COORDINATION AS A FUNCTION OF SKILL LEVEL IN THE GYMNASTICS LONGSWING

Running Title: Longswing Coordiantion

Abstract

The purpose of this study was to investigate the nature of inter-joint coordination at different levels of skilled performance to: (1) distinguish learners who were successful versus unsuccessful in terms of their task performance; (2) investigate the pathways of change during the learning of a new coordination pattern; and (3) examine how the learner's coordination patterns relate to those of experts in the longswing gymnastics skill. Continuous relative phase (CRP) of hip and shoulder joint motions was examined for longswings performed by two groups of novices, successful (n=4) and unsuccessful (n=4) over five practice sessions, and two expert gymnasts. Principal component analysis showed that during longswing positions where least CRP variability occurred for expert gymnasts, high variability distinguished the successful from the unsuccessful novice group. CRP profiles of successful novices became more out-of-phase over practice and less similar to the closely in-phase coupling of the expert gymnasts. Collectively, the findings support the proposition that at the level in inter-joint coordination a technique emerges that facilitates successful performance but is not more like an expert's movement coordination. This finding questions the appropriateness of inferring development towards a "gold champion" movement coordination.

Word count: 191

Key words: *coordination, continuous relative phase, principal component analysis, motor learning, longswing*

1.0 Introduction

A major focus of the dynamical systems approach to motor learning is to understand how the components within a system (e.g., joint space degrees of freedom (DF)) become coordinated in order to more effectively and efficiently meet task demands (Kugler, Kelso, & Turvey, 1980; 1982; Newell, 1985; Kelso, 1995). Coordination is the process by which the components of the movement system are assembled into proper relations with each other during goal directed activity (Turvey, 1990). The development of general principles for the learned changes in coordination patterns of whole body tasks with many DFs has proved, as anticipated by Bernstein (1967), to be a challenge.

Newell (1985) developed an interpretation outlined by Kugler et al. (1980; 1982) of the constructs of “Coordination”, “Control” and “Skill” during motor learning. Based on the interaction of the task and intrinsic dynamics of the performer the first stage of learning, “Coordination”, was defined as the function that constrains potentially free variables into a task relevant behavioural unit with practice. “Control”, inherently embedded with “Coordination” and a reduction in coordination variability, is defined as the process by which parameters are assigned to the coordination mode in order to increase the effectiveness of the coordination. “Skill” was defined by the ability to assign optimal parameters to the controlled variables to achieve an efficient or consistently successful performance even when faced with changing constraints (Newell, 1986). Empirical research suggests however that the mechanical and dynamical nature of these three stages of learning are inherently task and individual specific and can move through multiple pathways of change (Newell et al., 2001; Ko, Challis & Newell, 2003; Chow, Davids, Button & Rein, 2008; Liu, Mayer-Kress &

Newell, 2012). Therefore, little progress has been made in the development of general principles for learned changes of coordination patterns in whole body movement tasks.

It is widely hypothesised that coordination variability holds important information about motor control during learning (Kugler et al., 1980; 1982; Newell, 1985; Kelso, 1995). In line with Newell (1985) empirical studies have provided evidence of decreased coordination variability during the early stages of practice (Huys, Daffertshofer & Beek, 2003; Yang & Scholz, 2005; Chow et al., 2008). On the other hand, repetitions of well-learned movements have been associated with higher coordination variability but a stable performance outcome (Bernstein, 1967; Arutyunyan, Gurfinkel & Mirckii, 1969; Broderick & Newell, 1999; Wilson, Simpson, Van Emmerik & Hamill, 2008). It appears to be the case that coordination variability can be driven in different directions during learning a given task. Further research is required to examine how coordination variability changes during learning for different skills, and from different qualitative and quantitative perspectives.

The current study examines changes in the patterns of coordination during the learning of a whole body skill in order to investigate aspects of the pathways of coordination change. Coordination is measured using continuous relative phase (CRP). CRP provides a measure of coordination between two oscillators, such segments of the body (Haken, Kelso, & Bunz, 1985; Kelso, 1995; Miller, Chang, Baird, Van Emmerik & Hamill, 2010; Busquets, Marina & Angulo-Barroso, 2013a) or joints of the body (Hamill, Van Emmerik, Heiderscheit & Li, 1999). CRP has been used to study coordination in a range of movement tasks (Haken et al., 1985; Hamill et al., 1999; Miller et al., 2010), and sports skills including the basketball free-throw (Robins, Wheat, Irwin & Bartlett, 2006), long jump technique (Wilson et al., 2008) and the gymnastics longswing technique (Irwin & Kerwin, 2007a; Busquets et al., 2013a,b). While CRP is a well established measure of coordination in movement science, it is a challenge to examine the continuous nature of the coordination; a characteristic that is often lost through the analysis of discrete points in time or through averaging over time.

Principal component analysis (PCA) is a technique that can be used to search for patterns in the variance of continuous data sets. PCA extracts a smaller set of relevant features from high dimensional data sets by considering only those independent principal components (PCs) that explain a large amount of variance in the entire data set (Daffertshofter, Lamoth, Meijer & Beek, 2004). PCA has been used to investigate intra-individual patterns in continuous joint motion data. For example, PCA has been used to capture changes in the dynamical DF during learning (Haken, 1996; Hong & Newell, 2006) and those involved in different gait (Lamoth, Daffertshofer, Huys & Beek, 2009) and swinging techniques (Post, de Groot, Daffertshofer & Beek, 2007). Other studies have used PCA to distinguish between patient and control groups based on the profile of continuous kinematic and kinetic variables (Deluzio & Astephen, 2007; Mantovani, Lamontagne, Varin, Cerulli & Beaulès, 2011; Federolf, Boyer & Andriacchini, 2013; Boyer, Federolf, Lin, Nigg & Andriacchini, 2012; Nigg, Baltich, Maurer & Federolf, 2012; Troje, 2002). A emerging technique is to use PC projections and a “discriminant vector” to identify the key features of the movement patterns that were associated with PC that distinguished between groups and the associated movement characteristics (Deluzio & Astephen, 2007; Mantovani et al., 2011; Federolf et al., 2013). Capturing characteristics of inherently continuous data, PCA could allow us to maintain the rich information contained in CRP profiles, avoiding the need to create discrete accounts of continuous phenomenon. However, to date higher order CRP profiles have not been examined using these techniques.

