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Changes in joint kinetics during learning the longswing on high bar

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Abstract
Biomechanics helps us understand the association between technique changes and performance improvement during learning. The aim of this research was to investigate joint kinetic characteristics of technique during learning of the longswing on the high bar. Twelve male, novice participants took part in the learning study. During swing attempts in 8 weekly testing sessions, kinematic data were collected. Inverse dynamics analysis was performed from known zero forces at the toes to quantify joint moments and power at the hips and shoulders. Key biomechanical constraints that limited performance outcome were identified based on changes in joint kinetics during learning. These constraints were the ability to perform a large shoulder power and to overcome passive kinetics acting during the downswing. Constraints to action at the level of joint kinetics differentially challenge learners and therefore could underpin more individual, specific learning interventions. Functional phases, defined by maximum hyperextension to flexion of the hips and maximum flexion to extension of the shoulders, did not describe the key joint kinetics of the hip and shoulder for novices. The functional phases may serve however to identify novices that were unable to overcome the passive kinetic constraint.

Keywords: *gymnastics, joint kinetics, technique, motor learning*

1. Introduction

The constraints to action concept hold that movement patterns emerge within the constraints or boundaries that are imposed on the system by the task, the environment and the organism (Newell, 1986). Identifying specific constraints that limit, mechanically, the performance outcome of learners could provide useful information for the development of skills and help explain the characteristics of changes in technique during learning.

The gymnastics longswing was chosen to study for a number of reasons. In gymnastics, the task and environmental constraints are well defined, while organismic constraints vary on an inter- and intra-individual basis (Newell, Liu, & Mayer-Kress, 2001). As the most basic swing, the longswing is the fundamental skill on the high-bar apparatus and underpins all other high-bar skills, for example flight elements, turns and "in-bar" elements or dismounts (Fédération Internationale de Gymnastique (FIG), 2013). In addition, this skill is typically novel to the general population making it appropriate for a learning study.

The biomechanics of performing successful longswings is well understood (Arampatzis & Brüggemann, 1998, 1999, 2001; Hiley & Yeadon, 2003; Hiley, Zuevsky, & Yeadon, 2013; Irwin & Kerwin, 2005, 2007a, 2007b; Okamoto, Sakurai, Ikegami, & Yabe, 1987; Sevrez, Rao, Berton, & Bootsma, 2012; Tsuchiya, Murata, & Fukunaga, 2004; Yeadon & Hiley, 2000). The skill consists of a rotation about the horizontal high-bar axis in the vertical plane, where the gymnast swings from handstand to handstand with arms and legs fully extended (Brüggemann, Cheetham, Alp, & Arampatzis, 1994; FIG, 2013). Irwin and Kerwin (2005) defined key components of technique as the "functional phase" actions. The functional phases describe the body "arch" to "dish" as the performer passes under the lower vertical position. Specifically, the hip functional phase was defined between the maximum hyperextension (open) to flexion (close). The shoulder functional phase was defined between maximum flexion (open) to extension (close) (Irwin & Kerwin, 2005; Figure 1). The functional phases are a relatively

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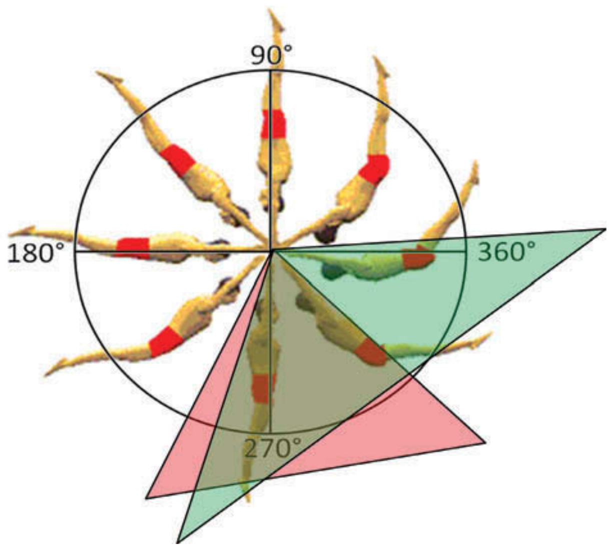

Figure 1. Schematic representation of a gymnast performing the looped longswing. A circle angle of 90° corresponds to the gymnast being in handstand above the bar and hanging under the bar at 270°. As defined by Irwin and Kerwin (2005), the position at which the hip functional phase starts and ends is represented by a small triangle and the shoulder functional phase by a larger triangle.

invariant feature of repeated longswings performed by elite gymnasts (Hiley et al., 2013).

