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Biomechanical evolution of the Tkachev on uneven bars in female gymnastics

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The development of joint kinematics and kinetics is fundamental to the successful performance of complex flight skills in gymnastics bar routines. Biomechanical understanding of these skills can provide coaches and scientists with key information to make training safe and effective. The Tkachev is a complex and popular gymnastics skill with many different variations. Recently, a new version has been performed, which has become popular with elite female performers. This study examined the key biomechanical characteristics of this skill and contrasted these to the earlier versions reported. Elite female gymnasts (n = 5) were recorded and manually digitised using twin video cameras (50 Hz) at the 2007 World Gymnastics Championships. Three-dimensional (3D) DLT was used to reconstruct the real world coordinates. Individualised inertia characteristics were calculated and used to determine mass centre kinematics. Inverse dynamics analysis was used to calculate joint kinetics at the hips and shoulders from the known values at the toes. The results of this study showed an increased flight time and rotational capacity during the aerial phase for the toe-on Tkachev, as well as a more simple movement pattern and joint kinetic demand with single power impulses at the hips and shoulders compared with previous versions. The key finding of this study was that the toe-on version appeared to be less physically demanding than that the inward and outward techniques, and provide the opportunity to perform more complex aerial phase body positions. These results can help coaches to physically prepare their gymnasts and biomechanists in terms of understanding the demands of these skills.

Keywords: biomechanics; joint kinetics; skill development

Introduction

The Tkachev is a high scoring flighted element that is often performed in elite asymmetric bar routines due to the highly ranked score associated with the skill. The Tkachev is a popular skill performed in men's and women's gymnastics bar routines and involves the gymnast to travel backwards over the bar while in flight, before regrasping. The skill was introduced into artistic gymnastics by Soviet biomechanist and methodologist Smovevski in 1969; it was first performed in the late 1970s in men's and 1980s in female gymnastics (Nissinen et al. 1985). For both men and women, the Tkachev has evolved into an essential skill for the attainment of high difficulty scores. Altering the body position in the flight phase increases difficulty based on the International Federation of Gymnastics (FIG) judging criteria (FIG 2013). Women most commonly perform the Tkachev in either a straddle or piked body position. Men have progressed the skill further and have performed it in a straight body position and have even added twists during the flight element. Biomechanical research has demonstrated the biophysical demands placed on the performance and importantly identified the determinants of successful performance. A main focus of this research has been on the angular momentum and release profiles of the Tkachev in addition to the joint kinematics and kinetics (Arampatzis & Brüggemann 1999, 2001; Kerwin et al. 2007; Kerwin & Irwin 2010; Manning et al. 2011). The Cologne group (Arampatzis & Brüggemann 1999, 2001) sought to include a bioenergetics analysis of the gymnast and their interaction with the elastic bar in men's and women's Tkachev routines, and developed a criterion score for the assessment of efficiency of these skills. The Loughborough group used a forward dynamics approach to investigate the influence of technique change, gymnast strength and flexibility on the consistency of the Tkachev (Hiley & Yeadon 2012). The preceding element that provides the gymnast with the mechanical energy to perform flighted skills is the longswing. The longswing has been a feature of the Cardiff group's research (Irwin & Kerwin 2005, 2007a, 2007b), which demonstrated the importance of the longswing in the development of more complex skills. Key phases, related to success, during the preceding longswing have been identified. Irwin and Kerwin (2005, 2007a, 2007b) termed these phases the 'functional phases', where the gymnast performs hyperextension to flexion at the hip joints and hyperflexion to extension at the shoulders, as they pass the lower vertical. Building on this research, Irwin and Kerwin (2007a, 2007b) and Manning et al. (2011) demonstrated that during the men's and women's Tkachev there was a second functional phase. During

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this phase, the gymnast performs flexion to hyperextension of the hip joints and extension to hyperflexion of the shoulder joints. These phases end at the point of release with an angular momentum about the mass centre that facilitates forward rotation around the gymnast's mass centre during the flight phase before regrasping the bar.