In the current study the motor skill chosen to examine coordination differences during the learning process was the gymnastics longswing on high bar (see Figure 1). Technique in the longswing emerges within strict, well-defined, and relatively invariant task and environmental constraints that standardise competition between individuals.

Insert Figure 1 about here

Previous research has investigated the mechanical energetic characteristics of longswings performed by elite gymnasts and found that the key input of mechanical work occurs at the hip and shoulder joints as the performer passes under the high bar (270° in the swing; Arampatzis & Brüggemann, 1999; Yeadon & Hiley, 2000; Irwin & Kerwin, 2005; Irwin & Kerwin, 2007b; Williams, Irwin, Kerwin & Newell, 2012; Williams, Irwin, Kerwin & Newell, 2014). Moreover, the positions between 220° - 340° in the circle captured both the swing of unsuccessful novices and contained the key input of mechanical work responsible for performance improvement and successful swings (Williams et al., in press). Therefore, this portion of the skill represents the key phase for identifying technique associated with progressions and learning the longswing.

Coordination between the hip and shoulder joints using CRP has been previously examined for expert gymnasts. Irwin and Kerwin (2007a) reported a tight in-phase relationship between 240º and 360º in the circle. For changes in discrete values of CRP during learning (but with reference to inter-segmental coordination between the thigh-trunk and trunk-arms) Busquets et al. (2013a) suggested that younger competition age groups were able to perform earlier swing coordination that was more similar to the elite gymnasts. With age coordination later in the swing also became more like the elite gymnasts (Busquets et al., 2013a). These results were paralleled the findings of Busquets et al. (2013b) who found that for adult learners discrete values of CRP during earlier swing event become more like that of expert gymnasts with better performance. In this approach, and other studies of sports skills, the coordination and control of the expert performer was taken as the "gold-champion" to-be-learned dynamics and was based on discrete measures of coordination (e.g. Temprado, Della-Grasta, Farrell & Laurent, 1997; Busquets et al., 2013a,b).

Pathways of technique change (qualitative and quantitative) during learning of sports skills are often assumed to progress towards a "gold champion". However, often observations are consistent with the perspective of degeneracy in biological systems (Edelman & Gally, 2001) whereby there are adaptive advantages of the potential to realize a given task goal through multiple pathways of movement organization. Thus, even in a highly constrained task like the longswing the multiple joint DF are likely to afford variation between and within participants in the qualitative and quantitative properties of the dynamics and how these dynamics, as well as how they change over practice time (Newell, 1986). The significance of technique changes with practice and skill at the level of inter-joint coordination is indicated by the nature of change with performance improvement.

The purpose of this study was to investigate the continuous nature of inter-joint coordination at different levels of skilled performance. The aims of this study were to: (1) distinguish learners who were successful versus unsuccessful in terms of their task performance by their movement coordination patterns; (2) investigate the coordination changes during the learning of a gross motor skill that requires the formation of a new coordination pattern; and (3) examine how the learner's coordination patterns relate to those of experts in a whole body gymnastics skill. It was hypothesised that: (1) successful novice participants would have established a stable coordination pattern that distinguished them from non successful participants; (2) changes in coordination and coordination variability during practice would progress to more like that of experts; and (3) the coordination of successful novices would be more similar to that of expert gymnasts than non successful novices. The emergence of more stable, task specific patterns of coordination that are indicative of performance outcome would provide evidence to decompose the notion of stages of learning (Newell, 1985), providing insight into the mechanisms of control and useful information for practice.

2.0 Methods

2.1. Participants

Ethical approval was gained from the host University's Ethics Committee and voluntary consent was obtained from all participants prior to the onset of the study.

The eight male novices participated in the study. After three weeks of training (see 2.2 Procedures) the novices were split post-hoc into two groups; group 1 who could perform successful longswings (n=4; M ± SD age: 20 ± 2 years, mass: 67.1 ± 4.8 kg and stature: 1.71 ± 0.05 m) and group 2 who could not (n=4; M ± SD age: 20 ± 1 years, mass: 79.8 ± 2.0 kg and stature: 1.80 ± 0.05 m). All novices continued to train for a further five weeks, and data were collected each week. Two expert male gymnasts, one International level gymnast (age: 23 years, mass: 70.9 kg and stature: 1.73 m) and one Collegiate athlete (age: 18 years, mass: 62.7 kg and stature: 1.75 m) were also recruited.

2.2 Procedures

Data were collected during longswing attempts by novice gymnasts after three weeks of training. During these three weeks of training novices attended two gymnastics sessions each week. Firstly, a 1.5 hour session in the gymnasium run by an International gymnastic coach. During this session they performed longswing specific strength and conditioning exercises and skill progressions such as holding a handstand and handstand to flatback, respectively (Readhead, 1997; Arkaev & Suchilin, 2012). Secondly, novice participants attended a 1 hour session during which they attempted the longswing on the high bar during five trials that each consisted of three consecutive independent longswings. During these trials participants were aided by the gymnastics coach to obtain an initial angular momentum during three swings, they then performed the three consecutive unaided swings. During each trial, participants were asked to try to increase their swing amplitude by beginning higher on the downswing and ending higher on the upswing until ideally, they were able to perform the complete longswing. Participants were instructed to keep knees and elbows fully extended during swinging. In the proceeding five weeks novices continued to train and data were collected for the three unaided swings performed during the second session of each week. Expert gymnasts attended a single data collection session where they were asked to perform five trials, each consisting of three longswings. During data collection sessions markers were attached to the performers as below.

2.3 Data Collection

Individual specific body segment inertia parameters were estimated from anthropometric data obtained using the digital image technique of Gittoes, Bezodis and Wilson (2009) (Canon EOS400D SLR, Japan) for use within Yeadon's (1990) geometric inertia model. Kinematic data (200 Hz) were collected using an automated 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Two CX1 scanners provided a field of view exceeding 2.5 m around the centre of the bar. The scanners were positioned behind the high bar floor sockets, facing inwards at an angle of 10° from the horizontal. 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, mid forearm, greater trochanter, femoral condyle, lateral malleolus, fifth metatarso-phalangeal and the centre of the underside of the bar.

