Influence of longswing technique on the kinematics and key release parameters of the straddle Tkachev on uneven bars

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Abstract

Tkachev on uneven bars is a release and re-grasp skill performed using variations of preparatory longswing techniques; but the reasons why different techniques are chosen remains unclear. This study examined kinematic and key release parameters specific to three distinct techniques with the aim of understanding the relative benefits of each. During two International Artistic Gymnastics competitions six arch, straddle and pike longswings preceding the straddle Tkachev were recorded using twin video cameras. Calibration and movement images were digitised and reconstructed using 3D DLT. Shoulder and hip angular kinematics, angular momentum and key release parameters were compared between techniques. In the arch longswing, the first and second hip functional phases began significantly earlier than the straddle or pike. No significant differences were established for release parameters although large effect sizes for horizontal release velocity and angular momenta about the mass centre and bar were reported between the arch and other two variants. Therefore, the arch variant may provide the opportunity to develop more complex combinations following the Tkachev. Providing insight into mechanical advantages of specific longswing techniques, and highlighting those that elicit desirable characteristics offers the potential to provide coaches with objective data on technique selection and ultimately skill development.

Introduction

Elite female gymnasts competing on the uneven bars aim to seamlessly combine swinging and flight skills that epitomise technical accuracy and high levels of execution. The last three decades of artistic gymnastics has seen prominent advances in difficulty and diversity in the skills being performed and in doing so have underpinned the rapid development of the sport (Brüggemann, 2005). The inclusion of complex skills in routines is essential in order to score highly. For example the addition of release and re-grasp elements continue to increase a start value theoretically by up to 5% (Fédération Internationale de Gymnastique, 2009). The straddle Tkachev is one of the most popular release and re-grasp elements particularly on the uneven bars. The gymnast is required to release on the upswing, reverse the direction of rotation whilst travelling backwards over the bar performing a straddled pike and then extend the body to re-grasp the high bar at the beginning of the downswing. Previous research has predominately focused on the male version of the skill (Gervais & Tally, 1993; Brüggemann, Cheetham, Alp, & Arampatzis, 1994; Arampatzis & Brüggemann, 1999; 2001; Holvoet, Lacouture, & Duboy, 2002; Hiley, Yeadon, & Buxton, 2007) but with the rapid development of women's gymnastics and female gymnasts developing their swing similarly to men preceding the Tkachev (Kerwin & Irwin, 2010), research focused on the female Tkachev needs to follow.

Fundamental in determining correct release parameters and dictating the success of the following release and re-grasp skills is the longswing preceding the skill; the preparatory longswing (Arampatzis & Brüggemann, 2001; Kerwin & Irwin, 2010). Female gymnasts, unlike their male counterparts, have a low bar within the apparatus design which constrains their movements in the longswing. The apparatus consists of two bars that run parallel to one another but at different heights; 250 cm for the high bar and 170 cm for the low bar (Fédération Internationale de Gymnastique [FIG], 2009). The bars can be adjusted so that a maximum distance of 180 cm can separate the two rails. Female gymnasts must consider a number of options to pass the bar to effectively complete circling skills. Differences in movement patterns employed by gymnasts during the preparatory longswing causes distinct techniques to be executed, even though the variants are still classified as the same skill. The Fédération Internationale de Gymnastique (FIG, 2009) states that the longswing should start and end in the handstand position. There are no requirements or regulations, other than the potential for judging deductions for poor execution (i.e. bent arms and/or legs) when the gymnast executes the skill.

Adjustment of the shoulder and hip joints through flexion and extension in the sagittal plane and hip abduction, enable different body configurations during the descent phase of the longswing allowing gymnasts to negotiate the low bar. A previous investigation (Manning, Irwin, Kerwin, & Gittoes, 2009) identified that gymnasts completed the Tkachev successfully using a number of different preparatory longswings. The backward longswing with hip extension (arch), lower limb abduction (straddle) or hip flexion (pike) prior to passing the low bar during the downswing were the three most common distinctive techniques used by elite female gymnasts preceding the straddle Tkachev (Figure 1). Technique selection for gymnasts and coaches is complex and it is a common coaching view that gymnast height is a key determinant in the selection process (Still, 1990). Determining advantages of different techniques through biomechanical analyses may allow an additional approach to explain why one technique could be chosen over another. Improving effectiveness in achieving the correct release parameters or facilitating the development of future skills should be key considerations in the selection process.

