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- This article was published in the journal, Sports Biomechanics [© Taylor & Francis] and the definitive version is available at: http://dx.doi.org/10.1080/14763140701324511

Metadata Record: https://dspace.lboro.ac.uk/2134/6090

Version: Accepted for publication

Publisher: © Taylor & Francis

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Consistency of performance in the Tkatchev release and re-grasp on high bar

Michael J. Hiley¹, Maurice R. Yeadon¹ and Emma Buxton²

¹School of Sport and Exercise Sciences, Loughborough University, Loughborough, UK
²HumanSciences, St. Mary’s University College, Twickenham, UK

Abstract
The Tkatchev on the high bar is a release and re-grasp skill in which the gymnast rotates in a direction during flight opposite to that of the preceding swing. Since the release window is defined as the time during which the gymnast has appropriate linear and angular momentum to ensure the bar can be re-grasped, it was speculated that the release windows for this skill would be smaller than for dismounts which are less constrained. One senior male gymnast competing at national level performed 60 Tkatchev trials. A four-segment planar simulation model of the gymnast and high bar was used to determine the release windows in 10 successful and 10 unsuccessful performances of the Tkatchev recorded using a Vicon motion analysis system. Model parameters were optimised to obtain a close match between simulations and recorded performances in terms of rotation angle (1°), bar displacements (0.01 m) and release velocities (1%). Each matched simulation was used to determine the time window around the actual point of release for which the model had appropriate release parameters to complete the Tkatchev successfully. The release windows for the successful trials were small compared to those of dismounts. The unsuccessful trials were associated with later release and later timing of the actions at the shoulders and hips.

Keywords: angular momentum, gymnastics, release window, simulation, Tkatchev

Introduction
The Tkatchev release and re-grasp skill is performed on the high bar and asymmetric bars in men’s and women’s artistic gymnastics, respectively. The skill requires the gymnast to rotate during flight in a direction opposite to that of the preceding swing. From a backward giant circle the gymnast releases with the mass centre above the bar, rotates forwards with the legs straddled, re-grasps with the mass centre above the bar (Figure 1) and continues to circle the bar in the backwards direction. In addition to changing the direction of rotation the gymnast must release the bar with sufficient horizontal and vertical velocity to travel backwards safely over the bar (Figure 1).

![Figure 1. The Tkatchev release and re-grasp skill performed on the high bar.](image)
A number of studies have looked at the Tkatchev release and re-grasp skill, ranging from mechanical descriptors of the preceding giant swing (Gervais and Tally, 1993), through detailed descriptions of how the energy within the gymnast / high bar system changes (Arampatizs and Brüggemann, 2001), to implementing corrective measures for unsuccessful performances (Holvoet et al., 2002). Although the general technique prior to releasing the bar is characterised by a closing of the shoulder and hip angles followed by an immediate opening of these angles (Figure 1), little has been reported regarding the sequencing of these actions at the individual joints.

Hiley and Yeadon (2003a, 2005) used a computer simulation model of the gymnast and bar to investigate release windows when dismounting the bar in men’s and women’s artistic gymnastics. The release window was defined as the time during which the gymnast has appropriate linear and angular momentum for performing the dismount. If the gymnast releases at any point during this window he/she will have sufficient angular momentum and flight to complete the dismount. The release windows for male and female gymnasts performing double layout somersault dismounts at the Sydney 2000 Olympic Games were calculated to be, on average, 114 ms and 69 ms, respectively. It is speculated that the release window for the Tkatchev skill will be smaller than those for the dismounts, since a successful Tkatchev requires the gymnast to re-grasp the bar. This places tighter constraints on the acceptable linear momentum possessed by the gymnast at release. For example, successful dismounts from the Olympic high bar final landed within a horizontal range of approximately 1.5 m to 3.0 m from the bar. Such a large range would not be possible for the Tkatchev.

One of the limitations of the studies by Hiley and Yeadon (2003a, 2005) was that the release windows were only calculated for single trials by individual performers. It could not be determined whether the release windows were consistent for a given gymnast. It was speculated that those gymnasts with a large release window would be able to land their dismounts more consistently over a number of trials since timing of the release would be less critical compared with a gymnast with a small release window. Holvoet et al. (2002) used a simulation model to demonstrate that an unsuccessful Tkatchev could have been caught if the gymnast had released earlier than in the actual performance. This suggests that even though a release window existed, the gymnast had released the bar outside this window. One possible explanation is that the release window for this gymnast was small, making consistent performance more difficult.

