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Biomechanical energetic analysis of technique during learning the longswing on the high bar

GENEVIEVE K. R. WILLIAMS[1], GARETH IRWIN[2], DAVID G. KERWIN[2] & KARL NEWELL~~[3]~~[1]

AQ1 [1]*Departmnet of Kinesiology, The Pennsylvania State University, State College, PA, USA,* [2]*School of Sport, Cardiff Metropolitan University, Cardiff, UK*~~*and* [3]*Department of Kinesiology, The Pennsylvania State University, Univ Park, PA, USA*~~

(~~*Accepted 18 November*~~ *2014*)

Abstract

Biomechanical energetic analysis of technique can be performed to identify limits or constraints to performance outcome at the level of joint work, and to assess the mechanical efficiency of techniques. The aim of this study was to investigate the biomechanical energetic processes during learning the longswing on the high bar. Twelve male, novice participants took part in a training study. Kinematic and kinetics data were collected during swing attempts in eight weekly testing sessions. Inverse dynamics analysis was performed from known zero forces at the toes. Joint work, total energy, and bar energy were calculated. Biomechanical constraints to action, that is, limits to novice performance, were identified as "total work" and "shoulder work". The most biomechanically efficient technique was associated with an onset of the hip functional phase and joint work that occurred between 10–45° before the bottom of the swing. The learning of gross motor skills is realised through the establishment of a set of techniques with task specific biomechanical constraints. Knowledge of the biomechanical constraints to action associated with more effective and efficient techniques will be useful for both assessing learning and establishing effective learning interventions.

Keywords: *gymnastics, energetics, constraints to action, motor learning*

Introduction

Biomechanical analysis can increase understanding of how the changes in technique that occur during motor learning enable us to better satisfy task demands. Particularly, a biomechanical energetic analysis can help explain the reasons why a given technique is more or less successful, or quantify the mechanical efficiency of that technique. Therefore, a biomechanical understanding of changes in technique during learning can provide objective, quantitative information which is useful for assessing and enhancing the process of skill learning.

Previous research has investigated the mechanical energy exchanges during gross motor skills such as the pole-vault (Schade, Arampatzis, & Brüggemann, 2000), sprint running (Bezodis, Kerwin, & Salo, 2008) and gymnastics high bar skills (Arampatzis & Brüggemann, 1999, 2001; Irwin & Kerwin, 2007; Okamoto, Sakurai, Ikegami, & Yabe, 1987). However, changes in mechanical efficiency during learning have more often been examined for laboratory based tasks such as crawling (Sparrow & Irizarry-Lopez, 1987) and reaching movements (Schneider, Zernicke, Schmidt, & Hart, 1989), for which efficiency improves with practice.

In this research the gymnastics longswing was used as a vehicle to study the skill learning process. The gymnastics longswing is a fundamental skill on the high bar apparatus. The longswing consists of a rotation about the horizontal high bar axis in the vertical plane, where the gymnast swings from handstand to handstand (Figure 1). Arms and legs of the performer remain fully extended throughout the swing, thus basic technique consists of flexion and extension actions at the hips and shoulders (Brüggemann, Cheetham, Alp, & Arampatzis, 1994; Fédération Internationale de Gymnastique (FIG), 2013).

Williams, Irwin, Kerwin, and Newell (2012) investigated joint kinematic strategies of novices during a period of learning the longswing. While the central goal of learning the task was to increase swing amplitude, the findings of Williams et al. (2012) established three groups of novices who were able to perform the skill after a similar number

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AQ2 Correspondence: Genevieve K. R. Williams, Department of Kinesiology, The Pennsylvania State University, 23 Recreation Hall, State College 16802, PA, USA. E-mail: ~~genkrwilliams@hotmail.com~~ gkw11@psu.edu

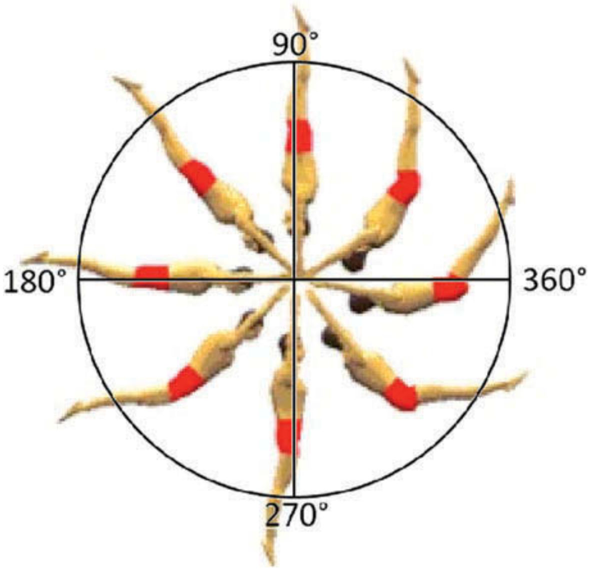

Figure 1. Schematic of a gymnast performing the looped longswing. Circle angle see the gymnast at 90° in handstand above the bar and hanging under the bar at 270°.

of practice attempts. The position of the hip functional phase action, which is defined between maximum hyper-extension to flexion of the joint during the swing, was common for individuals in each group. As such, degeneracy in successful techniques was identified, that is, two different techniques were used to achieve the same task outcome (Edelman & Gally, 2001). It is unclear how the two techniques differ in terms of their joint work contribution.