Hiley and Yeadon (2003) highlighted that differing longswing techniques provided varying spatial and temporal characteristics at the shoulder and hip joints. Diverse movement ‘patterns’ and therefore different release ‘parameters’ were noted for the execution of the same final skill. The importance of the shoulders and hips in successful longswing performance has been highlighted as a key focus in previous literature (Arampatzis & Brüggemann, 1998; 1999; 2001; Irwin & Kerwin, 2005; 2007; Kerwin & Irwin, 2010; Naundorf, Lehmann, & Witte, 2010). Rapid hyper-extension to flexion at the hips and a hyper-flexion to extension at the shoulders has been deemed paramount and termed the functional phase (Irwin & Kerwin, 2005). Musculoskeletal work during the functional phases facilitates the ascent phase and correct release parameters during the Tkachev (Kerwin & Irwin, 2010). A central focus of the current study is to determine the precise movement patterns employed by female gymnasts at the shoulders and hips in order to negotiate the low bar with minimal loss to the contribution from the functional phases.

It has been noted that gymnasts should be in an extended position during the descent phase of the longswing when passing the low bar in order to benefit from the mechanical energetic processes of the longswing (Witten, Brown, Witten, & Wells, 1996; Arampatzis & Brüggemann, 1999). Hiley and Yeadon (2005) showed that an early hip extension in the longswing leads to greater angular momentum and highlights the need to gain insight into the biomechanics of different longswing techniques.

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Flight height and rotation are paramount for the successful execution of the straddle Tkachev (Gervais & Tally, 1993) but it is unknown whether one preparatory longswing technique is more influential than any other in producing the ideal trajectory and counter rotation. Therefore, an investigation into the underlying mechanics of distinctive longswing techniques and their effect on key release parameters may provide coaches and scientists with greater technical knowledge and hence inform technique selection. The key objective of this paper was to compare three distinctive longswing techniques preceding the straddle Tkachev on uneven bars with the primary purpose of investigating how the kinematics and angular momentum alter as a function of technique. Increasing mechanical understanding of these three distinctive techniques has the potential to determine which technique provides greater flight time and/or rotation and hence can be used to establish more systemised development pathways towards more complex skills on the uneven bars.

Method

Participants

Data were obtained from the International Olympic Committee Research Project at the 2000 Sydney Olympics and the FIG approved Research Project from the 2007 Stuttgart World Gymnastics Championships. Selected Tkachevs across the two competitions were categorised as arch, straddle and pike with each longswing being defined by the gymnast's body configuration as she passed the low bar (Figure 1). For the arch longswing, hip extension was greater than 180° with legs together, for the straddle, hip abduction was evident with minimal flexion or extension at the hips, and for the pike, hip flexion was greater than 45° with the legs together. A representative sample of each version of the longswing was selected by a National level coach based on the technique used and the success of the Tkachev performance. The coach ensured that each selected skill had been completed in accordance with the relevant FIG Code of Points. The selected representative sample comprised six gymnasts in each group. Across the two competitions on uneven bars in the qualification round the gymnasts performing the arch, straddle and pike longswings were ranked 1st – 45th, 2nd – 77th, and 5th - 60th respectively. Height and mass of the selected gymnasts were obtained from the competitors' records for the two events (Arch=1.47 ± 0.07 m, 40.93 ± 5.63 kg, Straddle=1.49 ± 0.05 m, 40.39 ± 6.59 kg and Pike=1.55 ± 0.06 m, 45.73 ± 3.92 kg).

Data Collection

Video data were collected from the 2000 Sydney Olympic Games and the 2007 Stuttgart World Championships. In both cases, two video camcorders were used to obtain images of the calibration and gymnasts' performances at a frequency of 50 Hz. Calibration prior to the Sydney 2000 Olympic Games comprised video images of a three dimensional volume encompassing the uneven bars (3.0 m x 4.3 m x 3.5 m). A single calibration pole consisting of five equally-spaced spheres (0.1 m diameter) of known coordinates was sequentially placed at six pre-measured positions providing 30 known locations within the field of view. The 2007 World Championship performances were calibrated using two static (1.0 m x 1.0 m x 3.0 m) cuboids giving 48 known coordinates and a calibration volume 2.0 m x 3.7 m x 3.0 m. The origin was defined as the centre of the high bar in its neutral bar position with the calibrated volume encompassing the analysed preparatory longswing.