The aim of the present study was to determine the release windows for a male gymnast performing multiple successful and unsuccessful trials of the Tkatchev release and re-grasp skill. An additional aim was to determine whether the technique in the giant circle leading up to release differed between successful and unsuccessful trials.

Methods

Subsections in Methods follow the protocol used to determine the release windows for a male gymnast performing multiple trials of the Tkatchev release and re-grasp skill. Initially data collection was carried out in which performances were captured using a three-dimensional motion capture system and the data were processed for subsequent use with computer simulation models. The models were then used to
obtain matching simulations of the actual performances which were in turn used to determine the release windows.

Data collection

One senior male gymnast competing at national level (mass = 64 kg, height 1.63 m) performed 60 Tkatchev trials, over two days, with 10 successful and 10 unsuccessful attempts chosen for further investigation. The 10 successful trials were selected for analysis along with 10 unsuccessful trials that narrowly missed re-grasping the bar. All trials were captured using nine Vicon M2 cameras operating at 100 Hz. Spherical reflective markers of 25 mm diameter were attached to the lateral side of the wrist, elbow, shoulder, hip, knee and ankle joint centres and toes on each side of the body. Offset measurements from each marker centre to the adjacent joint centre were recorded for subsequent location of the joint centres. Additional markers were attached to each side of the gymnast's head (above the ear) and to the centre of the high bar. Prior to data collection a volume centred on the high bar spanning 2 m x 5 m x 5 m was wand calibrated using the Vicon motion analysis system. Three-dimensional marker coordinates were reconstructed and joint centres were calculated using the measured offsets from which arm orientation and joint configuration angles were calculated (Yeadon, 1990a). Arm orientation angles and joint angles for the left and right sides of the body were averaged to produce input for a planar computer simulation model of swinging on high bar. Quintic splines (Wood and Jennings, 1979) were used to fit the orientation and joint angle time histories so that derivatives could be obtained (Yeadon, 1990a).

A set of 95 anthropometric measurements were taken on the gymnast and inertia parameters were calculated using the model of Yeadon (1990b). The angular momentum about the mass centre during the flight phase was calculated for each trial and was normalised for moment of inertia and flight time to give a value in straight somersault units (Yeadon, 1990c). The horizontal and vertical displacements of the mass centre during flight were used to calculate the horizontal and vertical velocities at release using a least squares fit and assuming constant acceleration. For the unsuccessful trials the time of flight was calculated from the time of release until the wrists passed the level of the high bar.

Simulation model

A four-segment planar model of a gymnast comprising arm, torso, thigh and lower leg segments was used to simulate the swinging movement around the bar (Hiley and Yeadon, 2003b). The high bar and the gymnast's shoulder structure were modelled as damped linear springs (Figure 2). The shoulder spring represented the stretch at the shoulder and the extension of the spine that occurs during a giant circle. The movement of the shoulder (gleno-humeral) joint centre due to scapular rotation was represented by allowing the torso length to vary as a function of shoulder (arm elevation) angle \( \alpha \) (Figure 2).

As it is not uncommon for gymnasts to initiate the straddle action before releasing the bar, the simulation software was modified to vary the inertia parameters of the leg segments as a function of thigh abduction angle.
Input to the simulation model comprised the segmental inertia parameters, the stiffness and damping coefficients of the bar and shoulder springs, the initial displacement and velocity of the bar, the initial orientation and angular velocity of the arm, and the joint angle time histories in the form of quintic splines obtained from the data collection. Output from the model comprised the time histories of the horizontal and vertical bar displacements, the linear and angular momentum of the model and the rotation angle $\phi$ (the angle from the vertical of the line joining the neutral bar position to the mass centre).