In female gymnastics post 1996 Olympics, the Tkachev skill has been made more popular due to change in the dimension of the bars with the interbar distance increasing from 1.6 to 1.8 m. Different versions are defined by shape in the flight phase, and swinging direction relative to the low bar (outward or inward) has also become an option (Figure 1). Kerwin and Irwin (2010) compared the outward and inward variants of the women's straddle Tkachev to investigate the influence of the positioning of the low bar on the musculoskeletal demands placed on the gymnast in performing each variant of the skill. These authors highlighted differences in the joint powers (JPs) at the shoulders as well as release characteristics, and suggested that the inward version of the skill has the potential to allow gymnasts to perform more complex variants. It appeared that the inward variant offered gymnasts greater potential to execute more advanced forms of the Tkachev. A newer variant, the toe-on Tkachev, has been adopted by a number of leading international competitors and has enabled straight Tkachevs to be performed by women gymnasts. The new variant requires the gymnast to accentuate the piking action, seen in some traditional Tkachevs, to the point where the gymnast places her feet on the high bar as she swings past the horizontal on the downswing (Figure 1).

The gymnast holds the toe-on piked position until close to the horizontal on the upswing and then opens hip and shoulder angles to prepare for release and flight backwards over the high bar. As with all Tkachevs, gymnasts are faced with the challenge of maintaining backwards angular momentum around the high bar to ensure suitable release conditions for flight over the bar, while also reversing the direction of angular momentum about their mass centre close to release providing forward rotation in flight. This study builds on the work of Kerwin and Irwin (2010) contrasting the toe-on version with the inward and outward techniques (Figure 1). The aim of the current study was to examine the fundamental biomechanical variables associated with successful performance during the longswing preceding Tkachev up to and including release and explore whether the actions made by gymnasts during the toe-on Tkachev enable them to develop greater forward rotating angular momentum. It is hypothesised that the toe-on version is less mechanically demanding and does provide the opportunity for the gymnast to perform more complex versions of the skill.

Method

Data collection

Data were collected during the 2007 Stuttgart World Gymnastics Championships. The best five elite international gymnasts were selected for this analysis based on their uneven bars ranking and performance of this specific skill, their mean and average age was (18 ± 2 yrs), height (1.55 ± 0.07 m) and body mass (46 ± 7 kg). Two video camcorders set to a frequency of 50 Hz were positioned with their optical axes intersecting the high bar recorded five toe-on Tkachevs (1 per gymnast). One camera was aligned along the high bar with the other approximately at right angles and viewing over the low bar. Two static cuboids (1 m × 1 m × 3 m) providing 48 known coordinates were positioned to calibrate the performance area. The calibrated volume encompassed the analysed straddle Tkachevs with the origin defined as the

Figure 1. Left = toe-on Tkachev; middle = inwards facing Tkachev; right = outward facing Tkachev.

centre of the high bar in its neutral bar position. During the competition, images of the calibration and five toe-on straddle Tkachevs were recorded from the cameras.

Data processing

Calibration and movement frames were digitised using PEAK Motus (Vicon Peak 9.0, Oxford, UK) motion analysis system for both camera views. Movement data for each trial comprised images from the preceding toe on action and the release and flight phase of the straddle Tkachev. The centre of the high bar and each gymnast's head, right and left wrists, elbows, shoulders, hips, knees, ankles and toes were digitised. The data-sets from both cameras were time synchronised using the methods of Yeadon and King (1999). A 12-parameter 3D direct linear transformation (Abdel-Aziz & Karara 1971) was used to reconstruct the coordinate data using the TARGET high-resolution motion analysis system (Kerwin 1995). Movement frames were analysed based on the circle angle of the gymnast defined by the vector formed between their mass centre and the neutral bar location and the right horizontal vector. Circle angle was defined as 90° when the gymnast was in a handstand position and continued to 450° as the gymnast returned to handstand. All movement data were analysed once the gymnast had passed 90° and initiated the toe-on action at ~180° through to the instant of release. These methods of analysis were the same as those used in a previous study by Kerwin and Irwin (2010), allowing direct comparison with the previously published data. The reconstructed 3D coordinate data were processed with the 'ksmooth' function (MathCad[14]™, Adept Scientific, Letchworth Garden City, UK) with the parameter 's' set to 0.10. This routine has similar characteristics to a Butterworth low-pass digital filter with the cut-off frequency set to 4.5 Hz (Kerwin & Irwin 2006). Yeadon's inertia model (1990) was implemented together with limb lengths determined from the video data and the height and mass of each gymnast, collected during the competition, to calculate each gymnast's customised segmental inertia parameters.