The aim of the current analysis was to investigate the biomechanical energetic process involved in novice technique during a period of learning the longswing. The research seeks to provide further insight into how the technique of novices was related to their biomechanical contribution via an analysis of the joint work intervention and the total energy of the system. This analysis will help to further understand degeneracy in successful techniques by revealing the nature of changes in mechanical efficiency during learning. The purpose of this analysis was to inform the coaching process for this skill by identifying the most mechanically efficient technique and the biomechanical constraints that limit the ability to perform this technique during learning.

Methods

The data presented in this paper are from the same participant groups as that reported in Williams et al. (2012), which investigated changes in kinematics. The numbering of participants is the same as in Williams et al. (2012).

Participants

Ethical approval was gained from the host University's Ethics Committee prior to the onset of the study. All participants gave voluntary informed consent to take part in the study. Data for twelve male participants (M ± s age: 20 ± 2 years, mass: 72.0 ± 6.7 kg and stature: 1.76 ± 0.06 m) were analysed. All participants were recreational athletes with no prior high bar experience. Eligibility to take part in the study was granted after participants successfully completed a health questionnaire and had been screened for the capability to perform skills reflective of the physical demands of the longswing and its associated progressions (Arkaev & Suchilin, 2004; Readhead, 1997). Skills included the ability to perform simple swinging actions on the looped bar and fundamental gymnastic movements including the handstand, dish, and arch body positions.

Procedures

The longitudinal study took place over 8 weeks. A period of eight weeks was chosen based on evidence from a previous study (Irwin, 2005; unpublished thesis) that suggested it would allow sufficient time for the majority of novices to perform the full longswing. In addition, eight weeks was the length of the term during which the students were available for testing. Initially, participants were shown videos and received an explanation of the aims of the longswing. A testing session was then performed on the same day of each week. Between each testing session a training session was completed (7 in total).

During testing sessions each participant performed 5 trials of 3 swings after a warm-up. The bar was highly polished and loops were fitted. During each trial, participants were given the ongoing aim of increasing their swing amplitude until, ideally, they were able to perform the complete longswing. Participants were instructed to keep knees and elbows fully extended during swinging. Technical instruction provided was kept to the relevant recommended techniques: "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 a gymnastics coach and comprised the structured implementation of longswing specific skill progressions and conditioning exercises (Irwin & Kerwin, 2005; Readhead, 1997). Training exercises were categorised by three themes: conditioning exercises, for example holding a handstand; early skill progressions, such as looped pendulum swing; and advanced skill progressions, such as an assisted looped layaway and swing down. Participants trained together and each individual performed all of the selected exercises.

Data collection

In order to obtain individual specific body segment inertia parameters, anthropometric data were obtained using the digital image technique of Gittoes, Bezodis, and Wilson (2009) (Canon EOS400D SLR, Japan; resolution 720 × 576 pixels) 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 (Figure 2). 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. Eight linear strain gauges (CEA/09/280UW/120; 1000 Hz) measured external reaction forces at the bar. Two pairs of gauges were mounted at the end of the bar, with their outputs combined to produce net vertical and horizontal outputs. The arrangement accommodated loading at any point along the bar. A Wheatstone bridge circuit allowed measurement of forces in the horizontal and vertical directions via four net channels (2 × vertical and 2 × horizontal), which were amplified using a strain gauge amplifier (model 2100, Measurement Group, Basingstoke, UK). Calibration of the instrumented high bar was performed in the vertical direction by loading and unloading the centre of the bar with known masses of up to 4000 N.

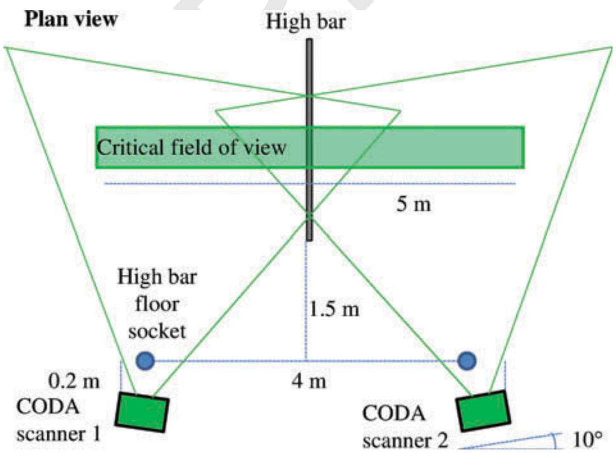

Figure 2. Plan view of the data collection set-up. Coda scanners provided a field of view of 2.5 m around the high bar.

Data analysis

Raw marker data and strain gauge outputs were identified from Coda output and all subsequent analysis took place using customised code written in MATLAB (The Mathworks, USA). 3D marker data were projected onto a 2D sagittal plane. Kinematic data were filtered using a fourth order, low pass Butterworth filter with a cut-off frequency of 6 Hz. 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, where a circle angle of 90° and 450° saw the CM of the gymnast above the bar in handstand (Figure 1).

During full rotation, a new swing was defined each time the performer's centre of mass passed through 90° in the circle (Figure 1). 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. Lines 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. The hip functional phase was defined between maximum hyperextension (opening) to flexion (closing) at the joint. The shoulder functional phase was defined between maximum flexion (opening) to extension (closing) occurring under the lower vertical (Irwin & Kerwin, 2005).