The equations of motion were derived using Newton’s Second Law and by taking moments about the neutral bar position and the segment mass centres. The angular momentum of the body about its mass centre was calculated as:

$$ h = \sum_{i=1}^{4} \left( I_i \dot{\phi}_i + m_i (Z_i X_i - X_i Z_i) \right) $$

where $X_i = (x_i - x_{cm})$, $Z_i = (z_i - z_{cm})$, $(x_{cm}, z_{cm})$ = whole body mass centre location, $m_i$ = segmental mass, $I_i$ = segmental moment of inertia, $\phi_i$ = segmental angular velocity.

The angular momentum at release was normalised by dividing by $2\pi$ times the moment of inertia of the body about its mass centre when straight. Division by $2\pi$ converts radians into revolutions (somersaults). The normalisation expresses the angular momentum in terms of the number of straight somersaults the gymnast could perform in one second. The time of flight of a simulation was calculated from the release and re-grasping heights of the model mass centre and the vertical velocity of the mass centre at release using the equation for constant acceleration under gravity. The height of the mass centre on re-grasping was taken from the motion analysis of each trial: for the unsuccessful trials the time of “re-grasp” was taken to be when the wrists passed through bar height.

The Student’s t test was used to identify significant differences between the successful and unsuccessful trials in terms of variables at release comprising: rotation angle, mass centre height, horizontal and vertical velocity, and angular momentum about the mass centre.

Matching Simulations
In order to determine the release window of a trial using the simulation model, a close match between simulated and recorded performance was required. The simulation model was implemented with the Simulated Annealing optimisation algorithm (Goffe et al., 1994) to minimise the difference between the recorded and simulated performance. The cost function $F$ defining this difference was:

$$ F = \phi + 160(x_b + z_b) + 80h + 10(\dot{x}_{cm} + \dot{z}_{cm}) + 0.25\phi_0 $$

Figure 2. The four-segment gymnast / high bar simulation model with damped springs representing bar and shoulder elasticity ($\alpha$ and $\beta$ are the shoulder and hip angles, respectively).
where $\phi = \text{root mean squared (rms) difference in degrees between recorded and simulated rotation angle}$, $x_b$, $z_b = \text{the rms differences between recorded and simulated bar displacements}$, $h = \text{absolute difference in normalised angular momentum at release between simulation and actual performance}$, $\dot{x}_{cm}$, $\dot{z}_{cm} = \text{absolute differences in linear velocity at release between simulation and actual performance}$, $\phi_o = \text{absolute difference in initial rotation angle between simulation and actual performance}$. The weightings of the cost function $F$ shown in equation (2) were chosen so that each of the seven components made approximately equal contributions since they were considered to be of equal importance.

Since the aim of the matching process was to provide close agreement between the simulation and the actual performance leading up to release only the last 180° of the final giant circle was simulated. The subject-specific inertia parameters calculated were used in the simulation model. The initial conditions, including the initial angle, angular velocity and bar displacements, for each simulation were taken from the corresponding trial. During the optimisation the following parameters were allowed to vary in order to improve the match between the recorded and simulated performance. The vertical bar stiffness was allowed to vary between 20,000 N/m and 27,500 N/m to conform with the specifications of the International Gymnastics Federation (FIG, 2000). The horizontal bar stiffness was allowed to vary between 16,000 N/m and 27,500 N/m since it has been shown that the bar can be less stiff in this direction (Kerwin and Hiley, 2003). The damping coefficient of the bar was allowed to vary between 0 N·m/s and 250 N·s/m. The stiffness and damping coefficients of the shoulder spring were allowed to vary over wider ranges than those of the bar springs, between 0 N/m and 60,000 N/m and 0 Nm/s and 25,000 N·s/m, respectively, since there was less information available regarding these parameters. The masses of the arms and legs were allowed to vary independently by ± 5%, since density values were taken from the literature, and the torso mass was adjusted to maintain whole body mass. The torso length parameter was allowed to vary between 0 and 0.15 m. In addition small variations in the initial conditions, rotation angle and angular velocity were permitted to compensate for any errors propagated in their calculation.