Kinetic analysis of novice technique is important because empirical evidence suggests that an input of positive power at the joints is associated with the rapid closing during the lower half of the circle (Arampatzis and Brüggemann, 1999; Irwin & Kerwin, 2007b; Okamoto et al., 1987; Tsuchiya et al., 2004). In addition, magnitudes of maximum net joint moment (JM) have been theoretically linked to the most effective position of the functional phase in the circle (Yeadon & Hiley, 2000). The occurrence of net JMs and the associated gravitational, muscular and interactive moments acting at the hips and shoulders have also been associated with the functional phase positions (Sevrez et al., 2012).

Williams, Irwin, Kerwin, and Newell (2012) investigated changes in swing amplitude and functional phase variables as a group of novices learnt the longswing over an eight-week period. These authors found that individuals with the fastest rate of performance improvement began the hip functional phase significantly later in the circle during the learning period towards a technique identified in coaching and biomechanics literature (Irwin & Kerwin, 2005). Unsuccessful participants did not significantly change the start position of the hip functional phase throughout the learning period. While a third group of individuals became successful by the end of practice, they performed the hip functional phase earlier in the circle with practice. The results of Williams et al. (2012) highlighted degeneracy in successful novice technique, that is, different techniques to achieve the same performance outcome (Edelman & Gally, 2001). Furthermore, the hip functional phase position was associated with the success of the novices throughout the practice period.

The work in this manuscript builds on the kinematic analysis of technique changes performed by Williams et al. (2012). The aim of the current study was to investigate the joint kinetic characteristics of novice technique during learning the longswing. The purpose was to identify joint kinetic factors that act as constraints to action, limiting performance, and explain the dominant role of the hip action in novice technique.

2. Methods

The data presented in this paper are from the same participant groups as that reported by Williams et al. (2012), which investigated changes in the kinematics. Bad data from the instrumented high-bar data meant that one of the thirteen participants' data were eliminated from this analysis.

2.1. Participants

Ethical approval was gained from the host University's Ethics Committee prior to the start of the study. Analysis was performed on data from twelve male participants (Table I), all of whom were recreational athletes with no prior high-bar experience. All participants gave voluntary informed consent to take part and were only eligible after successfully completing a health questionnaire and a screening for the capability to perform skills reflective of the physical demands of the longswing and its associated progressions (Arkaev & Suchilin, 2004; Readhead, 1997). Screening skills included the ability to perform simple swinging actions on the looped

Table I. Participant information.

Alias	Age (years)	Mass (kg)	Height (m)	Group
PT01	21	67.1	1.67	1
PT09	21	61.3	1.72	1
PT11	18	67.1	1.68	1
PT13	19	73.0	1.78	1
PT02	18	67.8	1.78	2
PT10	23	69.5	1.83	2
PT12	19	65.6	1.75	2
PT15	20	73.4	1.71	2
PT03	18	82.0	1.82	3
PT04	19	77.5	1.82	3
PT05	20	81.1	1.82	3
PT14	20	78.9	1.73	3

bar and fundamental gymnastic movements including the handstand, and dish and arch body positions (Readhead, 1997).

2.2. Procedures

The longitudinal study took place over 8 weeks, during which a testing session was performed on the same day of each week. Between each testing session, a training session was completed (7 in total). Initially, participants were shown videos and received an explanation of the longswing. A study length of 8 weeks was chosen since this was the length of term ~~available~~ during which the students were available for testing. Limiting the amount of time spent learning the skill could always be considered a limitation.

During testing sessions, each participant performed 5 sets of 3 swings after a warm-up. The bar was highly polished, and loops were fitted by a national-level gymnastics coach (Readhead, 1997). During each trial, participants were given the ongoing aim of increasing 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. The only technical instruction provided were: "an extended body shape during the downswing"; "the hips lead the swing under the bar" and "rapid acceleration of the legs into the upswing, closing the hip and shoulder angles" (Readhead, 1997, p. 189).

Training sessions were run by the gymnastics coach and took place in a gymnasium. Exercises were categorised by three themes: conditioning exercises, for example holding a handstand; early skill progressions, such as the looped pendulum swing; and advanced skill progressions, such as an assisted looped layaway and swing down (Arkaev & Suchilin, 2004; Irwin & Kerwin, 2005, 2007a, 2007b; Readhead, 1997). Participants were trained together and each individual performed all the selected exercises.

2.3. Data collection

In order to obtain individual~~,~~ specific body segment inertia parameters, anthropometric data were obtained using the digital image technique reported by 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. 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 metatarsophalageal and the centre of the underside of the bar. Data were collected for each trial performed by each participant.

