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Functional Phases and Angular Momentum Characteristics of Tkatchev and Kovacs

Running Title: Tkatchev and Kovacs on high bar

Key words: Biomechanics, Coaching, Men's Gymnastics, High Bar

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Abstract

Understanding the technical requirements and underlying biomechanics of complex release and re-grasp skills on high bar allows coaches and scientists to develop safe and effective training programmes. The aim of this study was to examine the differences in the functional phases between the Tkatchev and Kovacs skills and to explain how the angular momentum demands are addressed. Images of 18 gymnasts performing 10 Tkatchevs and 8 Kovacs at the Olympic Games were recorded (50 Hz), digitised and reconstructed (3D Direct Linear Transformation). Orientation of the functional phase (FP) action, defined by the rapid flexion to extension of the shoulders and extension to flexion of the hips as the performer passed through the lower vertical, along with shoulder and hip angular kinematics, angular momentum and key release parameters (body angle, mass centre velocity and angular momentum about the mass centre and bar) were compared between skills. Expected differences in the release parameters of angle, angular momentum and velocity were observed and highlighted the specific mechanical requirement of each skill. Whilst there were no differences in joint kinematics, hip and shoulder FP were significantly earlier in the circle for the Tkatchev. These findings highlight the importance of the orientation of the FP in the preceding giant swing and provides coaches with further understanding of the critical timing in this key phase.

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Introduction

Complex release and re-grasp skills on high bar provide male artistic gymnasts with the opportunity to maximise scoring potential. In men's gymnastics of the many release skills the two most commonly performed are the Tkatchev and Kovacs (Samuels et al., 2009), as detailed in the Fédération Internationale de Gymnastique (FIG) code of points (2013 Tkatchev page 140, Kovacs page 143).

Body segment orientation during the aerial phase (e.g. straddled, tucked, and straight) determines the difficulty rating of each skill (FIG, 2013). Previous research has reported angular momentum profiles and release characteristics associated with successful performance of each of these skills (Arampatzis and Brüggemann, 1999, 2001; Hiley et al., 2007; Irwin et al., 2007). These studies have also shown that accelerated giant swings are used to create the necessary release characteristics (Arampatzis and Brüggemann, 1999, 2001; Hiley et al., 2007). The accelerated giant swing has been previously split into the 'traditional' and 'scooped' (Hiley et al., 2007) or 'conventional' and 'power' (Arampatzis and Brüggemann, 2001) techniques; however, research investigating both techniques has agreed on the fundamental contribution of the hip and shoulder joint actions. Yeadon and Hiley (2000) explained that the gymnast is attempting to create a positive balance between the angular momentum gained in the descent and lost in the ascending phase. Irwin and Kerwin (2006) showed that the positive balance is achieved through hyper flexion of the shoulders and hyperextension of the hips followed by a rapid extension of the shoulders and flexion of the hips as they passed the lower vertical and that 70% of the work done occurred during this lower phase. Irwin and Kerwin (2005) referred to these actions as the *functional phases* (hips and shoulders) and highlighted them as key to the development and ultimately to the successful performance of the giant swing and more so for the one preceding release.

The formal evaluation of this skill is performed by qualified judges and is based on the technique requirements dictated by the FIG (2013) which shows the movement patterns and body positions used by judges to evaluate successful performance. Coaching instruction and feedback focuses attention on extension and flexion at the hips and shoulders all of which are dependant upon the specific requirements of the skill. The interesting feature of these two skills is that the mass centre trajectories in the flight phase are similar but their respective flight angular momenta are opposite in direction. The gymnast is thus faced with the challenge of creating the release characteristics, which will enable him to fly backwards over the high bar, but in the Tkatchev he has the added challenge of reversing the direction of his angular momentum vector as he approaches release.

Based on these key technical requirements and the underlying biomechanics of the Tkatchev and Kovacs, the aim of this study was to examine the differences in the functional phases between these two skills and to explain how the angular momentum demands are addressed. Ecological validity and coaching relevance were maintained through the analysis of data from Olympic Competition.

