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2   Functional Phases and Angular Momentum Characteristics of Tkatchev and Kovacs

3   **Running Title:** Tkatchev and Kovacs on high bar

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

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Abstract

28   Understanding the technical requirements and underlying biomechanics of complex release and

29   re-grasp skills on high bar allows coaches and scientists to develop safe and effective training

30   programmes. The aim of this study was to examine the differences in the functional phases

31   between the Tkatchev and Kovacs skills and to explain how the angular momentum demands

32   are addressed. Images of 18 gymnasts performing 10 Tkatchevs and 8 Kovacs at the Olympic

33   Games were recorded (50 Hz), digitised and reconstructed (3D Direct Linear Transformation).

34   Orientation of the functional phase (FP) action, defined by the rapid flexion to extension of the

35   shoulders and extension to flexion of the hips as the performer passed through the lower

36   vertical, along with shoulder and hip angular kinematics, angular momentum and key release

37   parameters (body angle, mass centre velocity and angular momentum about the mass centre

38   and bar) were compared between skills. Expected differences in the release parameters of

39   angle, angular momentum and velocity were observed and highlighted the specific mechanical

40   requirement of each skill. Whilst there were no differences in joint kinematics, hip and shoulder

41   FP were significantly earlier in the circle for the Tkatchev. These findings highlight the

42   importance of the orientation of the FP in the preceding giant swing and provides coaches with

43   further understanding of the critical timing in this key phase.

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47 **Introduction**

48 Complex release and re-grasp skills on high bar provide male artistic gymnasts with the

49 opportunity to maximise scoring potential. In men's gymnastics of the many release

50 skills the two most commonly performed are the Tkatchev and Kovacs (Samuels et al.,

51 2009), as detailed in the Fédération Internationale de Gymnastique (FIG) code of points

52 (2013 Tkatchev page 140, Kovacs page 143).

53 Body segment orientation during the aerial phase (e.g. straddled, tucked, and straight)

54 determines the difficulty rating of each skill (FIG, 2013). Previous research has reported

55 angular momentum profiles and release characteristics associated with successful

56 performance of each of these skills (Arampatzis and Brüggemann, 1999, 2001; Hiley et

57 al., 2007; Irwin et al., 2007). These studies have also shown that accelerated giant

58 swings are used to create the necessary release characteristics (Arampatzis and

59 Brüggemann, 1999, 2001; Hiley et al., 2007). The accelerated giant swing has been

60 previously split into the 'traditional' and 'scooped' (Hiley et al., 2007) or 'conventional'

61 and 'power' (Arampatzis and Brüggemann, 2001) techniques; however, research

62 investigating both techniques has agreed on the fundamental contribution of the hip and

63 shoulder joint actions. Yeadon and Hiley (2000) explained that the gymnast is

64 attempting to create a positive balance between the angular momentum gained in the

65 descent and lost in the ascending phase. Irwin and Kerwin (2006) showed that the

66 positive balance is achieved through hyper flexion of the shoulders and hyperextension

67 of the hips followed by a rapid extension of the shoulders and flexion of the hips as they

68 passed the lower vertical and that 70% of the work done occurred during this lower

69 phase. Irwin and Kerwin (2005) referred to these actions as the *functional phases* (hips

70 and shoulders) and highlighted them as key to the development and ultimately to the

71 successful performance of the giant swing and more so for the one preceding release.

72 The formal evaluation of this skill is performed by qualified judges and is based on the

73 technique requirements dictated by the FIG (2013) which shows the movement patterns

74 and body positions used by judges to evaluate successful performance. Coaching

75 instruction and feedback focuses attention on extension and flexion at the hips and

76 shoulders all of which are dependant upon the specific requirements of the skill. The

77 interesting feature of these two skills is that the mass centre trajectories in the flight

78 phase are similar but their respective flight angular momenta are opposite in direction.