2.4. Data analysis

Raw marker data in the horizontal and vertical directions were identified from 3D CODA output, and all subsequent analyses took place using customised code written in MATLAB (The Mathworks USA). Kinematic data were filtered by way of a fourth-order low-pass Butterworth filter, cut-off frequency 6 Hz (Winter, 2005). The angular orientation of the gymnast about the bar was described by the circle angle. Circle angle was defined by the mass centre to bar vector with respect to the horizontal (Figure 1). For example, a circle angle of 90° and 450° saw the CM of the performer above the bar (in handstand). During full rotation~~,~~ a new swing was defined each time the performer's centre of mass passed 90° in the circle. Incomplete swings were defined by instances when the angular velocity of the circle angle vector became zero.

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; the line joining the greater trochanter, femoral condyle and lateral malleolus defined the knee angle. Flexion of the hip and knee~~,~~ and extension of the shoulder joints (closing)~~,~~ was defined as positive.

A 2D inverse dynamics analysis was performed to calculate net moments acting at the shoulder, hip and knee joints during the longswing (Winter, 2005). Known zero forces at the toes were combined with the kinematic and inertia data. The human performer was modelled as a four-link system consisting of segments: arms (representative of hands, forearms and upper arms), trunk (head, neck and torso), thighs and shanks (lower legs and feet). Each of the four segments was assumed to be rigid with a uniform density and to be joined by hinge joints. The assumptions associated with modelling the performer as a link system allow us to estimate net JM~~s~~, and although they are reflective of those used in previous literature (Arampatzis & Brüggemann, 1999; Irwin & Kerwin, 2007b; Yeadon & Hiley, 2000)~~,~~ movement of the spine may have made some contribution.

The sign of JM and joint angular velocity values determined whether a positive action (joint opening as net moment and angular velocity are in the same direction) or a negative action (joint opening as net moment and angular velocity are in opposing directions) was occurring. Resultant power at the shoulder and hip joints was calculated as the product of the JM and joint angular velocity. JM and power values were normalised for individual participants by height and total body mass according to a modified version of Hof's (1996) scaling procedure (Equations (1) and (2)).

$$\mathrm{NJM}_j = \frac{\mathrm{JM}_j}{m_p \cdot g \cdot h_p} \quad (1)$$

$$\mathrm{NJP}_j = \frac{\mathrm{JP}_j}{m_p \cdot g^{3/2} \cdot h_p^{1/2}}, \quad (2)$$

where NJM_j is the normalised JM and NJP_j is the normalised joint power (JP) of the jth joint. m is the mass, h is the height of the participant (p) and g is acceleration due to gravity.

Data were interpolated in 1° increments of rotation about the bar using a cubic spline. Swing two in each trial was analysed, resulting in five swings representing each session per participant.

2.4.1. Grouping of participants. Three groups of participants were identified based on the number of sessions it took each individual to perform the full longswings (Williams et al., 2012). Participants in Group 1 (G1, n = 4) were able to perform the full longswing by session 3, participants in Group 2 (G2, n = 4) by session 8, while participants in Group 3 (G3, n = 4) were unable to perform the full longswing throughout the 8 sessions. Data were analysed based on a multiple single-participant design while an individual's group provided an indication of whether certain characteristics of technique were common for more or less successful novices.

To enable comparison, the naming of participants is the same as those used in Williams et al. (2012).

2.4.2. Variables. Changes in the magnitude of maximum hip and shoulder ~~moment and power~~ were examined over the learning period. The downswing phase of continuous profiles for hip and shoulder moment were examined and associated with the functional phases. JP profiles were described and associated with the kinematics of functional phase actions.

2.4.3. Statistical analysis. Differences between discrete variables across testing sessions were quantified using repeated measures analysis of variance based on a single-participant design. The level of statistical significance was set *a priori* to $P < 0.05$, where the Bonferroni correction was applied for multiple comparisons. Normality of data was assessed using the critical appraisal approach (Peat & Barton, 2005). Mauchly's test was used to determine the sphericity assumption within the data; where sphericity was violated, probability was corrected according to the Greenhouse-Geisser procedure. Cohen's d, effect size, was calculated between data for sessions that were statistically different (Cohen, 1992).

3. Results

3.1. *Magnitude of maximum JM* and *JP*

Values for mean maximum hip moment ranged between 0.05 and 0.18 NJM for all novices and did not distinguish between successful and unsuccessful novices. For example, during session 8, the maximum JMs of successful performers in G1 did not differ from those of unsuccessful performers in G3, Figure 2. Significant increases in maximum hip moment occurred for participant (PT) PT02 and PT10 in G2, and PT04, PT05 and PT14 in G3 between sessions 1 and 8 ($P < 0.05$; $d > 0.3$).

Mean values for maximum shoulder moment ranged between 0.16 and 0.31 NJM for all participants during the 8 sessions. A significant increase in the maximum shoulder moment occurred for PT10 (G2) and PT04 (G3) ($P < 0.05$; $d > 0.4$).