Method

Data collection: The data for this study were collected during the 2000 Sydney Olympic Games as part of the International Olympic Committee Research Project where ethical approval was obtained from the Federation of International Gymnastics and University Ethical Committee. Two camcorders (Sony Digital Handycam DCR VX1000E, Japan) were positioned on one side of the bar approximately 35 m away from and 8 m above the high bar. The optical axes of the cameras intersected at approximately 66˚ over the centre of the high bar. Both cameras captured the images at 50 Hz with a shutter speed of 1/600 s. Prior to the performances, images were recorded of a three dimensional calibration matrix comprising 40 known points encompassing the apparatus (5.2 m x 6 m x 3 m) (Figure 1). During the competition, images of the straight Tkatchev (n=10) and Kovacs (tucked, n=4; straight, n=4) were recorded. The inclusion criterion was based on the highest scoring gymnasts from the competition. The 10 straight Tkatchev's were selected based on the FIG judging criterion, with the 10 performances that were scored highest by different gymnasts being selected for analysis. A set of Kovacs was also selected, which included 4 tucked and 4 straight. An analysis of the 2 versions of the Kovacs demonstrated no difference in the key variables; as such the Kovacs were pooled giving a match set (Table 1).

The FIG difficulty rating of these skills at the time of data collection was Kovacs tucked = D; Kovacs piked or stretched = E, Tkatchev stretched = D. In total data from 18 gymnasts with masses and heights (60.1 ± 4.72 kg and 1.65 ± 0.04 m) included.

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Images of the calibration object and gymnast performing the preceding giant swing (from 20 fields preceding handstand to 20 fields post catch) and Tkatchev and Kovacs were digitised using the TARGET (v1.1, APEX, Loughborough, UK) high resolution motion analysis system (Kerwin, 1995). The centre of the high bar and the gymnast's head, and his right and left wrists, elbows, shoulders, hips, knees, ankles, and toes were digitised. A 12 parameter direct linear transformation (Marzan and Karara, 1975) was implemented to calibrate the cameras and reconstruct the coordinate data. The inertia parameters of each segment were customised using Yeadon's inertia model (1990), limb lengths determined from the video analyses and each gymnast's height and mass. Accuracy and reliability were established through repeated digitisations of six spherical markers (0.10 m in diameter) at known locations within the calibrated volume and digitised on different days.

Data analysis: The 3D coordinate data were processed with the 'ksmooth' function (Mathcad[14]™, Adept Scientific, 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 and Irwin, 2006). The left and right sides of the body were averaged to produce a four segment planar representation of the gymnast, (arm, trunk, thigh and shank). The instants of release and re-grasp were defined by quantifying 'grip radius' as the linear separation between the 'mid-wrists' and the centre of the high bar. Release was considered to have occurred once the grip radius exceeded 10% more than the maximum value obtained during the preceding giant swing. The angular position of the gymnast about the bar was defined by the mass centre to neutral bar location. In order to compare within and between gymnasts all data were interpolated in 1° intervals throughout the circle angle using a cubic spline function, (Mathcad[14]™). A circle angle was defined as 90° when the gymnast was in a handstand position and continued to 450° as he returned to handstand. The previously defined 'functional phases' (Irwin and Kerwin, 2005) were used, with the start and end points described by maximum hip extension to flexion and maximum shoulder flexion to extension for the Kovacs. Due to the fact that the Tkatchev ended with the gymnast performing a hyper flexion of the shoulder and hyperextension of the hips a third phase was also included in this analysis. In order to accurately locate the start and end points of these phases, the zero crossing points in the hip and shoulder angular velocity time histories were used for each gymnast. Circle angles for the gymnast at the start (Event 1), middle (Event 2) and end (Event 3) of the functional phases for the shoulders and hips for each Tkatchev were calculated. When the third phase angular velocity of the joints did not reach zero prior to release the gymnast's circle angle at release was reported. Lines joining the elbow, shoulder and hip defined the relative shoulder angle (θ_s) with the corresponding hip (θ_h) defined by lines joining the shoulder, hip and knee. Shoulder and hip angles were defined as zero with the gymnast in a handstand position. Positive angles were defined as extension at the shoulders and flexion at the hips. Linear velocity time histories for the whole body CM in the horizontal (V_h) and vertical (V_v) direction were calculated.