A two-dimensional inverse dynamic analysis was performed from known zero forces at the toes combined with kinematic and inertia data to calculate net moments acting at the shoulder, hip, and knee joints during the longswing. Resultant power at the shoulder and hip joints was calculated as the product of the joint moment and joint angular velocity. Net mechanical work at the joint (JW) was calculated as the integral of joint power (JP) with respect to time (Equation (1)).

$$\mathrm{JW}_{\mathrm{total}} = \sum_{j=1}^{3} \mathrm{JP}_{j} \cdot dt \qquad (1)$$

Total work was calculated as the sum of the work done at the shoulder, hip, and knee joints. Total energy of the performer was calculated as the sum of the angular kinetic, gravitational potential and linear kinetic energy possessed by the performer, modelled as a series of segments (Equation (2)),

$$E_{total} = \sum_{i=1}^{4} \frac{1}{2} I_i \omega_i^2 + \sum_{i=1}^{4} m_i \cdot g \cdot h_i + \sum_{i=1}^{4} \frac{1}{2} m_i v_i^2 \tag{2}$$

where total energy = E_{total}, moment of inertia = I, angular velocity = ω, mass = m, acceleration due to gravity = g, vertical position relative to neutral bar position = h, linear velocity = v, and i = i^{th} segment.

Total energy was calculated relative to the neutral bar position, where the neutral bar was at (0,0) in the reference system.

Energy stored by elastic properties of the bar was calculated from forces measured at the bar ($F_{b\_measured}$) in the horizontal (y) and vertical (z) directions (Equation (3)).

$$E_{bar} = \frac{1}{2} \cdot \frac{F_{b\_measured\_}y^2}{K_y} + \frac{1}{2} \cdot \frac{F_{b\_measured\_}z^2}{K_z} \tag{3}$$

Energy transferred by the performer to the elastic bar (E_{bar}) was calculated using the measured forces on the bar and stiffness values (K) (Equation (3)). Conversion from the measured vertical stiffness (K_z) to the horizontal (K_y) was taken from Kerwin and Hiley (2003), where horizontal stiffness was 85% of the vertical stiffness.

Efficiency score. Net energy (E_{net}) was calculated as the total energy (E_{total}) with the total work (JW_{total}) and energy of the bar (E_{bar}) removed (Equation (4)).

$$E_{net} = E_{total} - (JW_{total} + E_{bar}) \tag{4}$$

The efficiency score was calculated as the root mean square differences (RMSD) between the profiles of total energy (E_{total}) and net energy (E_{net}) (Equation (5)).

$$RMSD = \left(\frac{1}{N} \sum_{i=1}^{N} (E_{total} - E_{net})^2 \right)^{\frac{1}{2}} \tag{5}$$

Energy values were normalised for comparisons between participants based on Equation (6) (Hof, 1996),

$$\hat{E} = \frac{E}{m_p \cdot g \cdot h_p} \tag{6}$$

where $\hat{E}$ = Normalised Energy, h = height, p = participant.

Moment of Inertia about the fingertips of each performer was calculated to represent a fully outstretched position about the bar. In order to provide inter-performer comparison between swings, time series data were interpolated to 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.

Data analysis

Grouping of participants. Data were analysed based on a multiple single-subject design while an individual's group provided an indication of whether certain characteristics of technique were common for more or less successful novices. 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; participant (PT) PT01, PT09, PT11 and PT13) were able to perform the full longswing by session 3. Participants in group 2 (G2 n = 4; PT02, PT10, PT12 and PT15) were able to perform the full longswing by session 8. While PT03, PT04, PT05 and PT14 in group 3 (G3, n = 4) were unable to perform the full longswing throughout the 8 sessions.

Variables. Discrete values for normalised total work and work at the hip, shoulder and knee joints were analysed over sessions, and compared between successful and unsuccessful swings of participants in each group. Continuous profiles of total energy, total work, and bar energy were presented simultaneously. A score of efficiency was reported for full longswings. To inform the comparison of efficiency between swings, moment of inertia of performers in a fully outstretched position and difference between total energy at the start and end of successful swings were calculated.

Statistical analysis. Differences between discrete variables across testing sessions were quantified using repeated measures analysis of variance (ANOVA) based on a single-subject 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). Group differences in variables were tested by a two-tailed independent t-test ($P < 0.05$).

Results

Normalised work

During incomplete swings by all participants in G3, who remained unsuccessful throughout the learning period, mean total work was 0.12 ± 0.02 normalised units (NJW), and ranged between 0.05 and 0.15 NJW (Figure 3). During full longswings performed by individuals in G1 mean total work was 0.20 ± 0.03 NJW and G2 0.21 ± 0.04 NJW, ranging between 0.15 and 0.29 NJW. Total work was significantly higher ($P < 0.01$) during successful swings than unsuccessful swings (within G1 mean difference 0.09 NJW, CI from 0.07 to 0.11 NJW, $t = 9.2$, $df = 30$, effect size 0.9; $P = 0.00$; within G2 mean difference 0.07 NJW, CI from 0.05 to 0.09 NJW, $t = 6.0$, $df = 30$, effect size = 0.7, $P = 0.00$; between G1 successful and G3 mean