2.4 Data Analysis

Raw marker data in the horizontal (y), and vertical (z) were identified from CODA output and all subsequent analysis took place using customised code written in MATLAB (The Mathworks, USA). Kinematic data were filtered using a fourth order Butterworth filter with a cut-off frequency of 6 Hz (Winter, 2005). The angular orientation of the gymnast about the bar was described by the circle angle (Figure 1). Circle angle was defined by the mass centre to neutral bar vector with respect to the horizontal, where, based on a classic mechanical definition, a circle angle of 270° saw the centre of mass of the gymnast below the bar (in hang). During each trial three unaided consecutive swings, which included a downswing and an upswing, were performed. A complete 360° swing was defined each time the performer's centre of mass passed through 90º (the top of the circle; Figure 1). Incomplete swings were defined by instances when the angular velocity of the circle angle vector went from negative to positive. The section of the swing between 224° and 340° was identified for analysis. Lines joining the shoulder centre, greater trochanter and femoral condyle markers defined the hip angle. Shoulder angle was defined by the lines joining elbow, shoulder and greater trochanter markers. Flexion of the hip and extension of the shoulder joints (closing) was defined as positive. Swing two in each trial was analysed, resulting in five swings representing each session per participant.

CRP was calculated based on the normalised angle and normalised angular velocity of each joint. Phase planes for each joint were constructed with the normalised angular position on the x-axis and normalised angular velocity on the y-axis (Hamill et al., 1999; Van Emmerik, Miller & Hamill, 2013). Angular position was normalised between ±1 based on the maximum and minimum of samples (Hamill et al., 1999; Van Emmerik et al., 2013). Angular velocity was normalised to the maximum of samples in order to keep zero velocity at the zero position of the phase plane. Phase angle was calculated as the four quadrant arctangent angle of the phase plane relative to the right horizontal. CRP of the coupling between the joints was calculated as the phase angle of the shoulder minus the phase angle of the hip joint. A CRP angle of 0° indicates an in-phase coupling and a ±180° indicates anti-phase. Values between 0° and 180° are considered as out of phase. In order to provide inter-performer comparisons between swings, data were interpolated, using a cubic spline, in 1° increments of the circle angle about the bar.

CRP variability (VCRP) was calculated as the standard deviation at each time point of the CRP curves over the five longswings representing a session (van Emmerik et al., 2013). A discrete value was calculated as the average of the standard deviation for each of the points in the swing.

Three separate PCAs were conducted. A PCA was performed on: 1) a matrix of the CRP profiles of all the participants' swings (eight novices x five session x five trials plus two expert gymnasts x one session x five trials); 2) the CRP profiles of each individual novice's trials (five sessions x five trials); and 3) the VCRP profiles of all the participants (eight novices x five sessions plus two expert gymnasts x one session). PCA of these matrices resulted in PC vectors (equal to the number of trials) indicating the directions of the variance in the data set. Each PC vector explains an amount of variance according to its respective eigenvalue. A loading factor indicates the association of each trial onto each PC vector. Pearson's correlation was used to determine if a systematic change existed in the loading of a trial onto a PC with practice during the individual analysis.

After testing for normality of data (Shapiro-Wilk; Peat and Barton, 1995) a t-test was used to determine if significant differences existed between the loading factor of trials onto each PC that belonged to each group of novices during the group analysis of PCA 1 ($p < 0.05$). A discriminant vector was calculated according to the methods of Federolf et al. (2013; Equation 1) to support PCA 1, 2 and 3:

$$\text{Discriminant vector} = \sum_i \delta_i \, EV_i \, PC_i \qquad \text{Equation 1.}$$

The discriminant vector was calculated as a linear combination of the PC onto which the loading of trials (δ) yielded; for PCA 1 and 3 large effect sizes (*d* > 0.8 (Cohen, 1992)) between groups of participants, for PCA 2 a high Pearson's correlation coefficient ($r \geq 0.6$; Hemphill, 2003) with practice; and was weighted according to the amount of variation in the data explained by each PC (EV).

3.0 Results

3.1 Novice performance

Unsuccessful novices improved swing amplitude over the five sessions of practice, by an average of 12° each session (Table 1.)

Insert Table 1 about here

3.1 Coordination – Group analysis

The CRP profiles for the expert gymnasts ranged between 50° and -90°, with a close to in-phase relationship between the hips and the shoulders under the bar at 270º in the circle angle (Figure 2). Although the profiles of the expert gymnasts were predominantly near in-phase, there were qualitative differences between the profiles (Figure 2). The collegiate gymnasts' CRP remained closer to in-phase than the elite gymnasts. Novice CRP profiles ranged between ± 150° demonstrating a more out-of-phase, tending towards anti-phase coordination between the actions at the hips and the shoulders compared to the expert gymnasts (Figure 3).

Insert Figure 2 and Figure 3 about here

----------- -----------------------------------

Investigating the common features in CRP profiles for the two novice groups (8 novices x 20 swings) and the expert gymnasts (2 gymnasts x 5 swings), loading onto PCs that accounted for up to 90 % of variance in the data (PC1 to PC5) did not distinguish between the successful and unsuccessful groups ($p = 0.01$; Cohen's $d < 0.8$; Table 2).

Insert Table 2 about here

3.2 Coordination - Individual CRP Analysis

Removing the inter-subject dimension from the analysis, that accounts for within-group variability per-se and changes over time, PCA was performed on the CRP profiles of individual learners over practice. For the successful participants between 2 and 4 PCs described 90% of variance in the data, while for the unsuccessful participants between 3 and 5 PCs explained 90% of the variance (Table 3). When loading onto the PCs was correlated with the practice number of the swing ($r \geq 0.6$; Table 3) the discriminant vector was calculated to represent the change that occurred in the CRP profile with practice (Figure 4). Discriminant vectors for three of the successful novices showed that CRP became more out of phase over the learning period, particularly during position in the swing where relative phase was tended toward anti-phase (180°, Figure 4, left). In this respect, the CRP of the successful novices at this stage of learning was progressing to become less like that of the expert gymnast (Figure 2). Two unsuccessful novices showed smaller deviation away from tightly in-phase coordination with practice (Figure 4, right).

