (S) events, while Pf stands for the final position. AT= arm-trunk coordination; TT= trunk-thigh coordination; Pos=positive area in the continuous relative phase; Neg= negative area in the continuous relative phase.

Results

Longswing amplitude increased from beginners to advanced gymnasts (Table 1). All gymnasts in G4 and G5 completed longswing amplitudes of 360º (Figure 2).

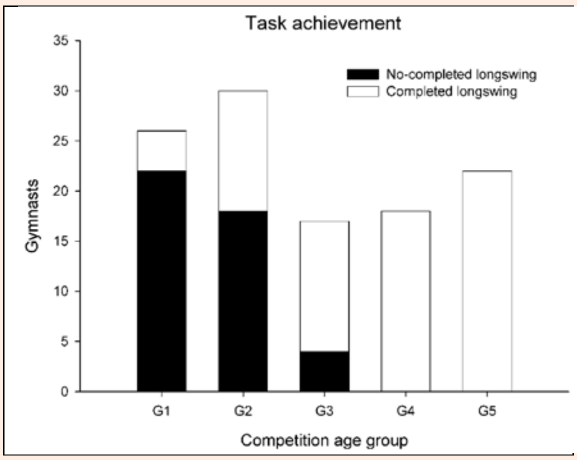

Figure 2. Gymnasts that achieved completed swing by group. Graphs illustrate the number of gymnasts that achieved the complete longswing (from handstand to handstand) and the number of gymnasts who performed no-completed longswings.

Variability values were compared by MANOVA with competition-age groups as a between-group factor and task achievement (completed versus non-completed longswings) as a control variable. Results from Pillai's Trace test showed a statistically significant effect for group ($F_{4,108}$ = 2.15, p = 0.001) with a large effect size (η^2p = 0.292). Ten variables (two from performance outcome variability and eight from coordination variability) yielded statistically significant differences when subsequent One-way ANOVAs were applied (Table 2).

Performance outcome variables (i.e. key task events) yielded significant variability differences across the age groups in two variables: the maximum opened angle of the hip (P2H) and the maximum closed angle of the shoulder during upswing (P3S) (Figure 3a, b). Variability in P2H decreased from G1 to G4, while advanced performers (G5) increased variability between trials. Results revealed that P3S became more consistent from beginners (G1) to intermediates (G3), whereas advanced performers (G4 and G5) increased variability in P3S. However, post-hoc analyses only showed significant differences in P3S between G3 (13-14 years) and G4 (15-16 years). Both variables fitted a U-shape function.

Regarding coordination variability across competition-age groups, significant differences for arm-trunk (AT) and trunk-thigh (TT) variables were found when subsequent One-way ANOVAs were conducted (see Figure 3c-j). Values of coordination variability differed across competition-age groups in eight variables (three from arm-trunk and five from trunk-thigh). Variability between trials in arm-trunk coordination decreased from the younger group (G1) to older groups (G4-G5). Post-hoc analyses showed that G1 displayed more variability than G5 in positive areas between shoulder maximum closed angle during downswing (P1S) and shoulder maximum opened angle (P2S) (Figure 3c). Regarding negative areas, G1 showed larger values of variability in P1S-P2S than G4 (Figure 3d) and larger values of variability in P2S-P3S than G3-G5 (Figure 3e). Variability in arm-trunk coordination across competition-age groups seemed to fit a back-slash-shaped (\-shaped) or L-shaped curve.