79 The gymnast is thus faced with the challenge of creating the release characteristics,

80 which will enable him to fly backwards over the high bar, but in the Tkatchev he has the

81 added challenge of reversing the direction of his angular momentum vector as he

82 approaches release.

83 Based on these key technical requirements and the underlying biomechanics of the

84 Tkatchev and Kovacs, the aim of this study was to examine the differences in the

85 functional phases between these two skills and to explain how the angular momentum

86 demands are addressed. Ecological validity and coaching relevance were maintained

87 through the analysis of data from Olympic Competition.

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91 **Method**

92 **Data collection:** The data for this study were collected during the 2000 Sydney

93 Olympic Games as part of the International Olympic Committee Research Project where

94 ethical approval was obtained from the Federation of International Gymnastics and

95 University Ethical Committee. Two camcorders (Sony Digital Handycam DCR VX1000E,

96 Japan) were positioned on one side of the bar approximately 35 m away from and 8 m

97 above the high bar. The optical axes of the cameras intersected at approximately 66°

98 over the centre of the high bar. Both cameras captured the images at 50 Hz with a

99 shutter speed of 1/600 s. Prior to the performances, images were recorded of a three

100 dimensional calibration matrix comprising 40 known points encompassing the apparatus

101 (5.2 m x 6 m x 3 m) (Figure 1). During the competition, images of the straight Tkatchev

102 (n=10) and Kovacs (tucked, n=4; straight, n=4) were recorded. The inclusion criterion

103 was based on the highest scoring gymnasts from the competition. The 10 straight

104 Tkatchev's were selected based on the FIG judging criterion, with the 10 performances

105 that were scored highest by different gymnasts being selected for analysis. A set of

106 Kovacs was also selected, which included 4 tucked and 4 straight. An analysis of the 2

107 versions of the Kovacs demonstrated no difference in the key variables; as such the

108 Kovacs were pooled giving a match set (Table 1).

109 The FIG difficulty rating of these skills at the time of data collection was Kovacs tucked

110 = D; Kovacs piked or stretched = E, Tkatchev stretched = D. In total data from 18

111 gymnasts with masses and heights (60.1 ± 4.72 kg and 1.65 ± 0.04 m) included.

112 -------------------------------------INSERT FIGURE 1 HERE---

5

113 Images of the calibration object and gymnast performing the preceding giant swing

114 (from 20 fields preceding handstand to 20 fields post catch) and Tkatchev and Kovacs

115 were digitised using the TARGET (v1.1, APEX, Loughborough, UK) high resolution

116 motion analysis system (Kerwin, 1995). The centre of the high bar and the gymnast's

117 head, and his right and left wrists, elbows, shoulders, hips, knees, ankles, and toes

118 were digitised. A 12 parameter direct linear transformation (Marzan and Karara, 1975)

119 was implemented to calibrate the cameras and reconstruct the coordinate data. The

120 inertia parameters of each segment were customised using Yeadon's inertia model

121 (1990), limb lengths determined from the video analyses and each gymnast's height

122 and mass. Accuracy and reliability were established through repeated digitisations of

123 six spherical markers (0.10 m in diameter) at known locations within the calibrated

124 volume and digitised on different days.

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127 **Data analysis:** The 3D coordinate data were processed with the 'ksmooth' function

128 (Mathcad[14]™, Adept Scientific, UK) with the parameter 's' set to 0.10. This routine has

129 similar characteristics to a Butterworth low-pass digital filter with the cut-off frequency

130 set to 4.5 Hz, (Kerwin and Irwin, 2006). The left and right sides of the body were

131 averaged to produce a four segment planar representation of the gymnast, (arm, trunk,

132 thigh and shank). The instants of release and re-grasp were defined by quantifying 'grip

133 radius' as the linear separation between the 'mid-wrists' and the centre of the high bar.