Data Processing

Calibration and movement frames were digitised using PEAK Motus (Vicon Peak 9.0, UK) motion analysis system for both camera views from both competitions. The calibration images consisted of 10 fields from each camera and the movement data comprised images of the preceding longswing and the straddle Tkachev. Circle angle of the gymnast was defined from the right horizontal by a vector joining the neutral bar position to the gymnast's total body mass centre. Circle angle was regarded as 90° when the gymnast was in a handstand position and continued to 450° as the gymnast returned to handstand through an anti-clockwise rotation about the bar (Figure 2). All movement data were analysed between a circle angle of 135° and continued until 20 frames after re-grasp occurred. The centre of the high bar and the gymnast's head, right and left wrists, elbows, shoulders, hips, knees, ankles and toes were digitised for each movement frame from each camera view. The data sets from both cameras were time synchronised using the methods of Yeadon and King (1999). A 12-parameter three-dimensional direct linear transformation (Marzan & Karara, 1975) was used to reconstruct the coordinate data using the TARGET high-resolution motion analysis system (Kerwin, 1995). Customised segmental inertia parameters for each gymnast were calculated using Yeadon's inertia model (1990) with limb lengths determined from the video data, combined with height and mass for each gymnast. The reconstructed 3D coordinate data were filtered with a low pass digital filter with a cut off frequency of 8 Hz based on a residual analysis (Winter, 2009). A four segment planar representation of the gymnast consisting of arms (hands, forearms and upper arms), trunk (including head and neck), thighs and shanks (including feet) was constructed by averaging the digitised coordinate data for the left and right sides of the body.

Data Analysis

Reconstruction accuracy was calculated through estimating six known location points within the calibration volume using the remaining known points to make up the calibration structure. The reconstruction accuracy for the known points was <0.017 m within the 7 m field of view.

In addition to gymnast height, gymnast-length was calculated through the summation of the digitised lengths of the arm, trunk, thigh and shank segments. The lengths were taken when the gymnast was at a circle angle of 135° where longswing technique had yet to be initiated and the gymnast began the descent phase un-weighted.

The instant of release was determined using a linear coordinate separation between the virtual mid-wrists and centre of the high bar (Kerwin and Irwin, 2010). A previously conducted release sensitivity analysis calculated that a marker separation 10% greater than maximum separation throughout the preparatory longswing was the most valid value to identify that the gymnast had released the high bar.

The previously defined 'functional phases' presented by Irwin and Kerwin (2005) were employed in the kinematic analyses, with the start and end points described by maximum shoulder flexion to extension and maximum hip extension to flexion. To locate the start and end points of the functional phases, the shoulder and hip angular velocity time histories were profiled. Maximum flexion and/or extension were deemed to be reached each time the respective joint angular velocity profile crossed the zero horizontal axis. The conclusion of the preparatory longswing preceding the flight phase of the Tkachev is characterised by the gymnast performing a hyper-flexion of the shoulder and hyper-extension of the hips; therefore, a second functional phase for the hips and shoulders was defined from maximum shoulder extension to flexion and maximum hip flexion to extension. The start and end of each functional phase (Figure 2) for both the shoulders and hips were reported and coincided with the two extension and one flexion phases reported by Arampatzis and Brüggemann (2001). For instances where the gymnast had released the high bar prior to the conclusion of the second functional phase at the shoulders and/or hips, the gymnast's circle angle at release was recorded as the end of the functional phase. Changes in joint angles at the shoulders and hips for each functional phase were reported such that shoulder extension and hip flexion were regarded as positive when the respective joint was 'closing' relative to the trunk segment.