Insert Table 3 and Figure 4 about here

3.3 Coordination Variability - Group

For the expert gymnasts the discrete VCRP was 6.8° and 5.0° across the 5 trials. Continuous profile of the VCRP showed that VCRP was greatest at 220° and 275°, and lowest at 250°, 260°, 295° and 310° in the swing for experts (Figure 5).

Insert Figure 5 about here

Novice values for VCRP in each session ranged between 11.7° and 52.4°, at least double the variability of the expert gymnast. Two of the successful novices reduced VCRP ($r = -0.76$ and -0.72), while an unsuccessful novice increased VCRP over the 5 sessions ($r = 0.72$). All other $r < 0.6$, indicating little or no linear trend in VCRP over the 5 sessions.

In order to investigate whether common characteristics of VCRP profiles distinguished between successful and unsuccessful novice groups a PCA was used to analyse the VCRP data. Loadings onto PC2 distinguished between the successful and unsuccessful novices (Cohen's *d* = 0.85; effect size *r* = 0.4). The discriminant vector shows that successful novice data deviated from the mean of the data with high variability at 250º in the circle and towards 340º (Figure 5).

4.0 Discussion

The aims of this study were to: (1) distinguish learners who were successful versus unsuccessful in terms of their task performance by their movement coordination patterns; (2) investigate the pathways of change during the learning of a new coordination pattern; and (3) examine how the learner's coordination patterns related to those of experts in the longswing gymnastics skill. The findings revealed that changes in hip and shoulder joint CRP and CRP variability for a learner do not become more like that of an expert performer as they improve performance outcome. Related to aim (1), the first hypothesis was not supported. Successful novices were not distinguished from unsuccessful novices based on their movement coordination profile. CRP variability during circle positions where least variability occurred for the expert gymnasts distinguished the successful from the unsuccessful novice group. The pathway of change in CRP was not becoming more like that of an expert gymnast with practice, contrary to the second hypothesis. Furthermore, the results did not support the hypothesis that successful novice participants would have established a basic, in-phase coordination pattern that is more like that of experts, and distinguishes them from non successful novice participants.

The closely in-phase hip and shoulder joint coupling near the lower vertical position (270° in the circle angle) for the expert gymnasts is congruous with the results of previous studies (Irwin & Kerwin, 2007). However, although the technique for this skill is highly constrained, qualitative differences in the CRP profiles of the expert gymnasts were identified. These findings exemplify the importance of investigating individual's movement patterns and their outcome (Newell et al., 2001) but provide further support for the closely in-phase nature of hip and shoulder coordination of expert gymnasts performing the longswing.

The group-based PCA did not distinguish learners who were successful versus unsuccessful in terms of their task performance by their movement coordination patterns (Table 2). This finding is contrary to the hypothesis that successful participants would have established a basic, task specific coordination more like that of experts, and distinguishes them from non successful participants. In coaching and sport science research and practice we would strongly consider the appropriateness of encouraging development towards a kinematic "gold standard" during motor learning. Not least because such a fundamental skill presents a basic action for expert gymnasts, who are able to modify the basic technique to achieve different aims, while for learners developing the movement patterns to be successful in this skill presents a high level of difficulty. A task-specific dynamic to underpin our understanding of successful and unsuccessful technique and our coaching is likely more closely related to variables that are associated with satisfying the biomechanical demands of the skill (Williams et al., in press), and not at the level of inter-joint coordination.

Changes in coordination were expected with practice (Figure 2; Figure 3), which might explain why no distinguishing features were identified in the group analysis. In addition, variability within the groups contributed to no differences being found between successful and non-successful novice groups in the PCA. Systematic changes in coordinative strategies of individuals with practice were found for five of the eight learners (Table 3; Figure 4). The discriminant vector for successful learners showed that CRP became more out-of-phase, towards anti-phase coordination, and less like the in-phase profile of the expert gymnasts with practice (Figure 4). Therefore, at the level of joint coordination and for this stage of practice it appears that the technique of successful novices is qualitatively different to that of expert gymnasts. Furthermore, establishing a strategy that facilitated successful performance for novices was not associated with patterns of coordination progressing to become more like those of expert gymnasts performing the skill. A possible explanation for this finding was shown in Williams et al. (2014) who found that the hip joint actions becomes more like those of expert gymnasts, whereas the contribution of the shoulder action is limited compared to expert gymnasts. A different pattern of coordination is elicited due to the biomechanical constraints of the shoulders for novices, which resulted in a more out-of-phase towards anti-phase coordination profile during the swing. That the coordination of non-successful novices was more similar to that of experts than the successful novices further suggests that the task-specific dynamic that distinguished between successful and unsuccessful technique is likely more closely related to variables that are associated with satisfying the biomechanical demands of the skill (Williams et al., 2014), and not at the level of inter-joint coordination.

In the work of Busquets et al. (2013a,b) who examined technique changes across age groups of gymnasts and novice adults, it was proposed that learning placement of the hip and shoulder events and inter-segment thigh-trunk coordination during the downswing should precede learning coordination of the shoulder in the downswing and the coordination in the upswing. Williams et al. (2012, in press) supports the proposal that the position of hip and shoulder functional phase events and their preparatory actions should be the initial focus for novices. The current study however, which examined inter-joint coordination highlights that the progression of coordination is complex. The task-specific coordination that is key to improving performance is likely more closely related to variables that are associated with satisfying the biomechanical demands of the skill, and not at the level of inter-joint or segment coordination.

Qualitative and quantitative differences in dynamics are consistent with the perspectives of degeneracy in biological systems (Edelman and Gally, 2001) whereby there are adaptive advantages of the potential to realize a given task goal through multiple pathways of movement organization. Therefore, if the aim is to become successful, learners should be encouraged to explore interactions between the constraints to action in establishing successful patterns of coordination, or at least guided with reference to knowledge of the specific constraints for the task, as opposed to being directed to the coordination patterns of expert individuals. If mechanical efficiency or aesthetics is the goal, however, the recommendations might be different. Accordingly, it is hypothesised that degeneracy in successful technique is a reflection of practice and experience and if the novices continued to practice additional changes would be made and their dynamics would become like the in-phase coordination demonstrated by the expert gymnasts..