Joint angles and changes in joint angles at the shoulders and hips for each functional phase were determined. Differentiation of linear and angular quantities was achieved using a variation of Ridder's divided difference method (Press *et al.,* 1992). The phases of the Tkatchev and Kovacs that were compared are illustrated in Figure 2.

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Angular momentum about the gymnast's mass centre (L_c) and about the bar (L_b) were calculated. Angular momentum of the gymnast represented as a point mass was determined by $L_b = m_s \cdot r \cdot V_R$ where m_s is equal to the mass of the body, r is the vector between the mass centre and the bar and V_R is the resultant linear velocity of the mass centre of the body. Lc was calculated using; $L_c = \Sigma\, I_s \cdot \omega_s + m_s \cdot r^2 \cdot \omega_c$, where I_s is the segment's moment of inertia about a transverse axis through its mass centre and ω_s is the angular velocity of the segment about it's mass centre and ω_c is the angular velocity of the segment about the mass centre of the body. To account for gymnasts of varying size, angular momentum values were normalised (Ln) by dividing by the product of 2 π and the moment of inertia in a theoretical straight body position (anatomical position with arm angle fully flexed), measured in straight somersaults per second (SS/s). Absolute and normalised moment of inertia were also reported. All variables included in the analysis are based on the underlying theoretical relationship that they have with successful performance. Successful performance was defined as those gymnasts that executed the skill following the guides lines of the FIG (2013)

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Statistical Intervention

Following tests for normality differences between the Kovacs groups (straight versus tucked) and differences in discrete variables between Tkatchevs and the Kovacs were quantified using independent 't' - tests with the alpha level (critical P value) set to a conservative 0.01. To establish the meaningfulness of these data, effect size was also reported as a d score (Cohen, 1988) and interpreted using Hopkins (2000) 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).

Results

Reconstruction accuracy was found to be similar to other video based analyses of gymnastics conducted within the laboratory at 5 mm. Measurement accuracy based on repeated digitizations of six known points within the calibrated volume was 6.5 mm with the corresponding reliability for a single digitization of ~0.1% of the field of view in all three dimensions. Initial comparison between tucked and straight versions of the Kovacs showed no significant differences and in general small effect sizes for any of the key variables associated with successful performance (Table 1); as such both data sets for the Kovacs were pooled. Therefore results presented here quantify the differences between the 'straight' Tkatchev and pooled 'tucked and straight' Kovacs.

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Release Characteristics

Six of the nine key release parameters associated with successful performance of these skills showed a significant difference P<0.01 (Table 2) with a general trend for moderate effect sizes. The Tkatchev and Kovacs skill requires the gymnasts' mass centre to travel backward over the bar, and for this sample of gymnasts the horizontal component of that velocity was not different between the two skills. In contrast the vertical velocity was significantly higher for the Kovacs compared to the Tkatchev ($P<0.01$), which was concurrent with a significantly lower release angle for the Kovacs.

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Differences in the biomechanical parameters at release that dictate the trajectory of the mass centre are highlighted in Figure 3. The average peak height was greatest for the Kovacs due to greater vertical velocity at release, and associated flight time, compensating for lower release angle. The timing of the peak height also differed between these two skills, specifically, the Tkatchev's peak height occurred before the gymnast passed over the bar compared to the peak height in the Kovacs being directly over the high bar (Figure 4).

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The technical requirements of the Tkatchev and Kovacs dictates that the polarity of the angular momentum about the gymnast mass centre (Lnc) is opposite at release, however angular momentum about the bar represented as a point mass (Lnb) demonstrated little difference between the two skills (Table 2). Interestingly even though Lnb was not different, the release characteristics that contributed to Lnb showed

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significant differences and moderate effect sizes (Table 2). Specifically, the vertical velocity of the mass centre at release was significantly lower during the Tkatchev, due in part to the higher angle of release. The gymnasts' moments of inertia at release were not significantly different in the Tkatchev. Which may explain the similarities in Lnb, due to the fact that this is an the homogenous population, i.e. the gymnasts' body masses were similar and hence the radial separation of the mass centre from the bar was also consistent across the two skills (Table 2).