**Release Windows**

Once the optimisation procedure had provided a simulation that matched the recorded performance of the final 180° of rotation leading up to the release, the matching simulation for each trial was continued beyond the point of release so that a release window could be determined. It was assumed that the model maintained contact with the high bar and continued with the same joint angle changes that occurred after the actual release. The release window was defined as the period of time for which the model possessed appropriate linear and angular momentum for re-grasping the bar. The normalised angular momentum was required to be within the range of actual successful release values ± 10% of that range. In order for the gymnast to be within successful re-grasping distance of the bar the vertical position of the mass centre was required to be within the range of the actual re-grasp heights ± 10% of that range (0.26 m – 0.42 m above the bar). When the mass centre was in this vertical “zone” it was required to be within the horizontal range of actual re-grasp distances ± 10% of that range (0.45 m - 0.73 m). So long as a simulation satisfied the above constraints, it was considered to lie within the release window.
Results

The information from the motion capture analysis was used to give the following results. The reconstruction error for the calibration of the motion capture system was calculated to be less than 0.003 m for a volume spanning approximately 2 m x 5 m x 5 m. The values for the normalised angular momentum and the horizontal and vertical velocity at release for the successful and unsuccessful trials are shown in Table 1.

The subject released the bar later in the giant circle in the unsuccessful trials as indicated by the rotation angle (p = 0.0002) and the height of the mass centre (p = 0.007) at release (Table 1). As expected with a later release, the unsuccessful trials had greater horizontal velocity (p = 0.0001) and smaller vertical velocity (p = 0.013) at release. However the angular momentum at release was not significantly different (p = 0.13) between the successful and unsuccessful trials (Table 1).

<table>
<thead>
<tr>
<th>trial (no.)</th>
<th>rotation angle (°)</th>
<th>mass centre height (m)</th>
<th>horizontal velocity (m/s)</th>
<th>vertical velocity (m/s)</th>
<th>angular momentum (straight somersaults) release window (ms)</th>
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<td>mean</td>
<td>305 ± 3</td>
<td>3.15 ± 0.04</td>
<td>-2.06 ± 0.14</td>
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<td>0.44 ± 0.02</td>
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<td></td>
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</tr>
<tr>
<td>mean</td>
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<td>-2.35 ± 0.06</td>
<td>2.82 ± 0.16</td>
<td>0.43 ± 0.02</td>
</tr>
</tbody>
</table>
Over the 20 performances studied, the simulation model was able to match the recorded rotation angle during the final 180° leading up to release to within 1° rms difference, and the horizontal and vertical displacements of the bar to within 0.01 m rms difference (Figure 3). The simulation model matched the normalised angular momentum and the linear velocities at release to less than 1%. For the 20 performances the mean stiffness coefficient (vertical and horizontal combined) of the bar obtained in the matching procedure was 21,868 N/m, which lay within the limits as set out by the FIG (2000). It was found that on average the bar was 15% less stiff in the horizontal direction. The average damping coefficient for the bar was 83 N·m/s. The average torso length parameter and the average stiffness and damping coefficients of the spring at the shoulder were 0.10 m and 32,899 N/m and 20,776 N·s/m, respectively.

![Rotation angle and displacement graphs](image)

Figure 3. Typical matches between simulation (solid line) and actual performance (circles) for (a) whole body rotation angle and (b) net bar displacement during the last 180° of the giant swing.

The release windows determined by simulation for the 10 successful and unsuccessful trials are presented in Table 1. The mean release window for the successful trials was 29 ms (range 9 - 74 ms) whereas the mean window for the unsuccessful trials was 3 ms (range 0 – 12 ms).

The variation in joint angle time histories at the shoulder and hip joints used in the successful and unsuccessful trials are shown in Figure 4. The mean shoulder angle in the unsuccessful trials (149°) was significantly smaller (p = 0.018) than the mean of the successful trials (155°) when compared at the average release angle of the successful trials. Similarly the mean hip angle for the unsuccessful trials (202°) was smaller (p = 0.001) than the mean of the successful trials (210°).

![Joint angle graphs](image)

Figure 4. The range of (a) shoulder and (b) hip joint angle time histories for successful (solid line) and unsuccessful (dashed line) Tkatchevs over the last 180° of the giant circle leading up to release.
Discussion

Computer simulation is a powerful tool for investigating technique in sports movements. Before simulation can be used for this purpose it is essential that the ability of the model to closely match an actual performance is investigated. In this study the simulation model was able to match the linear and angular momentum of 20 giant circles to within 1% and the whole body rotation and bar displacements with similar accuracy (1° and 0.01 m). To determine the release window for a gymnast requires knowledge of what would have happened had the bar been released later than in the actual performance. Using a computer simulation model provided a means for investigating this hypothetical scenario. This approach is limited by the assumption of configuration changes when releasing later than in the actual performance and also by the somewhat arbitrary criteria for a successful re-grasp. Although altering the criteria may lead to small changes in the size of the release windows, it is likely that similar changes would occur across all trials and so the findings would not change.