Expert gymnasts had low overall VCRP (6.8º and 5.0°), which was expected due to their level of skill and also the highly constrained nature of the task (Figure 5). VCRP of successful learners well exceeded that of expert gymnasts and did not distinguish them from the unsuccessful group (ranging from 11.7° to 52.4°), suggesting that the "Control" stage of learning (Newell, 1985) may not yet be established. While specific changes in the discrete single joint actions of the hip for novices learning the longswing have been shown (Williams et al., 2012), the joint coupling between the hips and shoulders remained highly variable. Since there were qualitative differences in task outcome, that we did not find clear differences in coordination variability is striking. This finding suggests that for novices relatively high VCRP exists during trying to achieve the task and while achieving the task, presumably for different functions. Clearly, different levels of the system provide different perspectives on the nature of change and stability of the technique over repeated trials; confounding the development of general principles that characterise the learned changes in movement patterns.

Some parallels and contrasts to our patterns of change in successful and unsuccessful learners have been reported by Wilson et al. (2008) who investigated skill acquisition in the triple jump technique. They identified a "U" shape as CRP variability was plotted against performance level since less skilled and highly skilled athletes had the highest variability in joint coordination. In contrast, the results of the current study have shown that the joint coupling for successful novices is more variable than unsuccessful novices and expert gymnasts. Although it would appear that these two studies have identified certain contrasting findings it is proposed that the stages of learning and the constraints imposed by the two tasks are different; resulting in specific characteristics of variability in joint coupling with skill level. The longswing is a highly constrained skill, and thus expert performers likely exploit effective and efficient movement patterns that have lesser requirements than longswing technique for functional variability to adapt to perturbations. Comparing more and less skilled trained gymnasts may reveal the 'U' relationship of coordination variability identified by Wilson et al. (2008).

Continuous characteristics of the VCRP distinguished between successful and unsuccessful groups of learners. Specifically, successful novices had higher VCRP at positions in the swing where the variability of the CRP for the expert gymnasts was low (Figure 5). From a mechanical perspective, this finding is surprising since Hiley, Zuevsky & Yeadon (2013) identified that the most mechanically important single joint actions (the circle position and joint angle magnitude of maximum opening to closing of the hips and shoulders underneath the bar) were less variable than those less mechanically important. However, single joint analyses by Williams et al (2012) and Busquets et al. (2013b) emphasised the reliance of adult learners on the hip actions, highlighting the disassociation between the hips and shoulders. It is suggested that high VCRP further highlights this disassociation, making it difficult to parallel VCRP and performance outcome.

While continuous profiles of coordination and coordination variability were examined, only a section of the swing performed by successful novices was included in the analysis (as they completed the whole circle). Busquets et al. (2011, 13a,b) reported that during learning the longswing, actions at the beginning of the swing become more similar to those of experts before actions that occur later in the swing. The first of these actions was a closing of the hips and shoulders that occurred during the downswing, preceding the functional phase. Busquets et al. (2011) reported that this action occurred at the hip at 198° and 175°, and the shoulders at 207° and 193° in the circle for less and more spontaneously talented novices, respectively. With practice these values progressed towards the expert values of 144° and 150° in the circle for the hips and shoulders, respectively. According to the study of Williams et al.

(in press) this action is a preparation action for a later functional phase; a technique shown to more effective and mechanically efficient for novices. This preparation action was not captured by the portion of the swing analysed in the current study, which is a limitation of the current study and an area recommended future work. However, the current analysis did capture the section of the swing where the key biomechanical energetic contribution of the performers occurred (Williams et al., in press). The small sample size, particularly of expert gymnasts, may limit the generalisation of these results, however the methodological approach has demonstrated some interesting findings with the current sample. Future work is also recommended to replicate these techniques with a larger and more diverse group of learners.

5.0 Conclusions

The significance of technique changes with practice and skill at the level of inter-joint coordination is indicated by the nature of change with performance improvement. The findings of this study support the position that in tasks with multiple joint space DF to coordinate and control, such as the longswing, changes in technique of a novice do not become more like that of an expert performing the skill as they improve performance outcome. Rather, a qualitatively different technique at the level of analysis inter-joint coordination ensues that facilitates the successful performance of a beginner. In addition, coordination variability profiles demonstrated a complex relationship to technique since the successful novice group were distinguishable from the unsuccessful novices by high variability at circle positions that were characterised by low variability for the expert gymnasts. These findings emphasise that in coaching and sports science research and practice we should strongly consider the appropriateness of encouraging (or inferring) development towards a kinematic “gold standard” during motor learning.

Future work is required to investigate the nature of change in coordination dynamics at different levels of the biomechanical system in order to increase our understanding of what variables are regulated during learning.

6.0 References

Arampatzis, A. & Brüggemann, 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.

Arkaev, L.I. & Suchilin, N.G. (2012). *Gymnastics, how to create champions*. Oxford: Meyer and Mayer Sport.

Arutyunyan, G.H., Gurfinkel, V.S. & Mirskii, M.L. (1968). Investigation of aiming at a target. *Biophysics, 13,* 536-538.

Bernstein, N. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon.

Boyer, K.A., Federolf, P., Lin, C., Nigg, B.M. & Andriacchi, T.P. (2012). Kinematic adaptations to a variable stiffness shoe: mechanisms for reducing joint loading. *Journal of Biomechanics, 45*, 1619-1624.

Broderick, M.P. & Newell, K.M. (1999). Coordination patterns in ball bouncing as a function of skill. *Journal of Motor Behavior, 31*, 165-188.

Busquets A., Marina, M. & Angulo-Barroso, R.M. (2013a). Changes in motor strategies across age performing a longswing on high bar. *Research Quarterly for Exercise and Sport, 3,* 353-362.

Busquets, A., Marina, M. & Angulo-Barroso, R.M. (2013b). Coordination analysis reveals differences in motor strategies for the high bar longswing among novice adults. *PLos ONE, 8(6)*, e67491.

Chow, J-Y., Davids, K., Button, C. & Rein, R. (2008). Dynamics of movement patterning in learning a multi-articular action. *Motor Control, 12,* 219-240.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112,*155-159.