Mean maximum hip power ranged between 0.008 and 0.030 NJP for the novices over the 8 sessions and did not distinguish between more or less successful novices (Figure 2). A significant increase in maximum hip power was evident for PT01 and PT11 (G1) and PT03 and PT04 (G3) between sessions 1 and 8 ($P < 0.05$; $d > 0.7$).

PT01 (G1) significantly increased shoulder power and also produced the largest shoulder power throughout the 8 sessions ($P < 0.05$; d 0.7; Figure 2). During successful swings, two novices from G1 (PT01 and PT09) performed the largest shoulder power (0.019–0.038 NJP) compared to other participants whose mean shoulder power ranged between 0.006–0.018 NJP throughout the 8 sessions (Figure 2). During successful swings for all participants except PT09, maximum hip power was equal or higher than maximum power at the shoulders.

While some knee flexion occurred during the swing, knee JMs and JPs were small, to a maximum of 0.003 NJM and 0.004 NJP, respectively. Knee flexion occurred during the downswing and during hip hyperextension. PT02 (G2) performed a larger amount of knee flexion during successful swings in

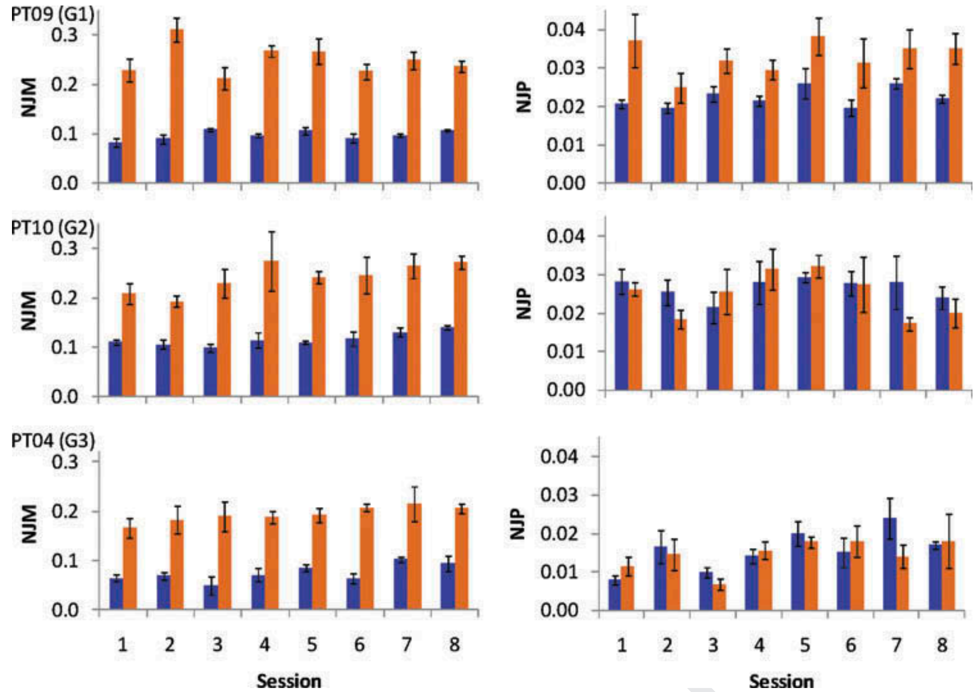

Figure 2. Mean ± s Maximum NJM (left) and NJP (right) for the hips (dark grey) and shoulders (light grey) during 8 sessions for PT09 in G1, PT10 in G2 and PT04 in G3.

session 8, performing JMs (mean 0.08 ± 0.02 NJM) to flex the knee into the upswing though a powerful action (mean 0.01 ± 0.003 NJP). AQ5

3.2. *Characteristics of hip and shoulder JM profiles*

Participants in G1 performed a consistent positive moment at the hip from the beginning of the swing that caused the maintenance and slight closing of the joint angle during the downswing. Maintaining a straight position enabled the functional phase to begin near the lower vertical (Figure 3). This characteristic of technique occurred from session 1 (PT09 and PT11) and from session 3 (PT01 and PT13). All other participants experienced opening of the hip from the start of the swing to the beginning of the functional phases (Figure 3) when no consistent positive net moment was produced until the start of the functional phase (Figure 3).