Trunk-thigh (TT) coordination variability also changed across competition-age groups. Variability of the positive areas between hip maximum closed angle during downswing (P1H) and hip maximum opened angle during upswing (P3H) decreased from beginners (G1) to advanced gymnasts (G5) (Figure 3f, g). Post-hoc analyses indicated significant differences between G1 and G5 in P1H-P2H and P2H-P3H. Both indicators of variability fitted a \-shaped graph. In addition, negative areas variability in trunk-thigh coordination from P1H and P3H decreased from beginners (G1-G2) to intermediates (G3) and increased in more advanced performers (Figure 3h-i). Post-hoc analyses showed that G4 displayed smaller negative area variability between trials than G2 during downswing (P1H-P2H), and also than G1 and G2 during upswing (P2H-P3H). Variability from P1H-P2H and P2H-P3H negative areas fitted a U-shaped curve. On the other hand, negative areas of the hip maximum closed angle in the upswing to final position (P3H-Pf) presented smaller variability values in G4 compared with G2 and in G5 compared with G1 and G2 (Figure 3j). Variability of the trunk-thigh negative area in P3H-Pf fitted a \-shaped graph.

Pearson correlations (*r*) were conducted to identify relationships between variability measures that yielded significant differences in MANOVA and longswing

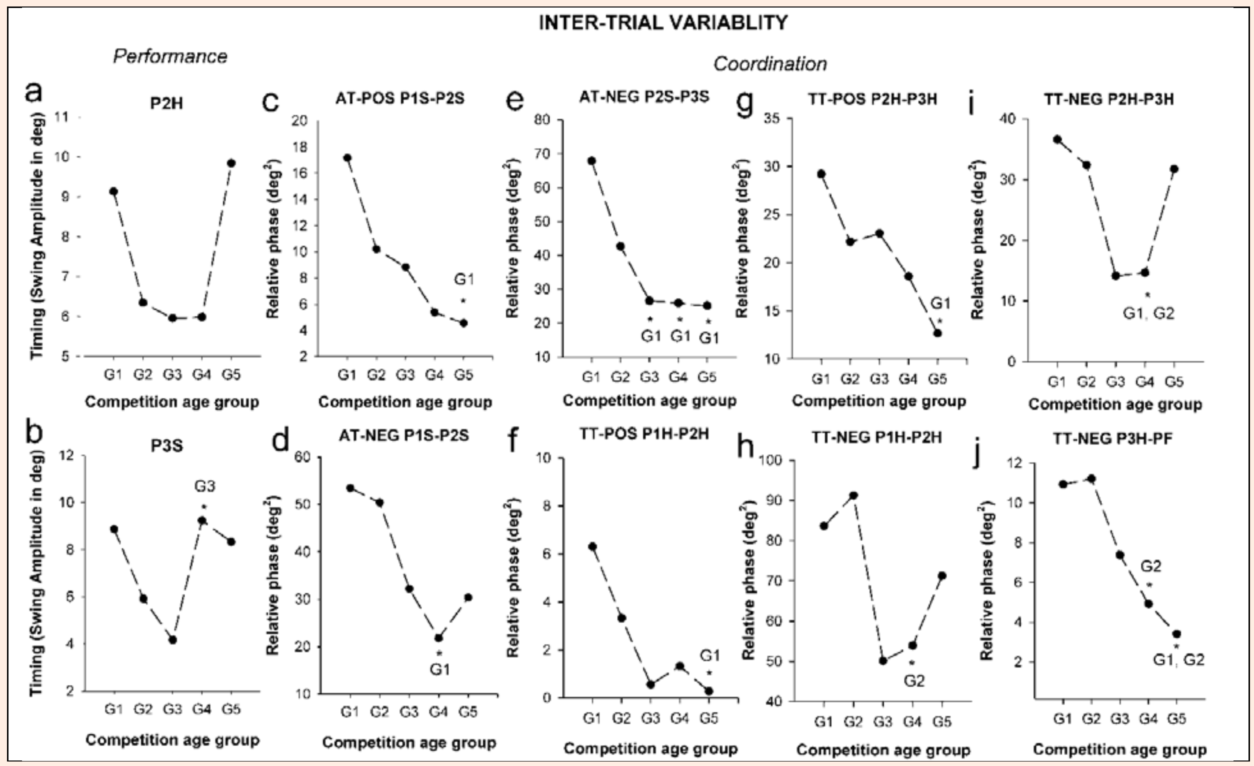

Figure 3. Inter-trial variability mean values from beginner to advanced groups. Performance and coordination inter-trial variability mean values for each group that yielded significant differences across competition ages are depicted. Significant differences (p<.05) between groups from ANOVAs post-hocs were also plotted (*) indicating which groups differed.

amplitude in G1, G2, and G3 (Table 3). Coordination variability displayed significant relationships in six of the measures, while no significant correlations were found in performance outcome variability.