Daffertshofer, A., Lamoth, C.J., Meijer. O.G. & Beek, P.J. (2004). PCA in studying coordination and variability: a tutorial. *Clinical Biomechanics*, *19,* 415-428.

Deluzio, K.J. & Astephen, J.L. (2007). Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. *Gait and Posture, 25,* 86-93.

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

Federolf, P.A., Boyer, K.A. & Andriacchini, T.P. (2013). Application of principal component analysis in clinical gait research: Identification of systematic differences between healthy and medial knee osteoarthritic gait. *Journal of Biomechanics, 46,* 2173-2178.

Gittoes, M.J.R., Bezodis, I.N. & Wilson, C. (2009). An image based approach to obtaining anthropometric measurements for athlete-specific inertia modelling. *Journal of Applied Biomechanics*, *25,* 265-270.

Haken, H., Kelso, J.A.S. & Bunz, H. (1985). A theoretical model of phase-transitions in human hand movements. *Biological Cybernetics, 51,* 347-356.

Haken, H. (1996). *Principles of brain functioning. A synergetic approach to brain activity, behaviour and cognition.* Berlin, Germany: Springer.

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

Hemphill, J.F. (2003). Interpreting the magnitudes of correlation coefficients. *American Psychologist, 58*, 78-80.

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.

Hong, S.L. & Newell, K.M. (2006). Practice effects on local and global dynamics of the ski- simulator task. *Experimental Brain Research, 169*, 350-360.

Huys, R., Daffertshofer, A. & Beek, P.J. (2003). Learning to juggle: On the assembly of functional subsystems into a task-specific dynamical organization. *Biological Cybernetics*, *88,* 302-318.

Irwin, G. & Kerwin, D.G. (2007a). Inter-segmental coordination in progressions for the longswing on high bar. *Sports Biomechanics, 6,* 131-144.

Irwin, G. & Kerwin, D.G. (2007b). Muskuloskeletal demands for progressions for the longswing on high bar. *Sports Biomechanics, 6,* 361-374.

Kelso, J.A.S. (1995). *Dynamic patterns: the self-organization of brain and behavior.* Cambridge, MA: MIT.

Ko, Y-G., Challis, J.H. & Newell, K.M. (2003). Learning to coordinate redundant degrees of freedom in a dynamic balance task. *Human Movement Science, 22,* 47-66.

Kugler, E.N., Kelso, J.A.S. & Turvey, M.T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G.E. Stelmach and J. Requin (Eds), *Tutorials in motor behavior* (pp. 3-47). New York: North Holland.

Kugler, P.N., Kelso, J.A.S. & Turvey, M.T. (1982). On the control and coordination of naturally developing systems. In J.A.S. Kelso and J.E. Clark (Eds.), *The development of movement control and coordination* (pp. 5-78). New York: Wiley.

Lamoth, C.J.C., Daffertshofter, A., Huys, R. & Beek, P.J. (2009). Steady and transient coordination structures in walking and running. *Human Movement Science, 28,* 371-386.

Liu, T-Y., Luo, Z-Y., Mayer-Kress, G. & Newell, K.M. (2012). Self-organized criticality and learning a new coordination task. *Human Movement Science, 31,* 40-54.

Mantovani, G., Lamontagne, M., Varin, D., Cerulli, G.G. & Beaulés, P.E. (2011). Is principal components analysis more efficient to detect differences on biomechanical variables between groups? *Portuguese Journal of Sports Sciences, 11*, 911-914.

Miller, R.H., Chang, R., Baird, J.L., Van Emmerik, R.E.A. & Hamill, J. (2010). Variability in kinematic coupling assessed by vector coding and continuous relative phase. *Journal of Biomechanics, 43,* 2554-2560.

Newell, K.M. (1985). Coordination, control and skill. In D. Goodman., I. Franks. and R.B. Wilberg (Eds.), *Differing perspectives in motor learning, memory and control* (pp. 295-318). Amsterdam: North Holland.

Newell, K.M. (1986). Constraints on the development of coordination. In M.G. Wade and H.T.A. Whiting (Eds.), *Motor development in children. Aspects of coordination and control* (pp. 341-360). Dordrecht, Netherlands: Martinus Nijhoff.

Newell, K.M., Liu Y-T. & Mayer-Kress, G. (2001). Time scales in motor learning. *Psychological Review, 108,* 57-82.

Nigg, B.M., Baltich, J., Maurer, C. & Federolf, P. (2012). Shoe midsole hardness, sex and age effects on lower extremity kinematics during running. *Journal of Biomechanics*, *45*, 1692-1697.

Peat, J. and Barton, B. (2005). Medical Statistics: A Guide to Data Analysis and Critical Appraisal. Malden, Massachusetts USA: Wiley-Blackwell.

Post, A.A., de Groot, G., Daffertshofer, A. & Beek, P.J. (2007). Pumping a playground swing. *Motor Control, 11,* 136-150.

Readhead, L. (1997). *Men's gymnastics coaching manual*. Huddersfield, UK: Crowood Press.

Robins, M., Wheat, J.S., Irwin, G. & Bartlett, R.M. (2006). The effect of shooting distance on movement variability in basketball. *Human Movement Studies*, *20*, 218-238.

Temprado, J., Della-Grasta, M., Farrell, M. & Laurent, M. (1997). A novice-expert comparison of (intra-limb) coordination subserving the volleyball serve. *Human Movement Science, 16,* 653-676.

Troje, N.F. (2002). Decomposing biological motion: A framework for analysis and synthesis of human gait patterns. *Journal of Vision, 2,* 371-387.

Turvey, M.T. (1990). Coordination. *American Psychologist, 45,* 938-953.

Van Emmerik, R.E.A., Miller, R.H. & Hamill, J. (2013). Dynamical systems methods for the analysis of movement coordination. In: Robertson, G., Caldwell, G., Hamill, J., & Kamen, G. (Eds.). *Research methods in biomechanics (2nd Edition).* Human Kinetics, Champagne, IL, USA.

Williams, G., Irwin. G., Kerwin, D.G. & Newell, K.M. (2012). Kinematic changes during learning the longswing on high bar. *Sports Biomechanics, 11*, 20-33.

Williams, G., Irwin. G., Kerwin, D.G. & Newell, K.M. (2014). Changes in joint kinetic during leaning the longswing on high bar. *Journal of Sports Sciences*, available online.