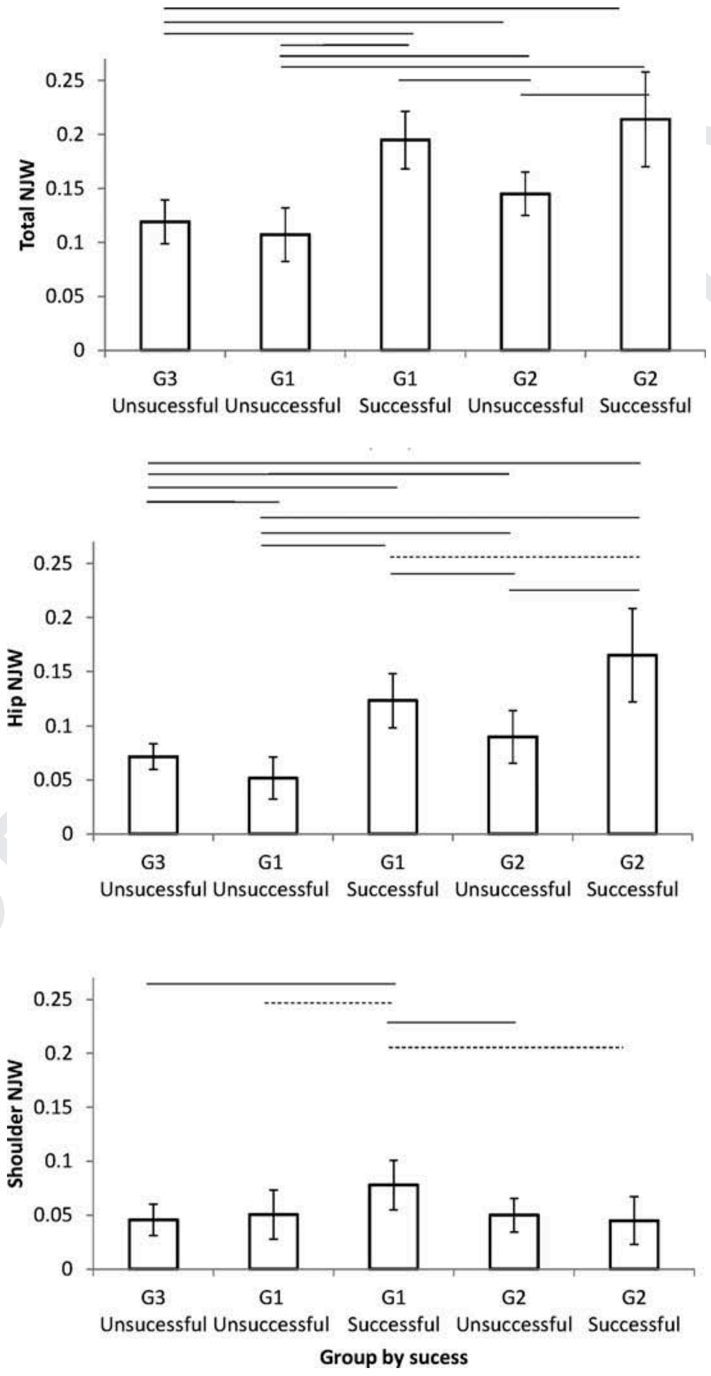

Figure 3. Mean and standard deviation of normalised joint work (NJW) total (top), at the hip (middle) and shoulder (bottom) for all unsuccessful sessions of group 3 (G3), and unsuccessful and successful sessions of group 1 (G1) and group 2 (G2). Solid horizontal lines lie between groups that are significantly different to $P < 0.01$, and dashed lines $P < 0.05$.

difference 0.08 NJW, CI from 0.06 to 0.09, $t = 11.6$, $df = 50$, effect size 0.9, $P = 0.00$; between G2 successful and G3 mean difference 0.09 NJW, CI from 0.07 to 0.12 NJW, $t = 8.6$, $df = 36$, $P = 0.00$, effect size = 0.81; Figure 3).

Post hoc analysis showed that significant increases occurred in hip work between early sessions (1–5) and later sessions (5–8) for all participants ($P < 0.05$; effect size >0.7; Figure 4). Individuals in G1 performed significantly more hip work during sessions where successful longswings were performed compared to unsuccessful sessions (mean difference 0.113 NJW, 95% CI from 0.08 to 0.14 NJW, $t = 7.8$, $df = 16$, effect size = 0.9, $P < 0.00$; Figure 3). Ranges of values for hip work did not distinguish between groups of learners during early sessions. For example, hip work for participants PT10, PT12 and PT15 in G2 ranged between 0.06 and 0.15 NJW during