134 Release was considered to have occurred once the grip radius exceeded 10% more

135 than the maximum value obtained during the preceding giant swing. The angular

136 position of the gymnast about the bar was defined by the mass centre to neutral bar

137 location. In order to compare within and between gymnasts all data were interpolated in

138 1° intervals throughout the circle angle using a cubic spline function, (Mathcad[14]™). A

139 circle angle was defined as 90° when the gymnast was in a handstand position and

140 continued to 450° as he returned to handstand. The previously defined 'functional

141 phases' (Irwin and Kerwin, 2005) were used, with the start and end points described by

142 maximum hip extension to flexion and maximum shoulder flexion to extension for the

143 Kovacs. Due to the fact that the Tkatchev ended with the gymnast performing a hyper

144 flexion of the shoulder and hyperextension of the hips a third phase was also included in

145 this analysis. In order to accurately locate the start and end points of these phases, the

146 zero crossing points in the hip and shoulder angular velocity time histories were used

147 for each gymnast. Circle angles for the gymnast at the start (Event 1), middle (Event 2)

148 and end (Event 3) of the functional phases for the shoulders and hips for each Tkatchev

149 were calculated. When the third phase angular velocity of the joints did not reach zero

150 prior to release the gymnast's circle angle at release was reported. Lines joining the

151 elbow, shoulder and hip defined the relative shoulder angle (θ_s) with the corresponding

152 hip (θ_h) defined by lines joining the shoulder, hip and knee. Shoulder and hip angles

153 were defined as zero with the gymnast in a handstand position. Positive angles were

154 defined as extension at the shoulders and flexion at the hips. Linear velocity time

155 histories for the whole body CM in the horizontal (V_h) and vertical (V_v) direction were

156 calculated.

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157   Joint angles and changes in joint angles at the shoulders and hips for each functional

158   phase were determined. Differentiation of linear and angular quantities was achieved

159   using a variation of Ridder's divided difference method (Press *et al.,* 1992). The phases

160   of the Tkatchev and Kovacs that were compared are illustrated in Figure 2.

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162   -------------------------------------INSERT FIGURE 2 HERE---

163

164   Angular momentum about the gymnast's mass centre (L_c) and about the bar (L_b) were

165   calculated. Angular momentum of the gymnast represented as a point mass was

166   determined by $L_b = m_s . r . V_R$ where m_s is equal to the mass of the body, r is the vector

167   between the mass centre and the bar and V_R is the resultant linear velocity of the mass

168   centre of the body. Lc was calculated using; $L_c = \Sigma I_s . \omega_s + m_s . r^2 . \omega_c$, where I_s is the

169   segment's moment of inertia about a transverse axis through its mass centre and ω_s is

170   the angular velocity of the segment about it's mass centre and ω_c is the angular velocity

171   of the segment about the mass centre of the body. To account for gymnasts of varying

172   size, angular momentum values were normalised (Ln) by dividing by the product of 2π

173   and the moment of inertia in a theoretical straight body position (anatomical position

174   with arm angle fully flexed), measured in straight somersaults per second (SS/s).

175   Absolute and normalised moment of inertia were also reported. All variables included in

176   the analysis are based on the underlying theoretical relationship that they have with

177   successful performance. Successful performance was defined as those gymnasts that

178   executed the skill following the guides lines of the FIG (2013)

179 *Statistical Intervention*

180 Following tests for normality differences between the Kovacs groups (straight versus

181 tucked) and differences in discrete variables between Tkatchevs and the Kovacs were

182 quantified using independent 't' - tests with the alpha level (critical P value) set to a

183 conservative 0.01. To establish the meaningfulness of these data, effect size was also

184 reported as a d score (Cohen, 1988) and interpreted using Hopkins (2000) complete

185 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

186 and >4.0 perfect).