The shoulder functional phase began early in the circle for all novices except PT09. Similar to performing the later hip functional phase, PT09 increased the positive shoulder moment from the beginning of the swing to maintain and slightly close to the shoulder angle before the functional phase. Moments were reduced to begin the

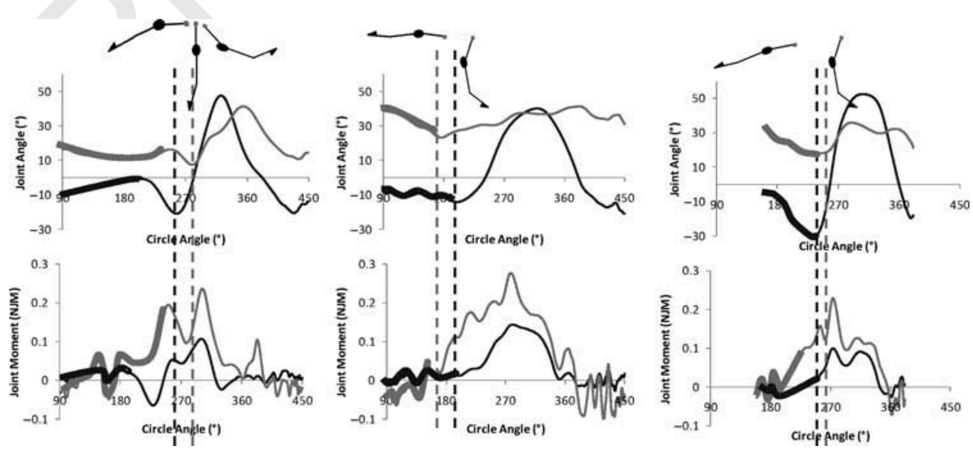

Figure 3. Hip (dark grey) and shoulder (light grey) angle (top) and net moment (bottom) during a swing in session 8 for PT09 G1 (left), PT10 G2 (middle) and PT04 G3 (right). Dashed lines indicate the beginning of the functional phase actions. Sections of the joint angle and moment curves are bolded to highlight key actions referred to in the text. Stick figures represent the body position before the functional phase and underneath the bar for clarity.

functional phase (Figure 3). For the majority of novices, however, small and inconsistent shoulder moment from the beginning of the swing resulted in the joint opening until the beginning of the functional phase action (Figure 3). An eccentric action of the shoulder was identified for individuals in G3 during the downswing as the shoulder joint opened while positive JMs were performed (Figure 3).

3.3. *Hip JP profiles*

Inputs of power appear as “peaks” in the power profile, where the magnitude increases from zero to a maximum and then returns towards zero (Figure 4). For two performers in G1 (PT01 and PT09), hip power profiles became characterised by a 3-peak pattern (Figure 4). Individuals in G2 performed a large peak (0.02–0.03 NJP) proceeded by a small peak (~0.01 NJP) throughout the 8 sessions (Figure 4, middle). However, a unique characteristic of this large positive power peak was that another increase occurred during the descending phase (Figure 4, middle right). Thus, the functional phase was not described by a single powerful action for performers in G2. All members in G3 (PT03, PT04, PT05 and PT14) performed a larger peak during swings that represented the functional phase after the initial swing attempt (Figure 4, bottom right).

3.4. *Shoulders JP profiles*

Few clearly defined patterns of peaks emerged. Shoulder power profiles contained a smooth large positive peak for participants in G1 (PT09, PT01 and PT11) and a participant in G2 (PT10) (Figure 5). For all other participants, a number of small amplitude peaks characterised shoulder power profiles throughout the training period (Figure 5). Unlike those of the hips, negative peaks were evident that corresponded to negative work. For less successful participants, this negative work was placed much earlier in the circle (220°) than for the more successful performers in G1 (260°) (Figure 5). The shoulder functional phase was not defined by a single positive peak for any participant (Figure 4).

4. Discussion

The aim of the current study was to investigate the joint kinetic characteristics of novice technique