Data analysis

A four-segment (arm, trunk, thigh and shank) planar representation of the gymnast was constructed by averaging the left and right sides of the body. The instants of release and regrasp were defined by quantifying 'grip radius' as the linear coordinate separation between the virtual mid-wrists and the centre of the high bar. Release was considered to have occurred once the grip radius exceeded 10% of the maximum separation value obtained during the preceding toe-on swing action. Release parameters and angular momentum were determined using the methods reported in Kerwin and Irwin (2010). Angular momentum (L) of each segment about its mass centre was calculated:

$$L_s = I\omega \quad (1)$$

where L_s = angular momentum about segment mass centre; I = segment moment of inertia and ω = segment angular velocity.

Each segment's L was also calculated about the whole body mass centre:

$$L_0 = mr^2\omega_c \quad (2)$$

where L_0 = segment angular momentum about whole body mass centre; m = mass of segment; r = distance between whole body mass centre and segment mass centre and ω_c = angular velocity of segment around whole body mass centre.

Values were then summed over the four segments to determine L about the body mass centre:

$$L = I\omega + mr^2\omega_c \quad (3)$$

where L = total segment angular momentum about whole body mass centre.

To account for gymnasts of varying size, L values were normalised by dividing by the product of 2π and the gymnasts' moment of inertia in the anatomical position to provide units of straight somersaults per second:

$$L_n = L/2\pi I_b \quad (4)$$

where L_n = normalised angular momentum; I_b = moment of inertia of whole body when in anatomical position.

Joint angles and angular velocities at the shoulders and hips were determined throughout the straddle Tkachev. Shoulder extension and hip flexion indicate closure of the respective joint angles and are reported as positive values throughout the kinetic analysis. Inverse dynamics analyses were used to determine joint moments (JMs) and combined with joint angular velocities (ω) to determine JPs. Integration of the power–time profiles was used to determine the respective joint work (JW) contributions. Due to the gymnast being in a fixed 'closed' position with minimal hip and shoulder movement while the toes were in contact with the bar, it was implicitly assumed that hip and shoulder torques were negligible during this phase. However, due to the uncertainty of JMs calculated from the toes-up whilst gymnasts' toes were in contact with the bar, JMs during this phase were intentionally not considered in the analyses. All values were normalised according to Hof's (1996) recommendations with the exception that each gymnast's height rather than leg length, often preferred for gait analyses, was used as the linear scaling component. JM and work values were divided by each gymnast's BW and height. JP was divided by body mass, gravitational acceleration ($g^{3/2}$) and height ($h^{1/2}$). This normalisation procedure resulted in joint kinetic results being dimensionless and

Table 1. Mean [±SD] release parameters for the toe-on, outward and inward straddle Tkachev on uneven bars.

	Toe-on ($n=5$)	Outward* ($n=5$)	Inward* ($n=5$)
T_{flight} (s)	0.57 ± 0.04	0.48 ± 0.02	0.40 ± 0.10
θ (°)	67 ± 3	40 ± 13	60 ± 6
V_y (m/s)	−1.58 ± 0.11	−1.67 ± 0.13	−1.92 ± 0.20
V_z (m/s)	1.98 ± 0.26	1.89 ± 0.33	1.49 ± 0.71
I_{ss} (kg/m^2)	7.63 ± 1.41	5.16 ± 1.39	6.14 ± 1.43
ω (rad/s)	−2.47 ± 0.70	−1.18 ± 0.15	−2.26 ± 0.44
L_n (SS/s)	−0.39 ± 0.11	−0.22 ± 0.05	−0.33 ± 0.07

*Data sourced from Kerwin and Irwin (2010).

also allowed for direct comparison of values between different gymnasts.