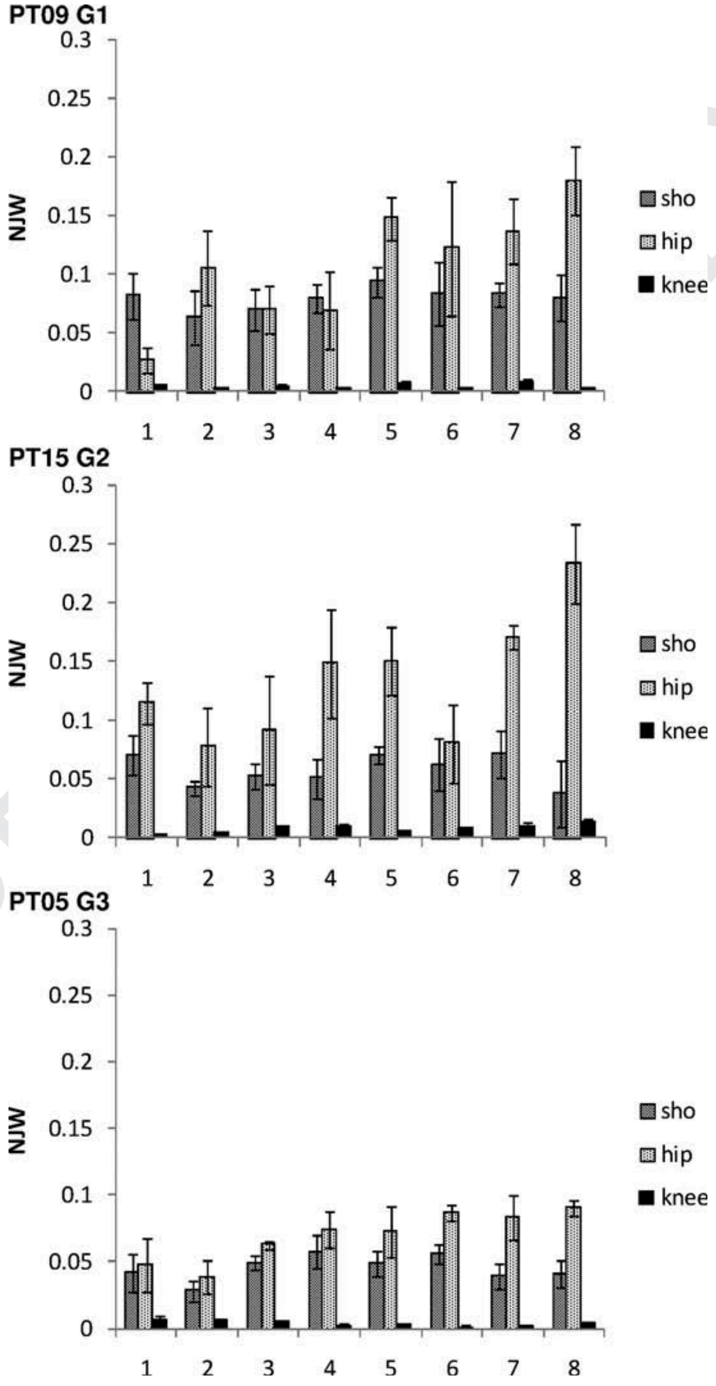

Figure 4. Mean (± *s*) normalised joint work performed at the shoulder joints (dark grey), hips (light grey) and knees (black) over eight sessions, for participants PT09 in G1 (top), PT15 in G2 (middle) and PT05 in G3 (bottom).

session 1–6, and 0.09 and 0.23 NJW during session 7 and 8 where they successfully performed longswings. Hip work for unsuccessful performers in G3 ranged between 0.03 and 0.12 NJW throughout the eight sessions. During successful swings by G2 significantly more hip work was performed than during unsuccessful swings (mean difference 0.08 NJW, 95% CI from 0.05 to 0.10 NJW, $t = 5.8$, $df = 30$, effect size = 0.7, $P < 0.00$; Figure 3).

Individuals in G1 performed >13% more net shoulder work during successful longswings (mean 0.08 ± 0.02 NJW; mean difference 0.03, CI from 0.01 to 0.04, $t = 3.3$, $df = 30$, effect size = 0.5, $P = < 0.00$), significantly more than ($P < 0.05$) individuals in G2 (successful swings mean difference 0.03 NJW, 95% CI from 0.01 to 0.05, $t = 3.1$, $df = 24$, effect size = 0.5 $P = 0.01$) or G3 (mean difference 0.03 NJW, CI from 0.02 to 0.04 NJW, $t = 6.2$, $df = 50$, effect size = 0.7, $P < 0.00$; Figure 3, 3). Mean shoulder work was ≤0.05 NJW throughout the learning period; less than hip work (Figure 3).

Interestingly, one participant (PT02) in G2 utilised knee work during successful longswings. Knee work accounted for 47% of total work during session eight, more than either hip (0.05 ± 0.01 NJW) or shoulder joints (0.02 ± 0.00 NJW). With the exception of PT02, knee work averaged less than 0.01 NJW for all other participants.

Total energy profiles: the effect of work and bar energy

During incomplete swings, total energy profiles consisted of an increase before and after the bottom of the swing (270° in the circle angle) as a result of positive work (Figure 5). This common pattern