Table 3. Significant results from the bivariate correlation analysis between the global-task variable (longswing amplitude) and variability variables.

	G1	G2	G3
	r	*r*	*r*
Coordination			
AT Pos P1S-P2S	.581**	.519**	-
AT Neg P1S-P2S	-	-.401*	-
AT Neg P2S-P3S	-.590**	-.515**	-.788***
TT Pos P1H-P2H	-.400*	-	-.527*
TT Pos P2H-P3H	-	-.491**	-
TT Neg P2H-P3H	-	-.398*	-.551*

P1, P2, and P3 represent hip (H) and shoulder (S) events. AT= arm-trunk coordination; TT= trunk-thigh coordination; Pos=positive area in the continuous relative phase; Neg= negative area in the continuous relative phase.

Correlation analyses for beginners (G1) yielded negative and statistically significant *r* values (V_{REST}) in arm-trunk negative areas between the maximum opened angle and maximum closed angle of the shoulder during upswing (P2S-P3S). The same relationship was also observed in the trunk-thigh positive areas between the maximum closed angle of the hip during downswing and maximum opened angle (P1H-P2H). In addition, arm-trunk positive areas between the maximum closed angle during the downswing and maximum opened angle (P1S-P2S) of the shoulder presented positive and significant correlations (V_{EXPL}) for G1. G2 showed negative and statistically significant correlations (V_{REST}) for two variables from arm-trunk (AT) coordination and two from trunk-thigh (TT). V_{REST} was observed in the arm-trunk negative areas from shoulder maximum closed angle during downswing to maximum closed angle during upswing (P1S-P2S and P2S- P3S). Regarding trunk-thigh coordination, the variables that revealed negative and significant correlations (V_{REST}) were both the positive and negative areas' variability values observed between the hip maximum opened angle and maximum closed angle during the upswing (P2H-P3H). In addition, arm-trunk positive areas in P1S-P2S displayed by G2 correlated positively (V_{EXPL}) with longswing amplitude. The intermediate group (G3) exhibited negative and significant *r* values (V_{REST}) in arm-trunk negative areas in P2S-P3S and trunk-thigh negative areas inP2H-P3H.

Discussion

In this study we examined the nature of inter-trial variability during longswing performance in beginners, intermediate level and advanced gymnasts. The magnitude of inter-trial variability, observed in younger, less experienced, participants was expected to be higher than that displayed in, older, intermediate level performers, and would increase again in the oldest, more advanced, performers. Two performance outcomes and two coordination variables supported our U-shaped variability hypothesis, originally mooted by Wilson et al. (2008). Six of the coordination variability measures displayed a decrease in variability values with increasing age (a \-shaped graph or an L-shaped graph).

The two performance variability measures that appeared to fit a U-shaped function were: the hip maximum opened angle (P2H) and the shoulder maximum closed angle during upswing (P3S). Successful execution of these phases is mechanically critical for maintaining angular momentum during the upswing and for achieving complete longswing amplitude (i.e, 360º) (Irwin and Kerwin, 2005). Larger values of inter-trial variability in P2H and P3S events displayed by beginners may have reflected their role in facilitating movement exploration in early stages of learning. Greater performance stability in the P2H and P3S phases observed in the intermediates may have been functional for attaining longswing amplitude improvements approaching 360º. Advanced gymnasts showed the largest P2H and P3S inter-trial variability values, perhaps displaying their capacity to adapt longswing execution for coordinating an ensuing movement component in the gymnastic sequence. As gymnasts increase their experience and expertise, the longswing becomes complementary action that allows them to link their current movements to other skills with higher difficulty levels (Arampatzis and Bruggemann, 1999; Hiley and Yeadon, 2003; Irwin and Kerwin, 2005, 2007). For example, this coordinative feature of the longswing would facilitate linkages with dismounts or flight elements during sequence performance. Although previous work by Hiley et al. (2013) reported less variability in the critical hip events of regular and accelerated longswings, the discrepancy of their data with our results may have been due to differences in participant numbers and/or the use of relatively fewer trials per participant (4 participants and 10 trials per participant in Hiley et al., 2013 vs. 113 participants and 3 trials per participant in the present study). These variations in research findings suggest how different, but equally valid, experimental designs, involving distinct numbers of participants and trials, need to be conducted to enhance understanding og the functional roles of movement in variability. Despite the validity of a particular selected design, the research strategy chosen could be a significant cause of different experimental outcomes, relative to other studies in the area, making it challenging to compare findings.