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Using the summation of the gymnast segments (arms, trunk, thighs and shanks) angular momenta was calculated about the gymnast's mass centre (L_{cm}) and about the bar (L_{bar}) using the equations (1) and (2) respectively; where I_s = segment's moment of inertia about a transverse axis through its mass centre, ω_s = angular velocity of the segment, m_s = segment mass, r = vector between the mass centre of the segment and mass centre of the body (r_c) or bar (r_b) respectively, ω = angular velocity of the segment mass centre about the mass centre of the body (ω_c) or bar (ω_b).

$$L_{cm}= \Sigma\ (I_s\ .\ \omega_s + m_s\ .\ r_c^2\ .\ \omega_c) \quad (1)$$

$$L_{bar}= \Sigma\ (I_s\ .\ \omega_s + m_s\ .\ r_b^2\ .\ \omega_b) \quad (2)$$

Inertia calculations were based on scaled limb lengths from the image data and projected onto the mid-plane bisecting the real gymnast. To account for gymnasts of varying size, angular momentum values were normalised by dividing by the product of 2 π and the moment of inertia in a theoretical straight body position, measured in straight somersaults per second (SS/s). Free flight displacement data were fitted quadratically for vertical motion and linearly for horizontal motion with each function being differentiated to calculate vertical and horizontal velocities of the mass centre, from which release velocities were extracted.

Reliability, based on repeated digitising of a Tkachev trial was determined using percentage Root Mean Squared Difference (%RMSD) and found to be <1% for all release parameters and <3% for the respective ranges of measured hip and shoulder angles and angular velocities.

Statistical Intervention

Differences in discrete variables were quantified using an Analysis of Variance (ANOVA). In order to meet the assumptions of the ANOVA, tests for normality (Shapiro-Wilkes) and homogeneity of variance (Levene's test) with the alpha level set to $P \leq 0.05$ were carried out. To establish the meaningfulness of these data effect size was also reported as a *d* score (Cohen, 1988) and interpreted using Hopkins (2002) complete scale (< 0.2 trivial, 0.2 – 0.6 small, 0.6 - 1.2 moderate, 1.2 – 2.0 large, 2.0 – 4.0 very large and > 4.0 perfect). To quantify the differences within the continuous wave form data sets Root Mean Squared Difference (RMSD) and percentage RMSD (%RMSD) were determined with each RMSD being divided by the range of the appropriate variable and expressed as a percentage.

Results

No significant differences between the three groups in height and mass ($P \leq 0.05$) were found. However, large effect sizes for height between the arch and pike longswing were established (>1.2). Calculated gymnast-length also revealed no significant differences between the three techniques as well as no large effect size. The following results section is focused on an examination of the functional phases, joint kinematics and key release parameters.

Functional Phase Joint Kinematics

The start of the shoulder functional phase occurred at a circle angle of 248° in the arch preparatory longswing, which was significantly earlier (25°) than the pike longswing (Table 1 and Figure 3). The change in circle angle over which the first functional phase at the shoulders occurred was greatest in the arch longswing (114°) compared to a smaller range for the other versions (93°). There was a 21° greater change in shoulder angle in the second shoulder functional phase for the arch longswing than the straddle longswing, which also had the lowest change in shoulder angle at 37°. Shoulder extension to flexion in the second functional phase of the straddle longswing was completed over a smaller range but from a greater circle angle than the arch technique (Table 1), supporting the 10% difference in the average angular velocity at the shoulders between the two longswings (Table 2). In addition the straddle longswing showed a significantly smaller, and therefore more 'closed', shoulder angle at release.

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The initiation of the hip functional phase occurred at a circle angle of 231° in the arch longswing which was significantly earlier (20°) than for the straddle and the pike (31°). As well as each technique having a significantly different initiation of the functional phase at the hips, the effect size of these differences ranged between 'large' and 'perfect'. The start of the hip functional phase was characterised by maximum extension of the hip joint, of which the arch longswing illustrated the greatest angle (-36°), which was 14° more extended than the pike technique. Significant differences between the arch and pike longswing, at the hip joints, were further highlighted by a 'very large' effect size and a 31% difference in the average angle profile throughout the functional phase (Table 2).