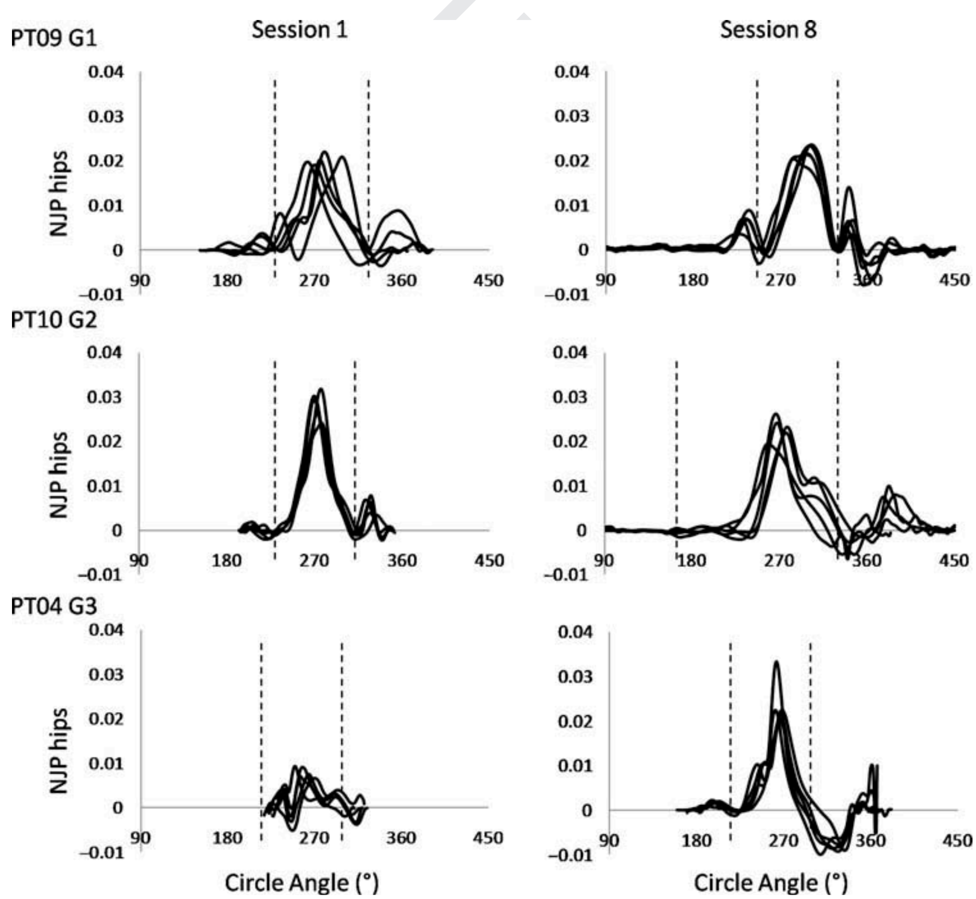

Figure 4. Normalised hip power profiles for PT09 G1 (top), PT10 G2 (middle), PT04 G3 (bottom) during 5 swings in session 1 (left) and 5 swings in session 8 (right). Dashed vertical lines represent the average start and end of the hip functional phase.

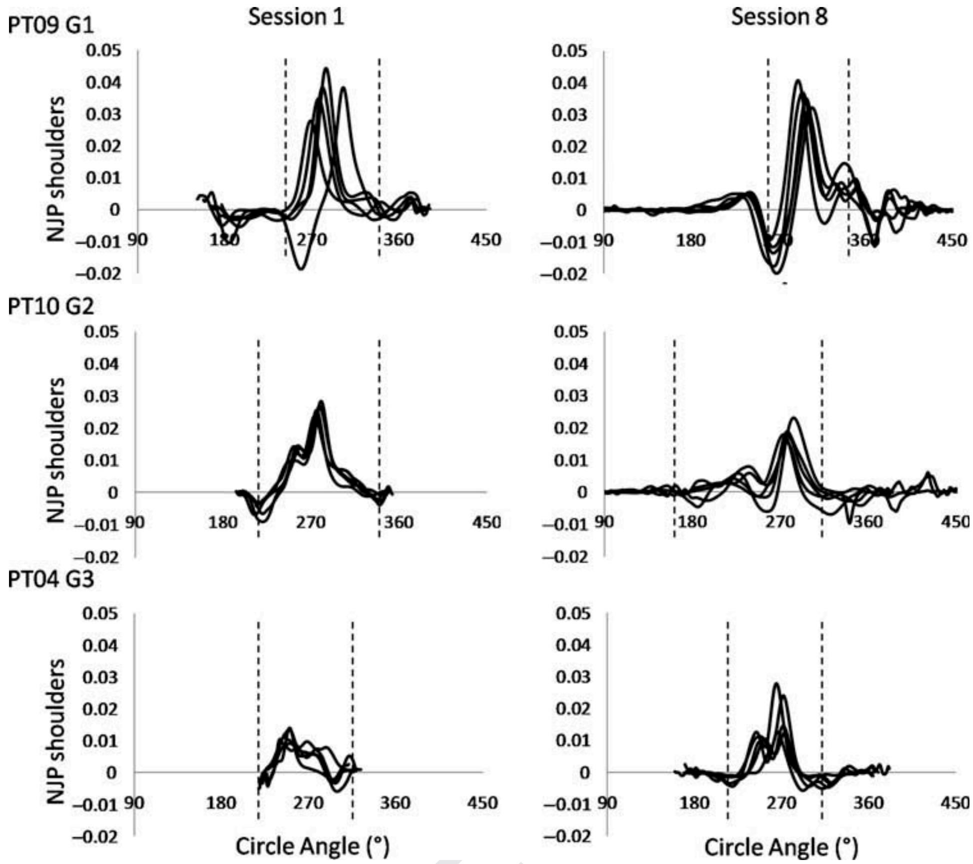

Figure 5. Normalised shoulder power profiles for PT09 G1 (top), PT10 G2 (middle), PT04 G3 (bottom) during 5 swings in session 1 (left) and 5 swings in session 8 (right). Dashed vertical lines represent the average start and end of the shoulder functional phase.

during learning the longswing. The purpose of this research was to identify joint kinetic factors that act as constraints to action, limiting performance, and explain the dominant role of the hip action in novice technique. Two key constraints to action were identified for the novices: shoulder power and passive kinetics that act during the downswing. These constraints were associated with the dominance of the hip joint actions in predicting success for the novices (Williams et al., 2012).