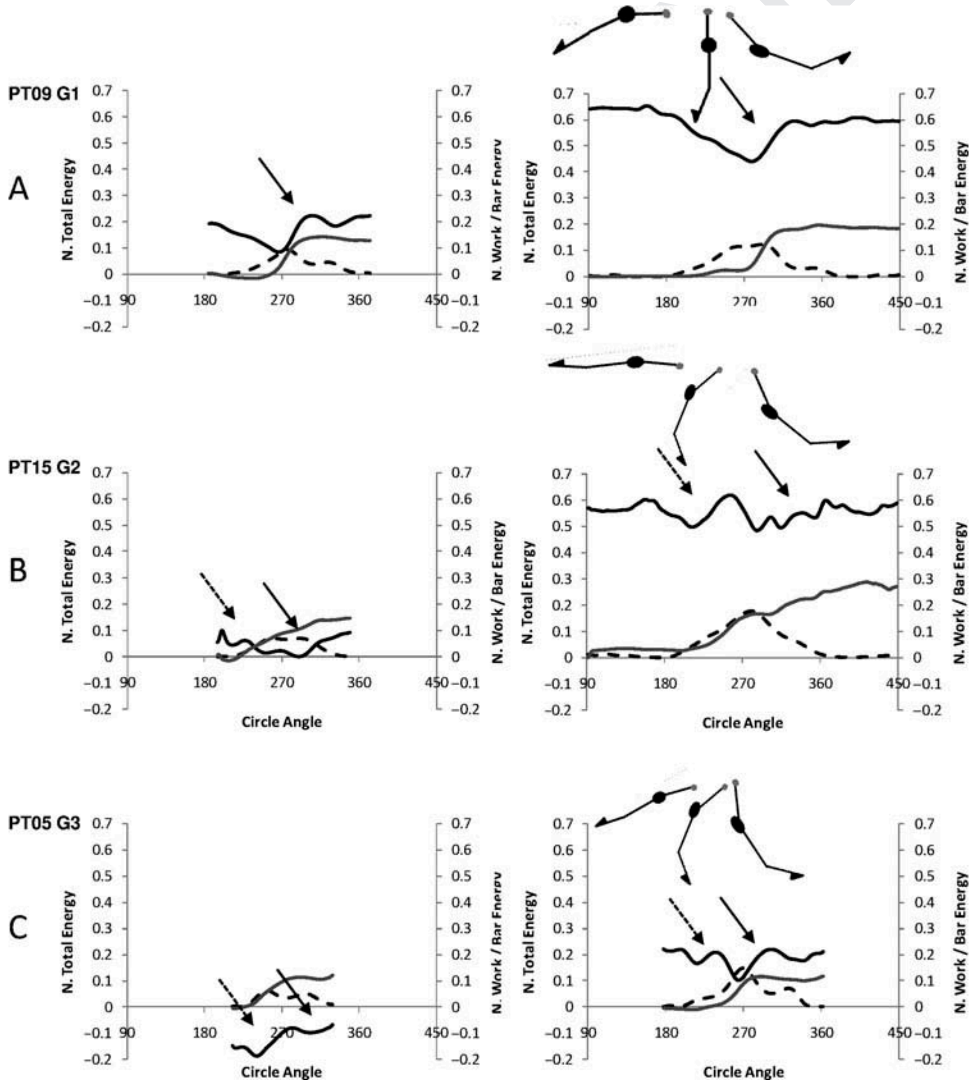

Figure 5. An example of a normalised total energy (solid black line), total work (solid grey line) and bar energy (dashed black line) profile for participants PT09 in G1 (top), PT15 in G2 (middle), and PT05 in G3 (bottom) during session 1 (left) and session eight (right). Solid arrows and dashed arrows indicate increases referred to within the text. Stick figures represent the key body positions.

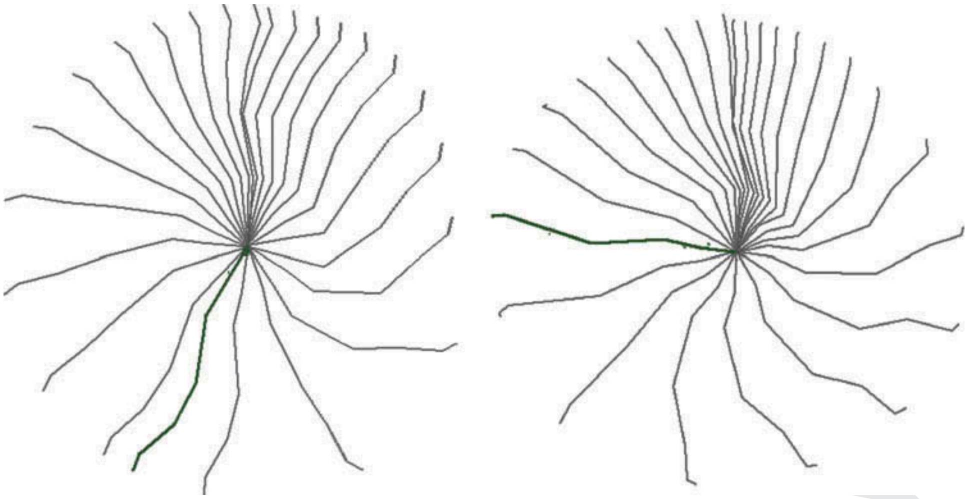

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Figure 6. Stick figure diagrams of a sample swing from a performer in G1 (left) and G2 (right) during session 8. ~~Green/d~~Dark figure highlights the start of the functional phases.

occurred for unsuccessful participants in G3 throughout the learning period (Figure 5).

Two total energy profiles emerged during successful swings. Firstly, profiles were characterised by a steady decrease from 180° until 280° in the circle, followed by a rapid increase during the upswing (solid arrow); a "decrease–increase pattern" (Figure 5A). Energy was rapidly replaced during the upswing via a large input of joint work and the return of bar energy. One participant (PT09) used this pattern from session 1 while for others (PT01 and PT11) the pattern emerged over sessions 1–3. Secondly, the total energy profiles described above were distinctly different for individuals PT13 (G1) and those in G2. The total energy profile of these participants were characterised by an "energy maintenance" pattern. Inputs of joint work increased total energy before and after the bottom of the swing, as shown in Figure 5B and C by dashed and solid arrows, respectively. Corresponding total work profiles were described by a gradual increase from 210° in the circle until the end of the swing caused predominantly by the early onset of hip work for PT10, PT12 and PT15 (G2), shoulder work for PT13 (G1) or knee work for PT02 (G2). The kinematics associated with each of these joint work patterns are displayed clearly in Figure 6. The key hip and shoulder closing actions begin near the bottom of the swing for G1 using the "decrease–increase" pattern, and much earlier for G2 using the "energy maintenance" pattern.

Efficiency score

Based on the difference between the total energy and net energy profiles G1 were ≥13% more efficient than G2 during successful swings in session 8 (Table I; $P < 0.05$). An outlier, PT02 in G2, performed a large amount of "prohibited" knee work that resulted in a technique as mechanically efficient as those of G1 (Table I).