Functional Phases

Significant differences and moderate effect sizes were observed between the Tkatchev and Kovacs for the start and end positions of the shoulder and hip functional phases (Table 3). The Tkatchev is characterised by earlier start and end positions compared to the Kovacs, however similarities between both skills were observed for the change in circle angle during the hip functional phase (Table 3, Figure 4).

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Shoulder flexion angles, at the start of the functional phase, were significantly greater for the Tkatchev compared to the Kovacs, highlighting a more open shoulder position when the Tkatchev skill is initiated (Table 4 and illustrated in Figure 2). The maximum angular velocity of the shoulders was similar for both skills; however due to the post functional phase actions required in the Tkatchev, a more dynamic hip action was observed with a significantly greater maximum angular velocity of the hips.

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Angular Momentum

The angular momentum profile shown in Figure 5 demonstrates an increase in angular momentum about the mass centre (Lnc) as the performer descends from handstand. As anticipated, the reversal of angular momentum begins early in the preparatory swing and has a greater rate of change, thus allowing the gymnast to begin reversing his angular momentum after 80% of the swing phase.

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Due to the specific needs of the Tkatchev (reversing the angular momentum to allow the gymnast to rotate forwards in flight) there is a clear polarity change in Lnc before the release point. In order to facilitate this reversal of angular momentum the gymnast performs extra hip and shoulder actions, which are reflected in the differences in the functional phase characteristics (Table 4).

The peak normalised angular momentum about the mass centre is similar for the Kovacs and Tkatchev (Lnc ≈ 1.4), but the Lnc reduction in the Kovacs is minimised to ensure sufficient angular momentum at release to achieve the required backward rotation in flight. Lnc for the Tkatchev changes from a peak of 1.4 to -0.5 at release, enabling the gymnast to rotate forwards as he travels backwards over the bar.

Discussion

The aim of this study was to examine the differences in the biomechanics of functional phases between the Tkatchev and Kovacs and to explain how the angular momentum demands of these complex release and re-grasp skills are addressed. Employing biomechanical analyses, understanding of how the performer achieves the technical requirements of these skills, as outlined by the international governing body, has been developed. In addition examining the similarities between the preceding giant swing provides useful information for coaching and scientists about skill development and training methodology.

The data were checked for accuracy and reliability and values concurrent with other similar studies were found (Kerwin and Irwin, 2010). The authors advocate the use of data collected at international competition to provide insight into performances, although the number of trials is low, the performances have high ecological validity and as such can ultimately underpin our understanding.

It is clear from a coaching and performance perspective that the technical requirements of these skills (Tkatchev and Kovacs) are different. Previous research by Brüggemann *et al.,* 1994 classified these two skills as Category I (in which the direction of the angular momentum is maintained) and Category II (in which the direction of the angular momentum is changed prior to release). These authors identified a need to understand and explain the mechanical demands underpinning the individual requirements of the movements. Gaining insight into the technical requirements of these skills, particularly at release and during the preceding giant swing, will allow coaches and scientists to better understand how gymnastics organise their body segments to achieve these skills (Brüggemann *et al.,* 1994).

At release, differences were observed between these two skills for the majority of release parameters (Table 2). The release parameters ensure the gymnast possesses sufficient angular momentum to somersault as required by the particular skill and to achieve a flight profile that guarantees a safe clearance and effective re-grasp of the bar (Figure 3). The Kovacs released earlier and achieved a greater peak height compared to the Tkatchevs highlighted in Table 2. These differences result in a different trajectory, in flight, for each skill as highlighted in Figure 3. In comparison to the data presented previously, for the Kovacs, (Arampatzis and Brüggemann, 1999) and the Tkatchev (Arampatzis and Brüggemann, 2001), the current study reported similar horizontal release velocities (Table 5). The angular momentum about the mass centre at release was 19 and 27% higher in the current study for the Tkatchev and Kovacs, respectively compared to the earlier data of Arampatzis and Brüggemann (1999, 2001), a finding that may suggest a progressive evolution of these skills between 1994 and 2000 as the straight body version become the more popular. However, normalized data were not available and this should be considered in the interpretation of these findings, although the difference in the height and mass of the subjects was less than 3% and 1% respectively.