Williams, G., Irwin. G., Kerwin, D.G. & Newell, K.M. (in press). Biomechanical energetic processes during learning the longswing on high bar. *Journal of Sports Sciences.*

Wilson, C., Simpson, S.E., Van Emmerik, R.E.A. & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, *7,* 2-9.

Winter, D. (2005). *Biomechanics and motor control of human movement* (3rd edition). Wiley, Hoboken, NJ.

Yang, J-F & Scholz, J.P. (2005). Learning a throwing task is associated with differential changes in the use of motor abundance. *Experimental Brain Research, 163,* 137-158.

Yeadon, M.R. (1990). The simulation of aerial movements. Part II: A mathematical inertia model of the human body. *Journal of Biomechanics, 23,* 67-74.

Yeadon, M.R., & Hiley, M.J. (2000). The mechanics of the backward giant circle on high bar. *Human Movement Science, 19,* 153-173.

Table 1. Start (C_1) and end (C_2) position of the swing in the circle angle, swing amplitude (SA) and standard deviation (sd) for the unsuccessful novice group during the 5 sessions of practice.

Table 2. For the first 5 principal components: The % of variance explained by each, and Cohen's *d* between the mean of the PC loadings of successful versus unsuccessful learners.

Table 3. Number of principal components (PCs) accounting for 90 % of variance in the data, and the correlation (r) between practice number and the loading of that swing onto a PC.

	C1 (°)	sd	C2 (°)	sd	SA (°)	Sd
Session 1	204	20	345	4	141	17
Session 2	193	5	350	5	157	8
Session 3	187	5	339	43	153	44
Session 4	173	7	368	6	196	13
Session 5	156	11	383	11	227	9

	PC				
	PC1	PC2	PC3	PC4	PC5
% variation explained	48	22	11	7	4
Cohen's *d*	0.43	0.28	0.65	0.17	0.46
Effect size	0.21	0.14	0.31	0.08	0.22

Note: Small effect sizes and Cohen's *d* < 0.8 indicated that the PC represented a source of variability in the CRP profile unrelated to the difference between groups. The first 5 PC describe > 90 % of variance in the data.

Participant	PCs = 90% of variance	r	
		PC1	PC2
S1	2	-0.2	-0.1
S2	3	**-0.6**	**-0.6**
S3	4	**-0.7**	-0.2
S4	4	0.2	**-0.6**
NS1	4	**0.9**	0.0
NS2	3	0.2	0.0
NS3	3	-0.3	0.5
NS4	5	**-0.6**	0.1

Note: $r \geq 0.6$ indicated that there was a high correlation between practice and characteristics of variance associated with that PC.

Figure 1. Schematic of the gymnastics longswing on high bar. The key section of the swing is highlighted.

Figure 2. Continuous relative phase between the hip and shoulder joints for expert gymnasts; an elite gymnast (left) and a collegiate level gymnast (right); during 5 longswings.

Figure 3. In black: Continuous relative phase (CRP) profiles of a successful novice (top) and an unsuccessful novice (bottom) in for 5 longswings performed in session 1 (left) and session 5 (right). In grey: CRP of elite (grey dot-dash) and collegiate (grey dot) gymnasts.

Figure 4. In black: Mean continuous relative phase (CRP) for two successful (left top and bottom) and two unsuccessful (right top and bottom) novices over 5 sessions (solid line) and the discriminant vector (dashed line) onto which the CRP profiles became more associated with practice. In grey: CRP of elite (grey dot-dash) and collegiate (grey dot) gymnasts.

Figure 5. In black: Mean of the variability of continuous relative phase (VCRP) during swings performed by successful and unsuccessful novices (solid line), the discriminant vector distinguishing VCRP for successful from unsuccessful novices swings (dashed line). In grey: VCRP over 5 swings for an elite (dot-dash) and collegiate gymnast (dotted) lines.

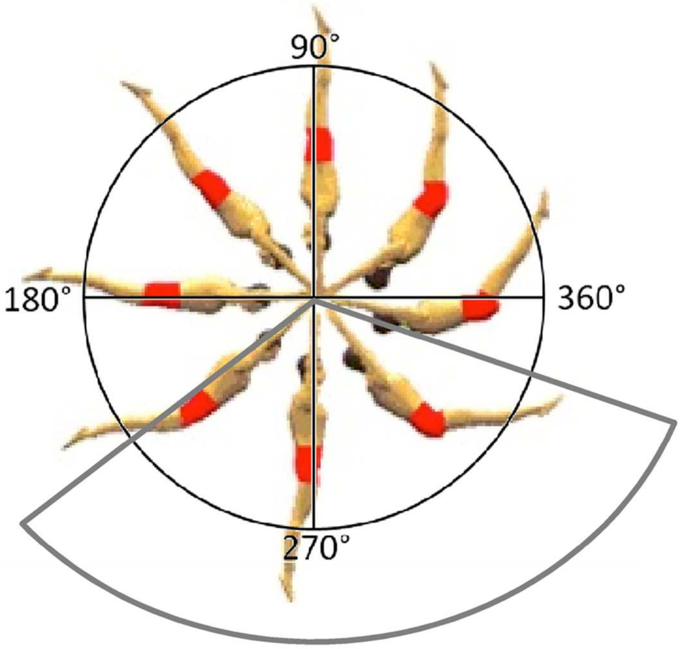

Figure 1. Schematic of the gymnastics longswing on high bar. The key section of the swing is highlighted.
110x91mm (300 x 300 DPI)

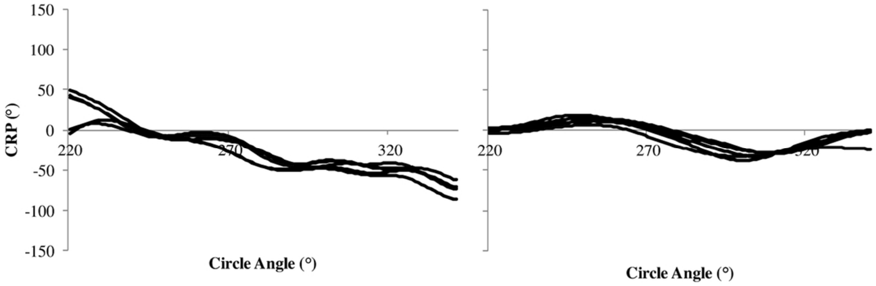

Figure 2. Continuous relative phase between the hip and shoulder joints for expert gymnasts; an elite gymnast (left) and a collegiate level gymnast (right); during 5 longswings.
117x67mm (300 x 300 DPI)