4.1. Magnitude of maximum JM and JP

The shoulder action of novices differs greatly from those reported for elite gymnasts in both magnitude and the characteristics of the closing action (Irwin & Kerwin, 2007b; Yeadon & Hiley, 2000). Contrary to the longswings performed by elite gymnasts, the maximum shoulder power of the novices was smaller than maximum hip power during full longswings, with the exception of one novice (PT09) (Irwin & Kerwin, 2007b; Tsuchiya et al., 2004). In addition, only novices with the highest shoulder power (PT09, PT01 range 0.019–0.035 NJP compared to all other participants range 0.006–0.018 NJP) performed a single closing action near the lower vertical. This rapid closing is a key coaching point for the skill which seems to be an indicator of more skilful performance (Arampatzis & Brüggemann, 1999; Irwin & Kerwin, 2005; Tsuchiya et al., 2004; Yeadon & Hiley, 2000).

The ability to perform a powerful closing action is theoretically and empirically linked to performing the shoulder functional phase near the lower vertical (Sevrez et al., 2012; Yeadon & Hiley, 2000). Therefore, it is important that coaches focus on both the timing and magnitude of the shoulder kinetics during the longswing. Quantitative biomechanical analysis of technique could provide useful information to support the coaching process in this endeavour. Furthermore, difference in JP contributions at the hips and shoulder suggest that an energetic analysis is required, such as that performed by Arampatzis and Brüggemann (1999).

Williams et al. (2012) found that the hip functional phase position distinguished between more and less successful novices, while changes in the shoulder action were unclear. The mechanics of the bodies' series of linked segments rotating about the bar in conjunction with the limits of shoulder kinetics helps explain the prominent role of the hip actions in novice technique. Mechanically, to reduce the work requirements for closing the shoulder joint, more distal joints such as the hips must be closed first. Reducing the work requirements at the joint is particularly important because the ability to perform a powerful closing action at the shoulder joint has been highlighted as a limiting factor for novices. That the hip action plays the key role during learning is contrary to the notion of a move from more proximal to distal control of joints during learning AQ6 (Bernstein, 1967; Hodges, Hayes, Horn, & Williams, 2005; McDonald, van Emmerik, & Newell, 1989). This contrasting finding is due to the specific mechanics of this task, which emphasises the performer as a series of rotating linked segments in confluence with organismic constraints such as the relatively novel and strenuous shoulder action (Newell & Vaillancourt, 2001).

Maximum hip and shoulder moment did not distinguish between more or less successful novices throughout the learning period. Therefore, maximum JMs were not clearly related to success for these novices. This finding is particularly surprising because Yeadon and Hiley (2000) theoretically determined the large influence of varying JM limits on optimal longswing technique. Maximum hip power ranged between 0.008 and 0.040 NJP during swings. There was a large range of maximum hip powers for the novices, while values reported in the previous literature for elite longswings have been relatively consistent (0.014 NJP by Irwin & Kerwin, 2007b; Williams, Irwin, & Kerwin, 2010; 0.013 NJM by Okamoto et al., 1987).

While some knee flexion occurred during the swing, knee JMs and JPs were small, to a maximum of 0.003 NJM and 0.004 NJP, respectively. Knee flexion occurred during the downswing, during hip hyperextension. Thus, the beneficial effects of reducing the moment of inertia about the bar during the upswing were negligible during these swings. PT02 (G2) performed a larger amount of knee flexion during successful swings in session 8, performing JMs (mean 0.08 ± 0.02 NJM) to flex the knee into the upswing though a powerful action (mean 0.01 ± 0.003 JNP). The effect of this knee power on the distribution of joint work between the shoulder, hip and knee joints for this performed could usefully be explored via an energetics analysis.

4.2. *Characteristics of hip and shoulder JM profiles*

Performing the hip and shoulder functional phases close to the lower vertical is associated with an effective technique (Irwin & Kerwin, 2005; Tsuchiya et al., 2004; Williams et al., 2012; Yeadon & Hiley, 2000). Positive net moments from the beginning of the swing were required to perform the hip and shoulder functional phase close to the lower vertical (Figure 3). Positive net moments overcome the passive kinetics, defined as the forces tending to open the joints as the body rotates as a series of linked segments, where distal segments have the tendency to rotate at a slower angular velocity about the bar (Sevrez et al., 2012; Yeadon & Hiley, 2000).