In the current study, the two coordination variability variables that appeared to fit a U-shaped function were the trunk-thigh negative areas between the hip maximum closed angle during downswing and the maximum closed angle during the upswing (TT Neg P1H-P2H and TT Neg P2H-P3H). Variability in trunk-thigh coordination seemed to be reduced from G2 to G3 for these two variables, possibly signaling that more movement stability was necessary during the central part of the longswing (P1H-P3H) to achieve 360º trajectories within G3. Beginners and advanced gymnasts displayed larger variability values in velocity of the thigh relative to the trunk for these two coordination variables, again likely due to exploratory behaviours, and an increased capacity to adapt skill performance to changing contexts, respectively.

An additional configuration of variability changes was found in six coordination variables, confirming to a \-shape or L-shape, indicating that variability decreased across competition-age groups and remained low for more skilled groups. The larger values of trunk velocity, with respect to the thigh, became more stable from beginners to advanced performers, when they moved from the hip maximum closed angle during the downswing to the maximum closed angle during upswing (P1H-P3H). When examining arm-trunk coordination variability, data showed more stability in arm-trunk positive and negative areas from the shoulder maximum closed angle during downswing to the maximum opened angle (P1S-P2S). Last, the variability observed around the lower velocity of the arm, relative to the trunk (negative area in the CRP) in P2S-P3S, was reduced from G1 to G3. G3 was the youngest group that showed longswing amplitudes similar to those of advanced gymnasts. It could be argued that reductions in variability values of arm-trunk coordination from the maximum closed angle during the downswing to maximum closed angle during the upswing may be necessary to perform a longswing to 360º. These results were in agreement with the findings in a study of adult novices by Williams et al. (2015a), where novices showed more variability in coordination at positions during the longswing, and where the variability reported for expert performers was low. In addition, differences found between arm-trunk and trunk-thigh coordination variability reinforced the idea of dissociations between the hip and shoulder actions (Busquets et al., 2013b; Williams et al., 2012; 2015a; 2015b).

Examining relationships between performance and coordination variability displayed across age groups in relation to longswing amplitude highlighted which variables were relevant to improve the key performance outcome and to understand the functional roles of observed variability. Correlations between variability measures and the key performance outcome may be indicative of exploration (V_{EXPL}, variability increased as longswing amplitude improved) or restricted behaviours (V_{REST}, variability decreased as longswing amplitude increased). These correlations were examined in the three youngest groups, given that the advanced performers displayed an almost constant value of longswing amplitude. We expected that the beginners would display more exploratory variability (V_{EXPL}) than other groups, while the intermediates would increase their restriction of variability (V_{REST}). Six of the ten variability measures that changed significantly across competition-age groups were related to the key performance outcome measure in the beginners.