The range in circle angle in which the initiation and conclusion of the functional phase for the hips occurred was 10° greater in the arch technique than the straddle and 24° greater than the pike (Table 1). The functional phase at the hips for the straddle longswing therefore occurred within a significantly smaller circle angle even though the straddle technique had a greater joint range to pass through. A more dynamic hip action was therefore evident during the straddle technique with a 15% greater hip angular velocity compared to the arch version (Table 2). The second functional phase (Figure 2) at the hips (maximum hip flexion to extension) begins the reversal of rotation during the ascent of the longswing. There were no significant differences in the change in circle angle for the second hip functional phase between the three techniques; however, the initiation of the functional phase was significantly earlier in the arch technique compared to the straddle.

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Release Parameters

The angle of release for the arch longswing was significantly earlier than the straddle technique, 401° compared to 409°. No significant differences were observed in the remaining key release parameters between the three longswing techniques. Interestingly 'large' effect sizes for release horizontal velocity and normalised angular momenta about the gymnast's mass centre (Ln_{cm}) and bar (Ln_{bar}) were found (Table 3).

When comparing the straddle and pike variants, angular momenta about the gymnast's mass centre and bar showed no statistically significant differences and 'moderate' effect sizes; a finding that was in agreement with the continuous profiles where less than 3% difference was observed (Table 2). The similarities in angular momentum profiles may also be the cause of no significant differences in vertical velocity at release.

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Figure 3 (c, e, g) illustrates the angular momentum profiles (Ln_{cm}) for each technique from a circle angle of 135° to release. The standard deviation along the profiles highlights greatest variability in the final phase of the downswing for the arch and the first phase of the upswing for the straddle techniques.

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Discussion and Implications

Technique selection is a challenge for the gymnastics coach in order to ensure the effective and safe development of skills on the uneven bars. The aim of this study was to gain insight into the mechanics of three distinctive longswing techniques and the influence of their varying movement patterns on the kinematics and angular momentum of the preparatory longswing.

A traditional coaching view in women’s artistic gymnastics is that technique selection is based on gymnast height (e.g. Still, 1990); specifically, taller gymnasts select the pike and straddle techniques whilst it is believed that shorter gymnasts select the arch technique. The results from this study have found no statistically significant differences in gymnast’s height between the three groups. However, a large effect size between the pike and arch longswing do support the premise that gymnast height may be one of the contributing factors determining the longswing variant, although this was found not to be the case for the straddle longswing in this study. Furthermore, an investigation into gymnast-length (summation of segment lengths from gymnast’s wrists to toes) reported no significant differences or large effect sizes between the three techniques.

With gymnast height and length not being the sole contributing factors to the selection of techniques, establishing mechanical variations in the key characteristics may highlight potential advantages of one longswing technique over another. This quantitative knowledge could provide coaches with meaningful information to allow objective decisions to be made regarding technique selection, facilitating the coaching process and making training more efficient. No significant differences in height and gymnast-length between the three techniques reported in this study may have been influenced by the small sample size (i.e. type II error). However, small sample sizes are a common feature when undertaking research at elite competition.

In comparison to the straddle and pike variants, the arch longswing was identified as deviating furthest from the other two techniques in terms of functional phase location and joint angular kinematics. The functional phases underpin the successful performance of the longswing. The hyper-extended body configuration during the arch longswing enabled the functional phases to be started at a significantly earlier circle angle compared to the straddle and pike variants. A significantly earlier hip functional phase for the arch longswing enabled the gymnast to reach a greater degree of hip extension. Previous research has identified that an earlier hip extension may lead to greater angular momentum in the longswing (Hiley & Yeadon, 2005) and is supported by the findings in this paper (Table 2 and 3).

The straddle Tkachev is unusual in requiring the gymnast to change the direction of angular momentum about the mass centre during their preparatory longswing. The significantly earlier initiation of the second hip functional phase in the arch longswing may be beneficial in facilitating this reversal of angular momentum when approaching release, potentially explaining values at the high end of the range compared to the other techniques.

When performing the pike longswing a delayed hip extension as well as a restricted angle range delayed the initiation of the hip functional phase. The constrained movement pattern restricted the functional phase and potentially the gymnast's ability to utilise energetic processes, shown to be important for generating angular momentum at release (Arampatzis & Brüggemann, 2001; Kerwin & Irwin, 2010). The body configuration may contribute to the pike longswing having a large effect size for angular momentum about the mass centre when compared to the arch.