For JW results, each positive and negative component is expressed as a percentage of the total JW. This is followed by a summation of the hips and shoulders to produce total positive and negative work; the percentage contribution of each joint is then reported. Due to the small sample size associated with analyses of elite sports people in competition, a descriptive analysis was undertaken.

Results

Summary data

The release characteristics for the toe-on Tkachev are shown in Table 1, along with comparable data for outward and inward facing Tkachevs, sourced from Kerwin and Irwin (2010). The selected release parameters were flight time (T_{flight}), circle angle at release (θ), horizontal (V_y) and vertical (V_z) velocities, moment of inertia (I_{ss}), angular velocity (ω) and normalised angular momentum (L_n). With the exception of V_y, all release parameters were larger for the toe-on Tkachev than the other two variations. Subject anthropometrics were similar between the current study and Kerwin and Irwin (2010), as such differences in biomechanical variables would not be due to difference in gymnast morphology. The toe-on version clearly demonstrating the potential, on average, to obtain greater height above the bar, increases potential to rotate during the aerial phase.

An examination of joint kinetics revealed that the knee JW contributed minimally with approximately 2% of the total work and, as such, was not included in this analysis. JW contributions for the hips and shoulders during the toe-on Tkachev are reported in Table 2, along with comparable data for outward and inward Tkachevs (Kerwin & Irwin 2010). Comparing the positive and negative contributions for each joint, the JW patterns for the hips were close to those seen for the outward Tkachev, while the shoulder contributions were similar to those seen for the inward variant. However in the toe-on Tkachev, it is interesting to note that there is an even higher negative work done at the shoulders, 72%, compared to 65% for the inward variant. When analysing the percentage contribution of each joint in terms of the total positive and negative works, the values for negative work are similar for all three versions of the skill with 10% of the work being performed at the hip joint. However, for positive work there was a much greater contribution from the hip joint during the toe-on Tkachev (77%) compared to the outward (48%) and inward (44%) Tkachevs.

Profile data

Figure 2 illustrates the group average (± SD) joint angle, normalised work and power profiles for the hip and shoulder joints during the toe-on Tkachev. Hip joint angle remained around 140° of flexion for the majority of the preparatory longswing, and opened as release was approached (Figure 2). The largest amount of inter-gymnast variability for hip joint angle was present approaching release. The shoulder angle was fixed in an extended position (approx. 60°) for half the circle (180°–360°) and then, all the gymnasts opened up to full flexion or hyperflexed position at release. There was more consistency across gymnasts for shoulder angle than hip angle approaching the point of release with a lower level of variability observed (Figure 2). The large hip moment after the lower vertical (270°) that appears consistently across the gymnasts highlights the eccentric action as the hips remain flexed, until the sudden extension and the large moment occur opening the hip joint. Interesting at

Table 2. Normalised hip and shoulder work for toe-on, outward and inward straddle Tkachev on uneven bars.

	Hips Toe-on (%)	Outward* (%)	Inward* (%)	Shoulders Toe-on	Outward* (%)	Inward* (%)
Joint work						
Positive	89	90	82	29	71	35
Negative	11	10	18	71	29	65
Total work						
Positive	77	48	44	23	52	56
Negative	10	5	10	90	95	90

*Data sourced from Kerwin and Irwin (2010).