Only one variable was related to exploratory variability (positive area P1S-P2S) in G1, and restricted behaviours were more evident in G2, than in the intermediates (G3). Gymnasts in G1 improved longswing amplitude when greater arm relative velocity variability emerged in P1S-P2S. These results suggest that modifying coordinating arm-trunk movements between trials allowed gymnasts to explore functional motor strategies to increase longswing amplitude (V_{EXPL}). On the other hand, G1 also restricted variability (V_{REST}) of trunk velocity relative to the thigh during downswing (P1H-P2H), and relative to the arm, between the shoulder maximum opened angle and maximum closed angle during upswing (P2S-P3S). Increased longswing amplitudes were achieved by G2 through use of restricting strategies (in 5 of 6 variability variables). G2 decreased variability (V_{REST}) of the trunk-thigh coordination from hip maximum opened angle to maximum closed angle during upswing (P2H-P3H) and arm velocity relative to the trunk from the point of shoulder maximum closed angle during downswing to maximum closed angle during upswing (P1S-P3S). To obtain larger longswing amplitudes, beginners needed to reduce variability rather than to explore different coordination modes by exploiting greater variability. These results contrast with the increased variability observed in novices who improved their longswing performance during the 8-week training programme (Williams et al., 2015a). However, it is important to note that the limited exploratory behaviours observed in the beginners revealed their already sufficient experience level (at least two years) compared to complete novices. In fact, the mean longswing amplitude in G1 was 237º, similar to values achieved by novices with just two months of practice (Williams et al., 2015a). The suggestion is that variability persists for different functions in novices and beginners. Our data indicate that the restricting strategies observed in our sample may be a valid approach needed by beginners in gymnastics. However, further longitudinal studies are needed to support this claim and to assess the functional role of the variability during an extended learning procgramme in sport.

The intermediate gymnasts (G3) demonstrated longswing amplitude improvements while decreasing variability of arm velocity relative to the trunk in P2S-P3S and thigh relative velocity to the trunk in P2H-P3H. Restrictive behaviours in P2S-P3S emerged in G1, G2, and G3, and restrictive behaviours in P2H-P3H also emerged in G2. These behaviours are clearly emergent and are aligned with predictions of the Uncontrolled Manifold hypothesis proposing that some coordination variables are regulated (restricted) while others are allowed to vary (exploratory) (Latash et al., 2007; Scholz and Schöner, 1999). In the longswing, some variability measures may be more related to the key performance outcome of amplitude, while others are not. As task experience improves, the number of variables to be regulated is decreased. The presence of variability restricting behaviours across competition-age groups indicates that decreasing variability of some coordination variables is critical to improving longswing amplitude. This observation seems especially true for arm velocity relative to the trunk between P2S and P3S, since G3 reduced this variable's level of variability to those observed in advanced gymnasts (G4, G5).

Conclusion

This cross-sectional analysis provided some important insights into the different roles of coordination variability, exploratory and restrictive, during longswing performance on the high bar across different experience groups. The utilization of performance and coordination variability, as task experience changed, seemed to be represented in two different configurations (U-shaped and L-shaped or \-shaped functions). Reduction in arm-trunk coordination variability is critical to complete the longswing (i.e. 360º). In contrast, high values of variability of the functional phase events (P2H, maximum opened angle of the hip, and P3S, maximum closed angle of the shoulder during upswing) and coordination around P2H could provide adaptive flexibility in longswing performance, to facilitate linkages to other skill components required in competitive gymnastic sequences (e.g. dismounts and flight elements).

Acknowledgements

This study was supported by Institut Nacional d'Educació Física de Catalunya (INEFC) and Grup de Recerca en Activitat Física i Salut (GRAFiS, Generalitat de Catalunya 2014SGR/1629).

References

Arampatzis, A. and Bruggemann, G.P. (1999) Mechanical energetic processes during the giant swing exercise before dismounts and flight elements on the high bar and the uneven parallel bars. *Journal of Biomechanics* **32,** 811-820.

Barris, S., Farrow, D. and Davids, K. (2014) Increasing functional variability in the preparatory phase of the takeoff improves elite springboard diving performance. *Research Quarterly for Exercise and Sport* **85,** 97-106.

Busquets, A., Marina, M. and Angulo-Barroso, R. M. (2013a) Changes in motor strategies across age performing a longswing on the high bar. *Research Quarterly for Exercise and Sport* **84,** 353-362.