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188 **Results**

189 Reconstruction accuracy was found to be similar to other video based analyses of gymnastics

190 conducted within the laboratory at 5 mm. Measurement accuracy based on repeated

191 digitizations of six known points within the calibrated volume was 6.5 mm with the

192 corresponding reliability for a single digitization of ~0.1% of the field of view in all three

193 dimensions. Initial comparison between tucked and straight versions of the Kovacs

194 showed no significant differences and in general small effect sizes for any of the key

195 variables associated with successful performance (Table 1); as such both data sets for

196 the Kovacs were pooled. Therefore results presented here quantify the differences

197 between the 'straight' Tkatchev and pooled 'tucked and straight' Kovacs.

198

199 ------------------------------------INSERT TABLE 1 HERE---

200 *Release Characteristics*

201 Six of the nine key release parameters associated with successful performance of these

202 skills showed a significant difference P<0.01 (Table 2) with a general trend for moderate

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203   effect sizes. The Tkatchev and Kovacs skill requires the gymnasts' mass centre to travel

204   backward over the bar, and for this sample of gymnasts the horizontal component of

205   that velocity was not different between the two skills. In contrast the vertical velocity was

206   significantly higher for the Kovacs compared to the Tkatchev (P<0.01), which was

207   concurrent with a significantly lower release angle for the Kovacs.

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209   -------------------------------------INSERT TABLE 2 HERE--

210   Differences in the biomechanical parameters at release that dictate the trajectory of the

211   mass centre are highlighted in Figure 3. The average peak height was greatest for the

212   Kovacs due to greater vertical velocity at release, and associated flight time,

213   compensating for lower release angle. The timing of the peak height also differed

214   between these two skills, specifically, the Tkatchev's peak height occurred before the

215   gymnast passed over the bar compared to the peak height in the Kovacs being directly

216   over the high bar (Figure 4).

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218   -------------------------------------INSERT FIGURE 4 HERE--

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221   The technical requirements of the Tkatchev and Kovacs dictates that the polarity of the

222   angular momentum about the gymnast mass centre (Lnc) is opposite at release,

223   however angular momentum about the bar represented as a point mass (Lnb)

224   demonstrated little difference between the two skills (Table 2). Interestingly even though

225   Lnb was not different, the release characteristics that contributed to Lnb showed

226   significant differences and moderate effect sizes (Table 2). Specifically, the vertical

227   velocity of the mass centre at release was significantly lower during the Tkatchev, due

228   in part to the higher angle of release. The gymnasts' moments of inertia at release were

229   not significantly different in the Tkatchev. Which may explain the similarities in Lnb, due

230   to the fact that this is an the homogenous population, i.e. the gymnasts' body masses

231   were similar and hence the radial separation of the mass centre from the bar was also

232   consistent across the two skills (Table 2).

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234   *Functional Phases*

235   Significant differences and moderate effect sizes were observed between the Tkatchev

236   and Kovacs for the start and end positions of the shoulder and hip functional phases

237   (Table 3). The Tkatchev is characterised by earlier start and end positions compared to

238   the Kovacs, however similarities between both skills were observed for the change in

239   circle angle during the hip functional phase (Table 3, Figure 4).

240   ------------------------------------INSERT FIGURE 4 HERE---

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242   ------------------------------------INSERT TABLE 3 HERE--

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244   Shoulder flexion angles, at the start of the functional phase, were significantly greater

245   for the Tkatchev compared to the Kovacs, highlighting a more open shoulder position

246   when the Tkatchev skill is initiated (Table 4 and illustrated in Figure 2). The maximum

247   angular velocity of the shoulders was similar for both skills; however due to the post

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248   functional phase actions required in the Tkatchev, a more dynamic hip action was

249   observed with a significantly greater maximum angular velocity of the hips.

250   ------------------------------------INSERT TABLE 4 HERE--

251

252   *Angular Momentum*

253   The angular momentum profile shown in Figure 5 demonstrates an increase in angular

254   momentum about the mass centre (Lnc) as the performer descends from handstand. As

255   anticipated, the reversal of angular momentum begins early in the preparatory swing

256   and has a greater rate of change, thus allowing the gymnast to begin reversing his

257   angular momentum after 80% of the swing phase.