Group differences in efficiency scores were validated by measures of moment of inertia and the differences between total energy at the beginning and end of the swing. No significant difference between groups was found for moment of inertia about the bar (G1: 99 ± 12 kg·m^2; G2: 106 ± 17 kg·m^2; G3; 117 ± 16 kg·m^2; G1 verses G2 mean difference 7 kg·m^2, CI from 19 to 33 kg·m^2, $t = 0.67$, $df = 6$, effect size = 0.2, $P = 0.53$; G1 verses G2 mean difference 18 kg·m^2, CI from 6.5 to 42.5, $t = 1.8$, $df = 6$, effect size = 0.5, $P = 0.12$;

Table I. Root mean square difference (RMSD) between total energy and net energy profiles for performers in G1 and G2, presented as mean and standard deviation for five full longswings.

RMSD (normalised energy)							
G1				G2			
PT01	PT09	PT11	PT13	PT10	PT12	PT15	PT02
Mean ± *s*							
0.14 ± 0.01	0.15 ± 0.01	0.12 ± 0.08	0.15 ± 0.02	0.16 ± 0.01	0.17 ± 0.01	0.20 ± 0.04	0.13 ± 0.03

G2 verses G3 mean difference 11 kg·m^2, CI from 17.6 to 39.6 kg·m^2, $t = 0.94$, $df = 6$, effect size = 0.3, $P = 0.38$). The difference in total energy at the start compared to the end of the swing was 4 ± 3% for participants in G1 was smaller than values for participants in G2's 12 ± 3% during five full longswings.

Discussion

The aim of current analysis was to investigate the biomechanical energetic process involved in novice technique during a period of learning the longswing. Biomechanical constraints to action, that is, limits to novice performance, were identified as "total work" and "shoulder work". The most biomechanically efficient technique was associated with an onset of the hip work that occurred 10–45° before the bottom of the swing.

The ability to perform total work during the swing was a biomechanical constraint to action for novices. Significantly more joint work was performed during full longswings, as demonstrated by successful performers in G1 and G2, and compared to G3 (Figure 3). Since some novices are limited by their ability to produce the joint work required, the skill presents a biomechanical problem. This is useful information for coaches who will need to increase the strength characteristics of the learners to help them to achieve successful performance.

Shoulder work was another biomechanical constraint that limited novices. The hips provided the dominant contribution to total work compared to the shoulder. The ability to perform more work at the shoulder joint was associated with the most effective and efficient novices. G1 performed 13% more shoulder work than participants in G2 and G3 (Figure 3). Furthermore, equal or greater amounts of joint work at the shoulder compared to the hip have been reported for elite longswings, suggesting that the ability to perform shoulder work is also a distinguishing factor between novice and elite longswing technique (Irwin & Kerwin, 2007; Okamoto et al., 1987). Therefore, the ability to perform the key shoulder actions recommended for the skill may well be a biomechanical problem for novices, and is certainly a characteristic of technique that is associated with skill development. Biomechanical reasons for the limited shoulder action include greater moment of inertia of the body about the shoulder joint compared to the hip. Shoulder extension is also more novel in sporting activity. Identifying biomechanical energetic limits at the shoulder provides useful information for coaches and helps explain why changes in hip actions were more clearly related to improvement in performance for all novices (Williams et al., 2012).

The amount of hip work significantly increased over the training period for participants who were able to perform full longswing. For example, individuals in G1 increased hip work by >40% over the training period. Interestingly, concentrating technique changes to the more distal joints during initial learning is contrary to the findings of other motor learning studies. For example, the action of more proximal joints has been emphasised during early practice attempts, with a move towards control of more distal joints with practice of kicking tasks (Anderson & Sidaway, 1994; Hodges, Hayes, Horn, & Williams, 2005), and bouncing a ball (Broderick & Newell, 1999). Despite these examples, evidence is not unequivocal since during a balance task (Caillou, Delignières, Nourritt, Deschamps, & Lauriot, 2002; Ko, Challis, & Newell, 2003), pedalo locomotion (Chen, Liu, Mayer-Kress, & Newell, 2005) and kicking tasks (Chow, Davids, Button, & Rein, 2008) the progression from distal to more proximal joint actions has been shown. This study provides further support for the task specific nature of technique changes during learning motor skills.

One participant that stood out as employing a very individual strategy was PT02 (G2) who demonstrated knee work that accounted for 47% of total work. Knee flexion reduced the hip and shoulder work requirements by reducing the moment of inertia of the performer about the bar. The current analysis suggests that the bent knee longswing (Arkaev & Suchilin, 2004; Irwin & Kerwin, 2005, 2007; Readhead, 1997) manipulates the task constraints in order to overcome the biomechanical constraints "total work" and "shoulder work" which limited novices.

Total energy profile: the effect of work and bar energy

Degeneracy, that is the same performance outcome achieved via different techniques (Edelman & Gally, 2001), was observed and can be expected based on inter-individual differences (Newell, 1986). The biomechanical constraints that contributed to degenerate techniques can be inferred by exploring different strategies for satisfying the mechanical demands of the task.