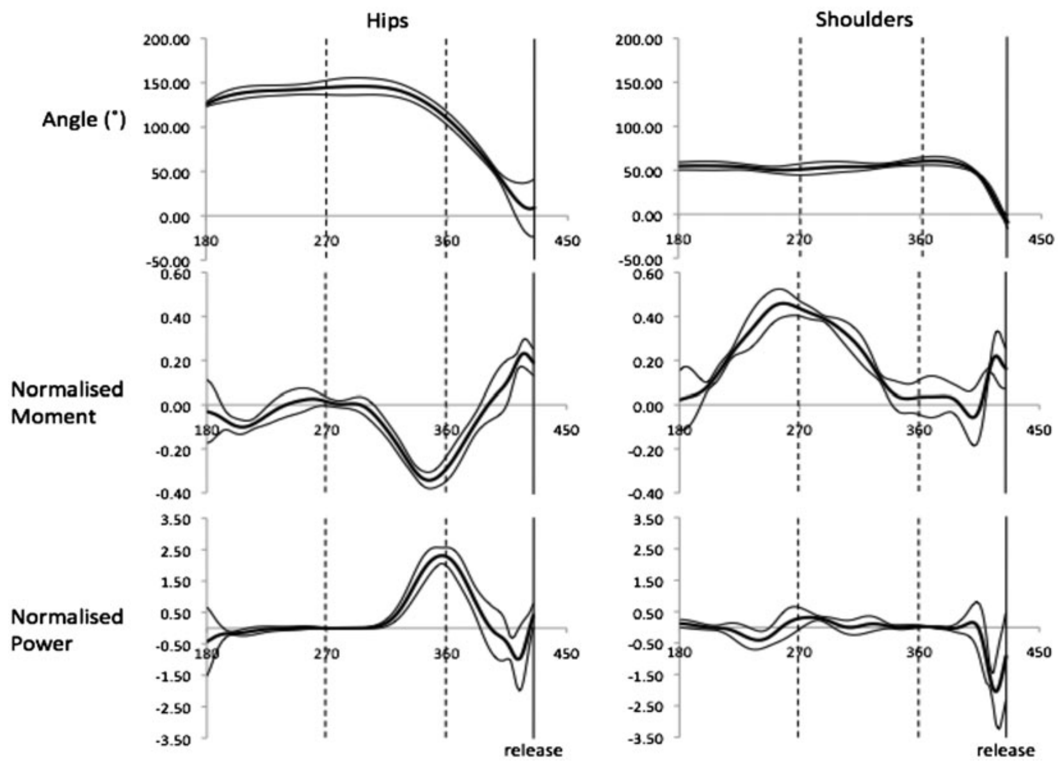

Figure 2. Joint angle (°), normalised JMs and normalised JPs for the hips and shoulders during toe-on Tkachev, from 180° (horizontal on the downswing) to release. Each graph shows a mean (bold) ±1 SD (feint) for five gymnasts.

release there is an eccentric-type action. Shoulder JMs peaked positively early in the circle as the gymnast concentrically extends the shoulders maintaining the body close to the bar. The gymnast extends the shoulders as they approach release. The interaction between joint angle and moment is apparent in the corresponding JP profiles, at release when a small negative spike in power occurs as the gymnast starts to close the shoulder joints (Figure 2).

Angular momentum profiles are shown in Figure 3 for the three main segments (arms, legs and trunk) and for the whole body about its mass centre. The dominant

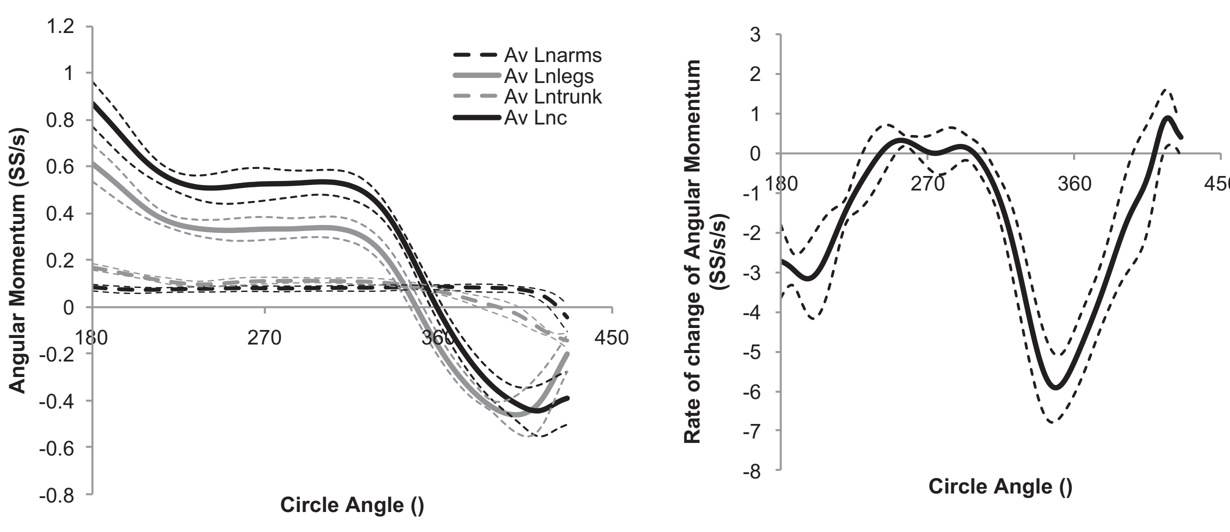

Figure 3. Angular momentum (left), about the mass centre, and for the arms, legs and trunk separately and the rate of change of angular momentum about the mass centre (right).