Busquets, A., Marina, M., Irurtia, A. and Angulo-Barroso, R.M. (2013b) Coordination Analysis Reveals Differences in Motor Strategies for the High Bar Longswing among Novice Adults. *PLoS One* **8,** e67491.

Busquets, A., Marina, M., Irurtia, A., Ranz, D. and Angulo-Barroso, R. M. (2011) High bar swing performance in novice adults: effects of practice and talent. *Research Quarterly for Exercise and Sport* **82,** 9-20.

Clark, J.E. (1995) On becoming skillful: patterns and constraints. *Research Quarterly for Exercise and Sport* **66,** 173-183.

Clark, J. E. and Phillips, S.J. (1993) A longitudinal study of intralimb coordination in the first year of independent walking: a dynamical systems analysis. *Child Development* **64,** 1143-1157.

Davids, K., Glazier, P., Araujo, D. and Bartlett, R. (2003) Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine. *Sports Medicine* **33,** 245-260.

de Leva, P. (1996) Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics* **29,** 1223-1230.

Edelman, G.M. and Gally, J.A. (2001) Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Science USA* **98,** 13763-13768.

Fédération Internationale de Gymnastique (FIG). (2015) *Code of points: Artistic gymnastic for men. FIG*. Moutier, Switzerland.

Fleisig, G.S., Barrentine, S. W., Zheng, N., Escamilla, R.F. and Andrews, J.R. (1999) Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of Biomechanics* **32,** 1371-1375.

Hamill, J., van Emmerik, R.E., Heiderscheit, B.C. and Li, L. (1999) A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics (Bristol, Avon)* **14,** 297-308.

Hiley, M.J. and Yeadon, M.R. (2003) Optimum technique for generating angular momentum in accelerated backward giant circles prior to a dismount. *Journal of Applied Biomechanics* **19,** 119-130.

Hiley, M.J., Zuevsky, V.V. and Yeadon, M.R. (2013) Is skilled technique characterized by high or low variability? An analysis of high bar giant circles. *Human Movement Science* **32,** 171-180.

Irwin, G. and Kerwin, D.G. (2005) Biomechanical similarities of progressions for the longswing on high bar. *Sports Biomechanics* **4,** 163-178.