Total energy in this task is manipulated by two key factors; work done and the elastic properties of the bar (Arampatzis & Brüggemann, 1999). During incomplete swings an increase in total energy occurred before and after the lower vertical. Total energy of the system increased as joint work was performed to close the hip and shoulder joints (Figure 5). Performers in G3 did not change this strategy during the eight sessions and remained unsuccessful. Degeneracy in successful technique was highlighted as two different profiles of total energy became evident during successful swings. The "decrease–increase" profile observed in Figure 5, occurred for three of the four participants in G1. The decrease–increase profile of total work corresponded with little work done during the downswing. A "passive kinetics" constraint was defined as the forces tending to open the joints as the body rotates as a series of linked segments (Williams, Irwin, Kerwin, & Newell, 2014). Overcoming the passive kinetics constraint facilitated the later onset of the hip functional phase action and powerful shoulder action, and concurrently the joint work occurred after the lower vertical position. It is interesting to note that the functional phase that started earlier in the swing did not distribute the joint work requirements but rather placed the performer in a position to input large amounts of positive work during the upswing. The kinematic characteristics of performing joint work during the upswing are described in Williams et al. (2012), as the hip functional phase is initiated near the lower vertical.

On the other hand, total energy profiles of participants in (G2) and PT13 (G1) became characterised by an "energy maintenance" pattern. In order to maintain total energy throughout the swing inputs of joint work began at 210° in the circle. Individual performers created this "energy maintenance" pattern via different combinations of hip and shoulder work that was distributed throughout the swing. For example, joint work was performed at the hip by PT10 (G2), shoulder by PT13 (G1), knee by PT02 (G2) or the hip and shoulder by PT12 and PT15 (G2). Although the degenerate technique associated with the "energy maintenance" profile was uncharacteristic of the technique reported for elite gymnasts (Irwin & Kerwin, 2005), it facilitated full longswings for individuals in G2 who were restricted by the shoulder work constraint.

Knowledge of the biomechanical constraints associated with the different techniques provides useful information about the predisposition of athletes to adopt a certain technique, and to become successful. These principles most likely apply across many motor tasks, although research on real work skills is limited (Chow et al., 2008; Delignières et al., 1998; Thelen & Smith, 1995).

Efficiency during successful longswings

Mechanical efficiency has been suggested to increase with learning and be optimised with expertise (Bernstein, 1967; Newell, 1985). During the full longswing, a technique that enables the performer to swing from handstand to handstand with the least amount of mechanical energy input is a more mechanically efficient technique. Correctly performed, successful swings by performers in G1 were at least 13% more efficient, compared to performers in G2. Since moment of inertia in an outstretched position did not distinguish between individuals in G1 and G2, and G1 had a smaller decrease in total energy at the end of the swing (of 4 ± 3%) compared to G2 (12 ± 3%) these results could be verified. These are particularly important findings, defining the successful technique of performers in G1 as not only more effective for performance improvement, but also more mechanically efficient.

Bernstein (1967) inferred that utilising and exploiting reactive forces that arise in a series of linked segments during movement is a sign of a more advanced technique, a proposition supported in previous motor learning literature (Sparrow & Irizarry-Lopez, 1987). However the current task places emphasis on the interaction of the segments to best exploit the gravitational forces that act on the CM and cause it to rotate about the high bar. Future research might investigate the more subtle nuances of efficient technique associated with elite longswings which are suggested to remain less variable for more skilled performers (Hiley, Zuevsky, & Yeadon, 2013), or the combination of interactive, passive, and muscular forces (Bernstein, 1967). The current analysis has shown that for G2 the inability to overcome specific biomechanical constraints leads to an inefficient technique.

These findings raise the question, is it more important to be effective in satisfying the task demands, or efficient in the process? This is an important problem for motor learning practitioners such as coaches. Knowledge of biomechanical constraints provides evidence for the specific task constraints that need to be manipulated in order to elicit the characteristics of an effective and/or efficient technique. For example, a bent knee longswing might enable a performer to overcome joint work constraints ("total work" and "shoulder work") while maintaining the more efficient technique characteristics associated with timing hip and shoulder actions. In a more general sense, it is likely that all motor skills present key constraints to learners, biomechanical and otherwise, and knowledge of these constraints and the performance level and technique that they are associated could be a valuable tool to increase the effectiveness of learning interventions.

Modelling the performer as a simplified series of linked segments incurs error. For example, although assuming the trunk and head to be a single rigid segment is a technique used in previous literature (Arampatzis & Brüggemann, 1999; Irwin & Kerwin, 2007; Yeadon & Hiley, 2000), there will certainly be some error involved. Future work might explore the influence of simplifications of the model used on the results of inverse dynamics analysis.

Conclusion

This research has identified the most mechanically efficient novice techniques and the biomechanical constraints that need to be overcome to become successful using this technique. The ability to perform more total work was associated with successful performance of the skill, and is a key biomechanical constraint to action. Hip work provided the dominant contribution to total work for novices. The ability to perform larger amounts of shoulder work was a characteristic of the most effective and efficient individuals, and was identified as another biomechanical constraint for novices. This particular biomechanical constraint highlighted the importance of differentiating between a control and a biomechanical problem during learning; particularly pertinent in physically demanding complex sports skills.

For degenerate successful longswing techniques, a later onset of joint work at the hips associated with the "decrease–increase" total energy profile was most efficient. However, distributing joint work throughout the swing, associated with the "energy maintenance" profile of total energy, allowed novices to become successful despite being unable to overcome the "shoulder work" constraint.

Coaches should consider whether achieving an effective or efficient technique is more important for novices learning this skill, and with this in mind manipulate task constraints to address the key biomechanical constraints to improve performance. The findings of this study invite the proposition that gross motor skills are likely to be mechanically satisfied through degenerate techniques that are associated with task specific constraints to action. Learning interventions based on knowledge of these constraints and their implications for performance and mechanical efficiency are likely a useful tool for practitioners and coaches.

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