role of the legs in the generation of angular momentum is demonstrated by the similarity between its profile and that of the whole body around its mass centre. The rate of change of angular momentum is greatest at approximately 360° of rotation as the gymnast passes the horizontal prior to release, which coincides with the point at which angular velocity peaks. The interaction of the joint kinetics and then angular moment generation appears to occur in a similar and consistent pattern.

Discussion

The complexity of gymnastics movements continues to increase and evolve, placing ever increasing demands on the performer. As new techniques emerge, the challenges for coaches and biomechanists rest with understanding the requirements for success, and ultimately answering questions such as: *what are the most effective techniques?* With the emergence of the toe-on Tkachev as one of the most popular complex skills, it becomes apparent that knowledge of this technique is necessary to make training effective and safe. The current study aimed to increase understanding of the actions made by gymnasts during the toe-on Tkachev and examine the key biomechanical performance variables that dictate the successful performance of this skill. The toe-on Tkachev on uneven bars is generally regarded as an advancement of the inward variant of this popular release and regrasp skill in women's artistic gymnastics.

Comparing the toe-on Tkachev to the outward and inward techniques (Kerwin & Irwin 2010) provides us with a measure of whether this skill is advantageous. Release characteristics demonstrated that the gymnasts released the bar at a later stage than during the inward or outward facing Tkachev. As such, a larger vertical velocity at release provided the gymnasts with an increased flight time compared to the other two variations. The angular momentum at release is a key biomechanical variable for gymnasts as this provides them with the opportunity to perform skills with body shapes that may allow greater marks to be achieved (Manning et al. 2011; FIG 2013). The angular momentum for the toe-on Tkachev was significantly higher compared to other versions, suggesting that this version would allow gymnasts the opportunity to perform this skill with more complex body shapes (e.g. straight body position) in the aerial phase. In addition, the larger angular velocity observed during the toe-on version will put the gymnast in a better position at regrasp.

During the toe-on Tkachev, the hips extend through a range of approximately 140° as the gymnast prepares for release. The hip angle at release demonstrated large variability between gymnasts (Figure 2), this was due to three gymnasts releasing with their hips in a hyperextended position, which is characteristic of the outward and inward versions. Previous research has suggested this body segment orientation relates to the gymnast reversing their rotation during the ascending phase (Exell et al. 2007; Kerwin et al. 2007). During the preceding longswing, the shoulders remained in a pseudo-static position with approximately 55° of shoulder flexion, until the final quadrant, when the shoulder joint opened (flexed) as the gymnasts prepared for release. The JP profiles of the hips and shoulders provide a useful insight into the mechanics of this skill, with an eccentric to concentric action of the hips from approximately 300° to 400° of circle angle. The gymnasts held the deep hip flexion up to approximately 360°, after which they actively extended up to the point of release. This one large hip power impulse is different from the numerous actions reported during the outward and inward versions in previous studies (Arampatzis & Bruggemann 2001; Kerwin & Irwin 2010). The shoulder JM switched direction as the gymnasts passed the lower vertical; this is due to the gymnasts actively maintaining a fixed shoulder position. After 360° of angular rotation one large shoulder power pulse occurred as the gymnasts concentrically flexed and rapidly opened the shoulder joints. These findings have direct implications in the physical preparation of this skill, and also the development of the skill. Specifically, hip joint kinetics were observed to be higher during the toe-on version compared to those reported by Kerwin and Irwin (2010). This observation suggests that the physical demands on the gymnast are different during the toe-on and, as such, physical preparation and skill development drills need to be tailored to the specific requirements of this skill. Customising drills will allow more effective and safer skill development to occur (Farana et al. 2014). In addition, injury risk of the hamstring complex (semitendinosus, semimembranosus and biceps femoris) may be increased during the oe-on Tkachev. This highlights the need for future epidemiology and clinical monitoring of specific hamstring lesions. The overall actions of the toe-on version seem less complex then the inward and outward variants, with only single large joint impulses, which may make the learning of this version easier.