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259   --------------------------------------INSERT FIGURE 5 HERE--

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263   Due to the specific needs of the Tkatchev (reversing the angular momentum to allow the

264   gymnast to rotate forwards in flight) there is a clear polarity change in Lnc before the

265   release point. In order to facilitate this reversal of angular momentum the gymnast

266   performs extra hip and shoulder actions, which are reflected in the differences in the

267   functional phase characteristics (Table 4).

268

269 The peak normalised angular momentum about the mass centre is similar for the

270 Kovacs and Tkatchev (Lnc ≈ 1.4), but the Lnc reduction in the Kovacs is minimised to

271 ensure sufficient angular momentum at release to achieve the required backward

272 rotation in flight. Lnc for the Tkatchev changes from a peak of 1.4 to -0.5 at release,

273 enabling the gymnast to rotate forwards as he travels backwards over the bar.

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277 **Discussion**
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279 The aim of this study was to examine the differences in the biomechanics of functional

280 phases between the Tkatchev and Kovacs and to explain how the angular momentum

281 demands of these complex release and re-grasp skills are addressed. Employing

282 biomechanical analyses, understanding of how the performer achieves the technical

283 requirements of these skills, as outlined by the international governing body, has been

284 developed. In addition examining the similarities between the preceding giant swing

285 provides useful information for coaching and scientists about skill development and

286 training methodology.

287 The data were checked for accuracy and reliability and values concurrent with other

288 similar studies were found (Kerwin and Irwin, 2010). The authors advocate the use of

289 data collected at international competition to provide insight into performances, although

290 the number of trials is low, the performances have high ecological validity and as such

291 can ultimately underpin our understanding.

292   It is clear from a coaching and performance perspective that the technical requirements

293   of these skills (Tkatchev and Kovacs) are different. Previous research by Brüggemann

294   *et al.,* 1994 classified these two skills as Category I (in which the direction of the angular

295   momentum is maintained) and Category II (in which the direction of the angular

296   momentum is changed prior to release). These authors identified a need to understand

297   and explain the mechanical demands underpinning the individual requirements of the

298   movements. Gaining insight into the technical requirements of these skills, particularly

299   at release and during the preceding giant swing, will allow coaches and scientists to

300   better understand how gymnastics organise their body segments to achieve these skills

301   (Brüggemann *et al.,* 1994).

302   At release, differences were observed between these two skills for the majority of

303   release parameters (Table 2). The release parameters ensure the gymnast possesses

304   sufficient angular momentum to somersault as required by the particular skill and to

305   achieve a flight profile that guarantees a safe clearance and effective re-grasp of the bar

306   (Figure 3). The Kovacs released earlier and achieved a greater peak height compared

307   to the Tkatchevs highlighted in Table 2. These differences result in a different trajectory,

308   in flight, for each skill as highlighted in Figure 3. In comparison to the data presented

309   previously, for the Kovacs, (Arampatzis and Brüggemann, 1999) and the Tkatchev

310   (Arampatzis and Brüggemann, 2001), the current study reported similar horizontal

311   release velocities (Table 5). The angular momentum about the mass centre at release

312   was 19 and 27% higher in the current study for the Tkatchev and Kovacs, respectively

313   compared to the earlier data of Arampatzis and Brüggemann (1999, 2001), a finding

314   that may suggest a progressive evolution of these skills between 1994 and 2000 as the

315   straight body version become the more popular. However, normalized data were not

316   available and this should be considered in the interpretation of these findings, although

317   the difference in the height and mass of the subjects was less than 3% and 1%

318   respectively.