With the exception of the angle of release between the arch and straddle techniques, no statistically significant differences were found in the key release parameters between the three longswing techniques. As such the significant differences preceding release do not seem to have a major effect on the flight phase. The three techniques appear to be similarly effective although mechanically different. Interestingly, effect size calculations did reveal a 'large effect' for three of the key release parameters between the arch and the pike longswing; horizontal velocity, normalised angular momentum about the gymnast's mass centre and normalised angular momentum about the bar. Effect size results provide further insight into the differences between these techniques, particularly as purposeful sampling was employed. Small samples are a common theme in research when examining elite performers and benefits in terms of ecological validity (Elliott, Alderson, & Denver, 2006) may adversely affect the identification of differences, type II errors (Mullineaux, Bartlett, & Bennett, 2001).

The significantly earlier angle of release during the arch longswing technique may be explained by the greater shoulder flexion (more opened shoulder angle). The more open shoulder configuration could be due to gymnasts actively 'pressing' on the bar prior to release. The subsequent body configurations at release may therefore explain the general trend of an increase in horizontal velocity and angular momentum and reduction in vertical velocity across the three techniques. A large shoulder angle at release was identified by Arampatzis and Brüggemann (2001) who stated that greater shoulder flexion was the product of muscular energy produced by the gymnast at the final stage of the longswing. Issues surrounding the musculoskeletal work at the shoulder have been highlighted previously and potentially could provide insight into the role of the shoulder joints preceding the straddle Tkachev. Future research examining kinetic differences between the three longswing techniques regarding musculoskeletal demand at the shoulders would be useful and timely. Previous research by Kerwin and Irwin (2010) highlighted differences in shoulder kinetics between two versions of the female Tkachev which had not been identified by kinematic analyses.

The current study has shown significant differences between the functional phase characteristics of the three longswing techniques. Differences were not reflected in the release characteristics and therefore no apparent advantages in performing one technique over another were identified. However, specific movement patterns utilised when performing the varying longswing techniques in order to achieve the same release parameters may imply the need for specific physical preparation within the coaching process. Large effect sizes between release characteristics suggest that purposeful sampling may have affected these findings; therefore, future studies using an increased sample size and trial number would be beneficial. Furthermore, an examination of the joint kinetics to identify the musculoskeletal energetic contributions would provide insight into any potential benefits offered by different longswing techniques.

Conclusion

This study aimed to gain further insight into the various longswing techniques used for the execution of the same final skill, the straddle Tkachev. Kinematic differences between the arch technique and other variants (straddle and pike) were observed in the functional phase at the hips. With the exception of release angle for the arch technique, the current study showed no significant differences in release parameters.

A large effect size between the arch longswing and other techniques for horizontal velocity and normalised angular momenta about the mass centre and the bar at release were observed, suggesting that the arch variant may potentially provide sufficient opportunity to develop more complex routines following the straddle Tkachev. However, in addition to an increase in trial numbers and sample size, advancing from single joint analyses to coordination through joint coupling analysis (Irwin & Kerwin, 2007) and an analysis of joint power and work for the musculoskeletal demand on the performer, may highlight potential advantages of different preparatory longswing techniques (Kerwin & Irwin, 2010). With a higher level of understanding of the different versions of the preceding longswing, coaches will have more knowledge at their disposal in order to effectively select technique and therefore develop a more efficient coaching process.

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Table 1. Circle angle of gymnast about the bar, changes in circle angle, relative joint angles and changes in joint angle at the start and end of shoulder and hip functional phases ($\bar{X}$ °±SD)