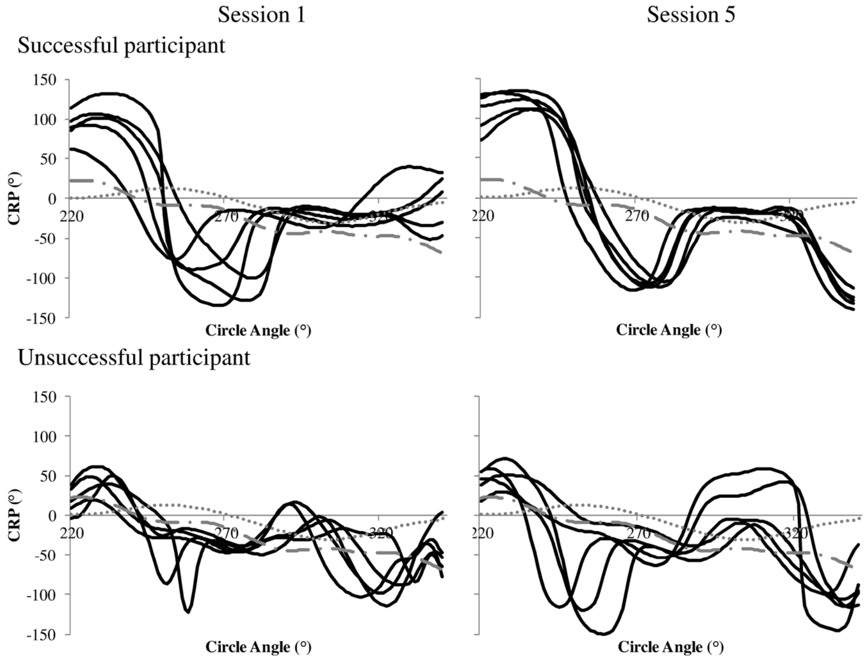

Figure 3. In black: Continuous relative phase (CRP) profiles of a successful novice (top) and an unsuccessful novice (bottom) in for 5 longswings performed in session 1 (left) and session 5 (right). In grey: CRP of elite (grey dot-dash) and collegiate (grey dot) gymnasts.
175x147mm (300 x 300 DPI)

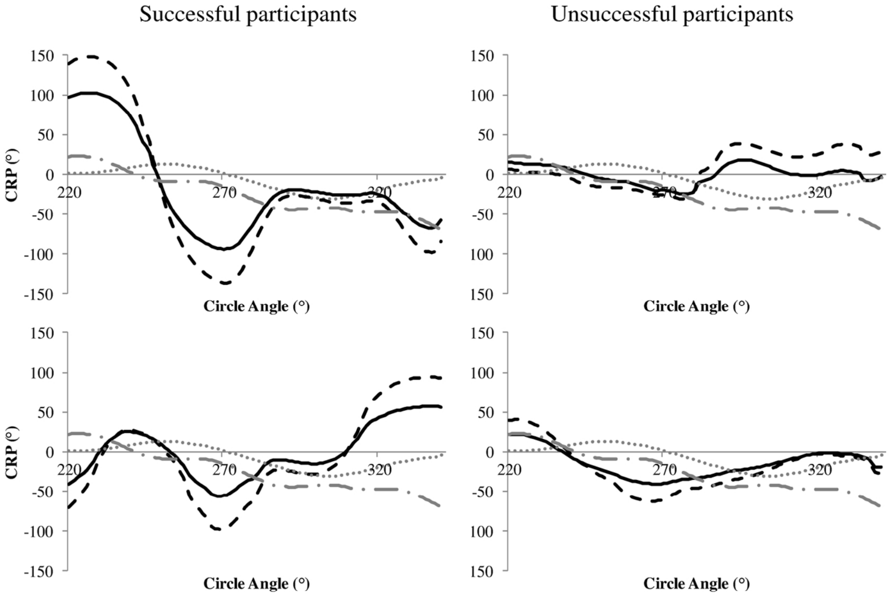

Figure 4. In black: Mean continuous relative phase (CRP) for two successful (left top and bottom) and two unsuccessful (right top and bottom) novices over 5 sessions (solid line) and the discriminant vector (dashed line) onto which the CRP profiles became more associated with practice. In grey: CRP of elite (grey dot-dash) and collegiate (grey dot) gymnasts.
159x121mm (300 x 300 DPI)

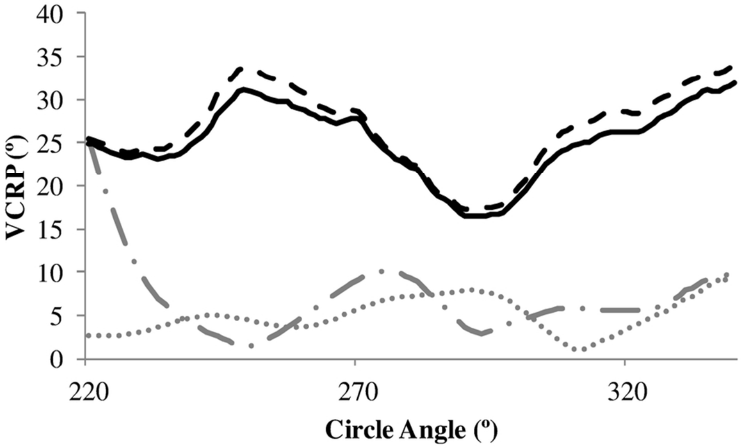

Figure 5. In black: Mean of the variability of continuous relative phase (VCRP) during swings performed by successful and unsuccessful novices (solid line), the discriminant vector distinguishing VCRP for successful from unsuccessful novices swings (dashed line). In grey: VCRP over 5 swings for an elite (dot-dash) and collegiate gymnast (dotted) lines.
105x71mm (300 x 300 DPI)