319   -------------------------------------INSERT TABLE 5 HERE---

320   The importance of the giant swing preceding the Tkatchev and Kovacs was highlighted

321   by the earlier work of Brüggemann et al. (1994). These authors identified changes in the

322   joint angular kinematics due to the direct relationship that these have on the production

323   of angular momentum about the bar and about the mass centre for the subsequent

324   aerial phase. Building on earlier research in which Irwin and Kerwin (2005, 2006)

325   introduced the term "*functional phase*s" to describe and explain the actions of the hips

326   and shoulders, observations from the current study highlight differences in the

327   orientation of the start and end points of the functional phases in the circle between the

328   two release and re-grasp skills. The functional phases of the Tkatchev start and finish

329   significantly earlier for the hips and shoulders (Figure 4, Table 3). The importance of this

330   finding rests with the development of these skills and the coach's understanding of the

331   location of the key functional phases in the circle and how this changes as a function of

332   the skill requirements. The reversal of angular momentum prior to release necessary for

333   the Tkatchev highlights the need for developmental drills and progressions to replicate

334   the spatial and temporal characteristics of these actions to allow the appropriate

335   bio-physical adaptations to occur in the most effective and safe fashion. With the

336   exception of the shoulder angle at the start of the Tkatchev, joint angles at the start and

337   end of these phases were generally similar between these two skills. These findings

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338 concur with the classic training principle of specificity and overload and point towards

339 the existence of a skill specific giant swing that may be taught in parallel, rather than in

340 series which is the current practice, which may facilitate a more effective skill

341 development programme.

342 **Conclusion**

343 The difference between the technical requirements of these skills is diverse and is

344 clearly evident due to the opposite polarity of the angular momentum at release.

345 However, with this in mind, the current study has highlighted that these complex skills

346 share a similar joint angular kinematic requirement during the functional phases,

347 although the orientation of these phases shift as a function of the type of skill. The

348 Tkatchevs functional phases started earlier and finished earlier compared to the

349 Kovacs. This information may lead to the development of skill specific giant swings that

350 can be used to elicit the specific requirements of these skills. The outcome of this would

351 be a more effective and safe training environment.

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410   **Acknowledgements**

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412 **Tables**

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

n	TUCK KOVACS 4	STRAIGHT KOVACS 4	df	p	ES
θc	375.50	364.50	8	P>0.05 0.09	0.58
sd	5.07	9.81			
vCy	-1.64	-1.64	8	P>0.05 1.00	0.00
sd	0.25	0.08			
vCz	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			

415 θc = angle of release (˚). vCy and vCz = velocity of the mass centre horizontally and vertically (m/s). Ln = normalised angular
416 momentum about the mass centre (c) and bar (b) (SS/s). tFlight = flight time (s). ωc = angular velocity about the mass centre
417 (rad/s). Icm = moment of inertia about the mass centre (kgm^2), Incm = normalised moment of inertia.
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439
440 **Table 2.** Average (±sd) release characteristics for the Tkatchev and Kovacs

n	TKATCHEV 10	KOVACS 8	p	ES
θc	406.30	370.00	P<0.01	0.91
sd	6.72	9.32		
vCy	-1.78	-1.64	P>0.01	0.27
sd	0.31	0.17	0.27	
vCz	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	

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442 θc = angle of release (˚). vCy and vCz = velocity of the mass centre horizontally and vertically (m/s). Ln = normalised angular
443 momentum about the mass centre (c) and bar (b) (SS/s). tFlight = flight time (s). ωc = angular velocity about the mass centre
444 (rad/s). Icm = moment of inertia about the mass centre (kgm^2), Incm = normalised moment of inertia.
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457 **Table 3.** Average (±s) Circle angle (θc) for the start (s) and end (e) of the functional phases for
458 the hips (H) and shoulders (S) during the Tkatchev and Kovacs
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	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		

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461 **θ = angle (degrees)**
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499 **Table 4** Average (±sd) joint kinematics at the start (s) and end (e) of the functional phases for
500 the hips (H) and shoulders (S) during the Tkatchev and Kovacs
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	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	

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503 **θ = angle (degrees)/ ω = angular velocity (Rad/s)**
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506 **Table 5.** Comparison of selected release characteristics (mean ±sd) from the current study and

507 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

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

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

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

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

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

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

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