	Shoulder			Hip		
	Arch	**Straddle**	**Pike**	**Arch**	**Straddle**	**Pike**
Circle Angle						
Start FP1	248 ± 11*	265 ± 16	273 ± 8*^{A}	231 ± 8*^{SP}	251 ± 7*^{AP}	262 ± 4*^{AS}
End FP1	362 ± 7	358 ± 20	366 ± 9	326 ± 8*^{S}	335 ± 5*	332 ± 3
End FP2	$\underline{401}$ ± 6^{S}	$\underline{409}$ ± 5	$\underline{408}$ ± 6	398 ± 7^{S}	$\underline{409}$ ± 5*^{AP}	401 ± 3
Δ Circle Angle						
FP1	14 ± 12	93 ± 26	93 ± 8^{A}	95 ± 9	85 ± 11^{P}	71 ± 5*^{A}
FP2	0 ± 6	51 ± 17	42 ± 8	72 ± 7	74 ± 7	68 ± 5
Joint Angle						
Start FP1	-4 ± 9	-4 ± 6	0 ± 6	-36 ± 8	-35 ± 7^{P}	-22 ± 4*^{A}
End FP1	34 ± 9	37 ± 10	40 ± 6	53 ± 7	57 ± 7	52 ± 8
End FP2	-24 ± 21*^{S}	1 ± 12*	-12 ± 15	-36 ± 9	-44 ± 9	-46 ± 6^{A}
Δ Joint Angle						
FP1	37 ± 6	41 ± 8	41 ± 7	89 ± 14	92 ± 13^{P}	73 ± 9^{A}
FP2	58 ± 15^{S}	37 ± 15	52 ± 15	89 ± 11	101 ± 9	97 ± 6

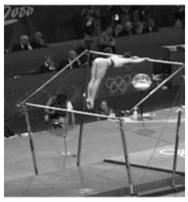
Key: FP1 = functional phase 1, FP2 = functional phase 2
$\underline{\ \ }$ denotes release prior to functional phase completion
^{A} = Arch, ^{S} = Straddle, ^{P} = Pike
In each row, the differences between one variant (e.g. arch) and the other two (straddle and pike) have been denoted by an '*' when significantly different (P<0.05) and by the corresponding letter when the effect size was large (i.e. >1.2)

Table 2. %RMSD of key kinematic and normalised angular momentum (Ln) variables for each of the three distinct longswing techniques

	Arch Vs Straddle % RMSD	Arch Vs Pike % RMSD	Straddle Vs Pike % RMSD
Shoulder Angle	11.2	10.3	8.5
Hip Angle	17.3	31.0	16.1
Shoulder Angular Velocity	9.5	6.7	6.5
Hip Angular Velocity	15.2	17.0	10.3
Ln about the mass centre	7.0	9.2	3.0
Ln about the bar	20.8	21.7	2.9

Note: All analyses occurred from a circle angle of 135° to release

Table 3. Release parameters of varying longswing techniques preceding the straddle Tkachev ($\bar{X}$±SD)

	Arch (n=6) 	Straddle (n=6) 	Pike (n=6) 
Circle Angle (°)	401 ± 6 $*^{SP}$	409 ± 5 ^{A}	408 ± 6 ^{A}
Vertical Velocity (m/s)	1.51 ± 0.42	1.67 ± 0.57	1.73 ± 0.62
Horizontal Velocity (m/s)	-2.20 ± 0.31 ^{SP}	-1.83 ± 0.28 ^{A}	-1.80 ± 0.28 ^{A}
Ln about the mass centre (SS/s)	-0.53 ± 0.14 ^{P}	-0.44 ± 0.17	-0.33 ± 0.16 ^{A}
Ln about the bar (SS/s)	3.01 ± 0.98 ^{P}	2.18 ± 0.61	2.09 ± 0.42 ^{A}

Key: Ln = Normalised angular momentum, SS/s = straight somersaults per second
^{A} = Arch, ^{S} = Straddle, ^{P} = Pike
In each column, the differences between one variant (e.g. arch) and the other two (straddle and pike) have been denoted by an '*' when significantly different (P<0.05) and by the corresponding letter when the effect size was large (i.e. >1.2)

Figure 1. Variations of preceding longswings for the straddle Tkachev on the uneven bars: a) arch b) straddle and c) pike

Figure 2. Dartfish™ image of the female longswing preceding the straddle Tkachev together with the defined circle angle and functional phase locations (FP1=First Functional Phase, FP2=Second Functional Phase)

Figure 3. Normalised angular momenta about (a) the mass centre (Ln_{cm}) and (b) the bar (Ln_{bar}) for the arch (dashed), straddle (black) and pike (grey) preceding longswing. Mean ± SD Ln_{cm} (left) and Ln_{bar} (right) of the arch (c-d), straddle (e-f) and pike (g-h) preceding longswings profiled with shoulder (S) and hip (H) functional phases (FP). (1=start of FP1, 2=end of FP1 and start of FP2, 3=end of FP2)