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The importance of the giant swing preceding the Tkatchev and Kovacs was highlighted by the earlier work of Brüggemann et al. (1994). These authors identified changes in the joint angular kinematics due to the direct relationship that these have on the production of angular momentum about the bar and about the mass centre for the subsequent aerial phase. Building on earlier research in which Irwin and Kerwin (2005, 2006) introduced the term "*functional phase*s" to describe and explain the actions of the hips and shoulders, observations from the current study highlight differences in the orientation of the start and end points of the functional phases in the circle between the two release and re-grasp skills. The functional phases of the Tkatchev start and finish significantly earlier for the hips and shoulders (Figure 4, Table 3). The importance of this finding rests with the development of these skills and the coach's understanding of the location of the key functional phases in the circle and how this changes as a function of the skill requirements. The reversal of angular momentum prior to release necessary for the Tkatchev highlights the need for developmental drills and progressions to replicate the spatial and temporal characteristics of these actions to allow the appropriate bio-physical adaptations to occur in the most effective and safe fashion. With the exception of the shoulder angle at the start of the Tkatchev, joint angles at the start and end of these phases were generally similar between these two skills. These findings concur with the classic training principle of specificity and overload and point towards the existence of a skill specific giant swing that may be taught in parallel, rather than in series which is the current practice, which may facilitate a more effective skill development programme.

Conclusion

The difference between the technical requirements of these skills is diverse and is clearly evident due to the opposite polarity of the angular momentum at release. However, with this in mind, the current study has highlighted that these complex skills share a similar joint angular kinematic requirement during the functional phases, although the orientation of these phases shift as a function of the type of skill. The Tkatchevs functional phases started earlier and finished earlier compared to the Kovacs. This information may lead to the development of skill specific giant swings that can be used to elicit the specific requirements of these skills. The outcome of this would be a more effective and safe training environment.

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Acknowledgements

Tables

Table 1. Average (±sd) release characteristics for the tucked and straight Kovacs

	TUCK KOVACS	**STRAIGHT KOVACS**			
n	**4**	**4**	**df**	**p**	**ES**
θc	375.50	364.50	8	P>0.05 0.09	0.58
sd	5.07	9.81			
***v*Cy**	-1.64	-1.64	8	P>0.05 1.00	0.00
sd	0.25	0.08			
***v*Cz**	4.50	5.05	8	P>0.05 0.06	0.64
sd	0.10	0.46			
Lnc	1.00	0.82	8	P>0.05 0.07	0.65
sd	0.10	0.11			
Lnb	3.30	3.65	8	P>0.05 0.26	0.43
sd	0.10	0.51			
tFlight	1.00	0.98	8	P>0.05 0.41	0.21
sd	0.03	0.06			
ωc	6.80	5.84	8	P>0.05 0.07	0.62
sd	0.30	0.80			
Icm	11.00	9.93	8	P>0.05 0.37	0.34
sd	1.30	1.65			
Incm	9.90	8.65	8	P>0.05 0.15	0.52
sd	1.30	0.67			

θc = angle of release (˚). *v*Cy and *v*Cz = velocity of the mass centre horizontally and vertically (m/s). Ln = normalised angular momentum about the mass centre (c) and bar (b) (SS/s). tFlight = flight time (s). ωc = angular velocity about the mass centre (rad/s). Icm = moment of inertia about the mass centre (kgm^2), Incm = normalised moment of inertia.

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Table 2. Average (±sd) release characteristics for the Tkatchev and Kovacs

	TKATCHEV	**KOVACS**		
n	**10**	**8**	p	ES
θc	406.30	370.00	P<0.01	0.91
sd	6.72	9.32		
***v*Cy**	-1.78	-1.64	P>0.01	0.27
sd	0.31	0.17	0.27	
***v*Cz**	2.70	4.78	P<0.01	0.91
sd	0.53	0.42		
Lnc	-0.51	0.89	P<0.01	0.99
sd	0.08	0.12		
Lnb	3.28	3.49	P>0.01	0.25
sd	0.44	0.38	0.30	
tFlight	0.62	0.97	P<0.01	0.95
sd	0.06	0.05		
ωc	-2.71	6.29	P<0.01	0.99
sd	0.50	0.74		
Icm	12.37	10.45	P>0.01	0.54
sd	1.48	1.49	0.02	
Incm	1.19	1.01	P>0.01	0.54
sd	0.14	0.14	0.02	