A key biomechanical constraint to action was the ability to attune to the passive kinetics during the downswing. Overcoming passive kinetics, the performer has to maintain a more extended position and slightly close the hip and shoulders during the downswing (Figure 3, top left panel). From an extended position, the performer was able to begin the functional phase at the bottom of the swing (Figure 2, left panel). Specifically, from an extended position, the hip functional phase was initiated by removing positive moments, which caused a more rapid opening of the joint near lower vertical until further positive moments commenced the functional phase (Figure 3, left panels). Tsuchiya et al. (2004) demonstrated the same characteristics of technique for skilled gymnasts. The JM profiles demonstrate that a more complex series of forceful actions is required to prescribe the more effective kinematics of the longswing (Williams et al., 2012). Understanding the kinetic characteristics of technique bridges the gap between the coach's external view of performance and the kinetics experienced by the performer during the task. In addition, an assessment of the continuous nature of technique variables as opposed to just discrete variables is important to fully understand how discrete aspects of technique, such as the functional phase positions, are achieved.

4.3. *Key characteristics of hip and shoulder JP profiles*

Hip power profiles of PT09 and PT01 (G1) were characterised by a more complex, "three-peak pattern" that caused arch-dish-arch actions throughout the swing. Three inputs of positive hip power may be considered a finer control strategy during this skill, where key elements of technique were sequentially adhered to. Evidence from the literature suggests that skilled gymnasts also perform this "three-peak pattern" of hip power (Tsuchiya et al., 2004). The series of three actions that began near the lower vertical was facilitated by the onset of positive net moments at the hips and shoulders from the beginning of the swing, as discussed above. These findings highlight the usefulness of a single-participant design (Bates, 1996) that has enabled some specific and more advanced characteristics of technique to be identified for individuals.

4.4. *Functional phase actions*

The hip functional phase did not fully describe the mechanics of the novice hip action. Irwin and

Kerwin (2007b) defined a functional phase by a single positive input of power between maximum hip hyperextension to flexion. While the definition of the hip functional phase provided by Irwin and Kerwin (2005, 2007b) corresponded with the technique of individuals in G1 and G3, a number of powerful inputs were identified between maximum hyperextension to flexion for individuals in G2. Thus, for novices, the functional phase variables may serve to identify a technique comparable with individuals in G2; however, it does not fully describe the mechanics of the hip actions.

In addition the shoulder, the functional phase did not describe the mechanics of the novice shoulder action since there was not a single positive powerful input between maximum extension to flexion. Shoulder power profiles of some of the most successful participants included a smooth larger positive peak after practice (Figure 5, top right). A preceding negative peak was indicative of positive moment while the joint was opening (Figure 5, top right). Thus, the performer allowed the shoulder to open using the passive kinetics (Sevrez et al., 2012) acting on his joint during the swing, a characteristic of technique that has been identified previously for elite longswings (Arampatzis & Brüggemann, 1998; Irwin & Kerwin, 2007b; Okamoto et al., 1987). If producing a powerful shoulder action was associated with strength limits, more training sessions per week might have changed this characteristic of technique.

Consistent with the finding of the previous literature, it is anticipated that shoulder flexion may play a key role in facilitating the larger positive power within the functional phase (Arampatzis & Brüggemann, 1998; Irwin & Kerwin, 2007b; Okamoto et al., 1987). A powerful shoulder extension action after the lower vertical is a more advanced skill, performed by the most successful participants. Based on these findings, future research might investigate the effect that different instructions ~~might~~ have on the ability of novices to learn these series of actions.

5. Conclusion

Novices did not perform a powerful shoulder action reflective of those reported in biomechanics studies of elite gymnasts, and subsequently, shoulder power was identified as a biomechanical constraint to action.

Passive kinetics that act to open the joints during the downswing were identified as a biomechanical constraint to action. Performing positive moments to overcome passive kinetics resulted in a more effective technique. Coaches might consider communicating forces to promote closing of the hips during the early downswing, allowing a passive opening before the lower vertical, followed by the rapid closing action of the functional phase in order to achieve the most effective ~~and efficient~~ kinematic characteristics of the technique.

Functional phases did not describe the key joint kinetics of the hip and shoulder actions for novices. The functional phases may serve to identify novices that were unable to overcome the passive kinetics constraint.

A broader conclusion is that constraints to action at the level of joint kinetics are likely task specific, and while they differentially challenge~~,~~ learners could underpin effective learning interventions.

Further work will explore the differences in mechanical efficiency between the successful techniques of novices.

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