Hip and shoulder JW results highlighted further differences between the toe-on Tkachev and the previous variations. The percentages of positive and negative work performed at each joint were similar to the outward variation for the hip joint, but for the shoulder joint, the values were closer to those reported for the inward variation (Table 2, Irwin & Kerwin 2010). If the percentages of total positive and total negative work produced by each joint are reviewed, then dominance of the hip contribution over the previous variants is clear with 77% of the positive work coming from the hips. This compares to less than 50% for the outward and inward variants. The smaller positive contribution from the shoulders is similar to the inward variant and less than half of that seen for the outward Tkachev. When negative work is considered, the hips contributed 10% or less in each of the three variants, but the shoulders made a substantial input to all three versions of this skill. It would appear that the adoption of the toe-on action in the Tkachev achieves the goal of attaining improved release conditions by extending the advantages previously attributed to the inward variant over its outward counterpart. The toe-on technique also appears to make little musculoskeletal demand on the gymnast in the early part of the circle, but places the gymnast in an advantageous position to deliver high positive hip power and moderate negative shoulder power in preparation for release.

Successful performance of this skill is determined by the trajectory of the mass centre and the reversal of angular momentum up to the point of release (Irwin & Kerwin 2012; Hiley et al. 2013). Figure 3 shows the dominant role the legs play in angular momentum, which coincided with the dynamic hip flexion action shown in Figure 2. Figure 3 reports the rate of change of angular momentum, this important variable was reported previously (Kerwin et al. 2007; Kerwin & Irwin 2010) when examining the angular moment characteristics of these release and regrasp skills. The greatest change in angular momentum occurred during the final stages of the movement, and corresponds to the large hip and shoulder actions. The importance of the JP impulses become more apparent and suggests that the gymnasts can achieve this skill with only two large actions. Therefore, it could be suggested that this version of the skill is actually less technically demanding than the inward and outward versions.

The toe-on Tkachev on uneven bars appears to be an advancement of the inward variant of this previously reported skill. The toe-on version enables gymnasts to increase key release variables, particularly vertical velocity, (and hence, flight time) and angular momentum. These favourable release characteristics create the environment in which body shape during the flight phase may be changed, to the point where straight Tkachevs are beginning to appear following toe-on Tkachevs in women's competitions. The apparent ease with which female gymnasts appear to be able to perform this skill indicates that it is likely to grow in popularity as gymnasts attempt to increase their difficulty scores by performing piked and straight version of the Tkachev.

The final body position of the gymnast at release also appears to be less demanding than has been previously reported for the outward or inward variants, and so provides the gymnast with more freedom to concentrate on working in the phase from a circle angle of 300°–400°. From this study, coaches should consider the dominant role of the hips in developing specific release characteristics.

It was hypothesised that the toe-on version is less mechanically demanding and provides the opportunity for the gymnast to perform more complex versions of the skill. It would appear from this sample of elite gymnasts that this is the case. However, while the ecological validity of this research is high in terms of an elite gymnastics population, the relative low sample size needs to be taken into account when interpreting these data.

Conclusion

The current study provides an example of how the coaching–biomechanics interface can use scientifically grounded data from an ecologically valid setting to inform technique development. This research has show that the toe-on version has numerous advantages compared to the traditional inward and outward versions. The increased flight time and angular momentum components provide shape options in the aerial phase. The technical complexity is also lower due to the need for two big actions at the hips and shoulders, with a clear hip dominance in terms of joint torque and power.

The implications of these finding for coaches is the need for physical preparation activities to replicate the demands of the skill, this will make training more effective, safe and efficient. From a scientific perspective, this study highlights the need for further research with larger sample sizes to examine inter-segment coordination as well as joint kinetics of gymnasts performing the toe-on Tkachev.

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