θc = angle of release (˚). *v*Cy and *v*Cz = velocity of the mass centre horizontally and vertically (m/s). Ln = normalised angular momentum about the mass centre (c) and bar (b) (SS/s). tFlight = flight time (s). ωc = angular velocity about the mass centre (rad/s). Icm = moment of inertia about the mass centre (kgm^2), Incm = normalised moment of inertia.

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Table 3. Average (±s) Circle angle (θc) for the start (s) and end (e) of the functional phases for the hips (H) and shoulders (S) during the Tkatchev and Kovacs

	TKATCHEV	**KOVACS**		
n	**10**	**10**	P	ES
θcHs	217	269	P<0.01	0.94
sd	12	6		
θcHe	314	371	P<0.01	0.90
sd	17	10		
θcSs	226	284	P<0.01	0.95
sd	12	7		
θcSe	347	368	P<0.01	0.50
sd	22	13		
ΔθcH	97	101	P>0.01	0.22
sd	9	9		
ΔθcS	121	84	P<0.01	0.81
sd	15	12		

θ = angle (degrees)

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Table 4 Average (±sd) joint kinematics at the start (s) and end (e) of the functional phases for the hips (H) and shoulders (S) during the Tkatchev and Kovacs

	TKATCHEV	**KOVACS**	P	ES
θHs	-39.5	-31.8	P>0.01	0.50
sd	8.3	4.4	0.03	
θHe	54.9	59.3	P>0.01	0.22
sd	6.5	12.0	0.33	
θSs	-16.5	-6.0	P<0.01	0.79
sd	4.8	3.1		
θSe	42.3	50.1	P>0.01	0.44
sd	7.9	7.9	0.05	
minωH	-8.0	-2.5	P<0.01	0.98
sd	0.7	0.4		
maxωH	9.8	8.0	P<0.01	0.60
sd	1.3	1.1		
minωS	-9.5	-1.5	P<0.01	0.96
sd	1.7	0.4		
maxωS	4.4	5.5	P>0.01	0.52
sd	0.8	1.00	0.02	

θ = angle (degrees)/ ω = angular velocity (Rad/s)

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Table 5. Comparison of selected release characteristics (mean ±sd) from the current study and Arampatzis & Brüggemann (1999 and 2001)

	Arampatzis & Brüggemann (1999) 1994 World Championships *"Kovacs"*	Current Study 2000 Olympic Games *"Kovacs"*	Arampatzis & Brüggemann (2001) 1994 World Championships *"Tkatchev"*	Current Study 2000 Olympic Games *"Tkatchev"*
***v*Cy**	-1.60	-1.64	-1.97	-1.78
sd	0.34	0.17	0.38	0.31
***v*Cz**	4.76	4.78	3.06	2.70
sd	0.4	0.42	0.44	0.53
Lc	46.1	58.5	-33.39	-39.6
sd	2.7	11.7	4.55	5.43

*v*Cy and *v*Cz = velocity of the mass centre horizontally and vertically (m/s). Lc = angular momentum about the mass centre (kgm^2/s).

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Figures

Figure 1. Graphical illustration of the dimensions of the men's high bar (above) three dimensional calibration object (below)

Figure 2. Illustration of the functional phase (shoulder and hips combined) and release point during the Tkatchev (above) and Kovacs (below) performed at the 2000 Olympic Games Sydney

Figure 3. Average mass centre trajectory during the flight phase (m) for the Tkatchev (Black) and Kovacs (grey)

Figure 4. Average shoulder (left) and hip (right) start and end points of the Functional Phases for the Tkatchev (black) and Kovacs (grey)

Figure 5. Average (±s) Normalised angular momentum (SS/s) about the gymnasts mass centre (Lnc) for the Tkatchev (black) and Kovacs (grey) from the start of the functional phase to release performed at the 2000 Olympic Games Sydney.