Irwin, G. and Kerwin, D.G. (2007) Musculoskeletal demands of pro-

gressions for the longswing on high bar. *Sports Biomechanics* **6,** 361-374.
Jensen, R.K. (1989) Changes in segment inertia proportions between 4 and 20 years. *Journal of Biomechanics* **22,** 529-536.
Jensen, R.K. and Nassas, G. (1988) Growth of segment principal moments of inertia between four and twenty years. *Medicine and Science in Sports and Exercise* **20,** 594-604.
Latash, M.L., Scholz, J.P. and Schöner, G. (2007) Toward a new theory of motor synergies. *Motor Control* **11,** 276-308.
Newell, K.M. (1985) Coordination, control and skill. In: *Differing perspectives in motor learning.* Eds: D. Goodman, R.B. Wilberg, & I.M. Franks. Amsterdam (North-Hollande: Elsevier. 295-317.
Polk, J.D., Spencer-Smith, J., DiBerardino, L., Ellis, D., Downen, M. and Rosengren, K.S. (2008) Quantifying variability in phase portraits: Application to gait ontogeny. *Infant Behavior & Development* **31,** 302-306.
Schöllorn, W.I., Mayer-Kress, G., Newell, K.M. and Michelbrink, M. (2009) Time scales of adaptative behavior and motor learning in the presence of stochastic perturbations. *Human Movement Science* **28,** 319-333.
Scholz, J.P. and Schöner, G. (1999) The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research* **126,** 289-306.
Scholz, J.P., Schöner, G. and Latash, M.L. (2000) Identifying the control structure of multijoint coordination during pistol shooting. *Experimental Brain Research* **135,** 382-404.
Seifert, L., Button, C. and Davids, K. (2013) Key properties of expert movement systems in sport: An ecological dynamics perspective. *Sports Medicine* **43,** 167-178.
Stergiou, N., Harbourne, R.T. and Cavanaugh, J.T. (2006) Optimal movement variability: A new theoretical perspective for neurologic physical therapy. *Journal of Neurologic Physical Therapy* **30,** 120-129.
Streepey, J.W. and Angulo-Kinzler, R.M. (2002) The role of task difficulty in the control of dynamic balance in children and adults. *Human Movement Science* **21,** 423-438.
Vereijken, B., van Emmerik, R.E.A., Bongaardt, R., Beek, W.J. and Newell, K.M. (1997) Changing coordinative structures in complex skill acquisition. *Human Movement Science* **16,** 823-844.
Williams, G.K.R., Irwin, G. , Kerwin, D.G., Hamill, J., van Emmerik, R.E.A. and Newell, K.M. (2015a) Coordination as a function of learning the gymnastics longswing. *Journal of Sports Sciences,* doi: 10.1080/02640414.2015.1057209
Willliams, G.K.R., Irwin, G., Kerwin, D.G. and Newell, K.M. (2012) Kinematic changes during learning the longswing on high bar. *Sports Biomechanics* **11,** 20-33.
Willliams, G.K.R., Irwin, G., Kerwin, D.G. and Newell, K.M. (2015b) Biomechanical energetic processes during learning the longswing on high bar. *Journal of Sports Sciences* **33,** 1376-1387.
Wilson, C., Simpson, S. E., van Emmerik., R. E. and Hamill, J. (2008) Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics* **7,** 2-9.
Yeadon, M.R. and Hiley, M.J. (2000) The mechanics of the backward giant circle on the high bar. *Human Movement Science* **19,** 153-173.

✉ **Albert Busquets**
Institut Nacional d'Educació Física de Catalunya, Universitat de Barcelona, Av. de l'Estadi 12-22, 08038 Barcelona, Spain

AUTHOR BIOGRAPHY

Albert BUSQUETS
Employment
Professor in Institut Nacional d'Educació Física de Catalunya - Universitat de Barcelona, Barcelona (Spain).
Degree
MSc, PhD
Research interests
Motor learning, sensorimotor adaptations and biomechanics.
E-mail: albertbussi@gmail.com

Michel MARINA
Employment
Professor in Institut Nacional d'Educació Física de Catalunya - Universitat de Barcelona, Barcelona (Spain).
Degree
MSc, PhD
Research interests
Assessment and training of strength as well as neuromuscular fatigue in motorcycle riders.
E-mail: michel.marina.1964@gmail.com

Keith DAVIDS
Employment
Professor in the Centre for Sports Engineering Research, Sheffield Hallam University (UK).
Degree
PhD
Research interests
Sports science, behavioural neuroscience, and human movement science
E-mail: k.davids@shu.ac.uk

Rosa ANGULO-BARROSO
Employment
Professor in Institut Nacional d'Educació Física de Catalunya - Universitat de Barcelona, Barcelona (Spain) and in Kinesiology, California State University, Northridge, CA (USA).
Degree
PhD
Research interests
Neuromotor and biomechanics adaptations in clinical and exercise settings, particularly applied to pediatric populations.
E-mail: rangulo@umich.edu

Key points

- Inter-trial variability while performing longswings on a high bar was assessed in a large sample (113 participants) divided into five age groups (form beginners to advanced gymnasts). Longswing assessment allowed us to evaluate inter-trial variability in representative performance context.
- Coordination variability presented two different configurations across experience levels depending on the variable of interest: either a U-shaped or a L- or \-shaped graph.
- Increased inter-trial variability of the functional phase events offered flexibility to adapt the longswing performance in the advanced gymnasts, while decreasing variability in arm-trunk coordination modes was critical to improve longswing and to achieve the most advanced level.
- In addition, the relationship between variability measures and the global performance outcome (i.e. the swing amplitude) revealed different functional roles of movement variability (exploratory or restrictive) as a function of changes in experience levels.