The release parameters of the successful Tkatchevs (Table 1) were similar to results from the literature. Brüggemann et al. (1994) found mean rotation angles and centre of mass velocities (horizontal and vertical) at release of 313°, -2.07 m/s and 3.05 m/s, respectively. Similarly Arampatzis and Brüggemann (2001) obtained horizontal and vertical mass centre release velocities of -1.97 m/s and 3.06 m/s for 20 Tkatchevs and Gervais and Tally (1993) reported rotation angles and centre of mass heights at release of 312° and 3.12 m, respectively, for seven Tkatchevs. The successful trials appear to have released somewhat earlier than those from the literature (305° compared with 312° and 313°) although identifying the moment of release visually can lead to a late estimate as discussed by Kerwin et al. (1993). Since the angular momentum presented in papers on the Tkatchev was not normalised it is difficult to compare the results directly with the present study.

It was found that in the unsuccessful Tkatchevs the gymnast released the bar later in the giant circle and at release the horizontal velocity of the mass centre was greater and the vertical velocity was smaller than in the successful trials. This was expected as it is consistent with the simple model of tangential release and explains why the gymnast was unable to re-grasp, due to excessive horizontal travel in flight.

The release windows obtained for the successful trials were small compared with those obtained for dismounts (Hiley and Yeadon, 2003a, 2005). Not only were the release windows small, they were also inconsistent (Table 1). This may explain why the gymnast only successfully re-grasped the bar in 10 out of 60 trials. It might be expected that a gymnast who is able to re-grasp the bar every time, would not only have larger release windows but would be able to reproduce these larger windows each time. This could only be established by determining the release windows for a gymnast who is more accomplished at the Tkatchev than the subject used in the present study.

Holvoet et al. (2002) showed that an unsuccessful Tkatchev could have been successfully caught had the gymnast released the bar earlier in the giant circle. This suggests that the gymnast had merely released outside the release window. However, in the present study the unsuccessful Tkatchevs had very small or no release windows at all (Table 1). If the gymnast had released earlier he would still have been unsuccessful. This may be explained by looking at the joint angle time histories in the preceding giant circle (Figure 4). It can be seen that the gymnast's
technique incorporates the characteristic closing of the shoulder and hip angles (angles decrease) followed by an immediate opening of these angles (angles increase) prior to release. The opening of the hip angle is initiated before the opening of the shoulder angle but continues through the point of release as does the shoulder angle. In the case of the unsuccessful Tkachevs, not only does release occur later in the giant circle than in the successful trials, but the opening of the hip and shoulder occurs later (Figure 4). By the time the gymnast has produced sufficient angular momentum to complete the Tkachev he no longer has the appropriate linear momentum to ensure he can re-grasp the bar. If the gymnast were to release the bar earlier in the unsuccessful trials he would not have had sufficient angular momentum to complete the Tkachev. It appears that producing sufficient angular momentum is the primary concern of the gymnast and explains why the gymnast achieves similar amounts of angular momentum at release for both the successful and unsuccessful trials. In order for the gymnast to turn an unsuccessful Tkachev into a successful Tkachev he would not only have to release the bar earlier, but perform the actions at the shoulder and hip joints earlier as well.

The release windows found in the present study were relatively small and inconsistent. It is speculated that a gymnast proficient at performing the Tkachev release and re-grasp skill successfully each time would have larger and more consistent release windows. This should form the next step of the study. However, the present study has given an insight into the technique used in the Tka�heв. It was found that the opening of the hip angle was initiated before the opening of the shoulder angle and that both continued to open through the point of release. It was found that the unsuccessful trials were associated with a later release and a later opening of the shoulder and hip angles. To determine how the gymnast’s technique should be altered to increase the size of the release window and the consistency of performance will require further investigation using the computer simulation model.

References