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Optimisation of backward giant circle technique on the asymmetric bars

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Abstract
The release window for a given dismount from the asymmetric bars is the period of time within which release results in a successful dismount. Larger release windows are likely to be associated with more consistent performance since they allow a greater margin for error in timing the release. A computer simulation model was used to investigate optimum technique for maximising release windows in asymmetric bars dismounts. The model comprised four rigid segments with the elastic properties of the gymnast and bar modelled using damped linear springs. Model parameters were optimised to obtain a close match between simulated and actual performances of three gymnasts in terms of rotation angle (1.5°), bar displacement (0.014 m) and release velocities (< 1%). Three optimisations to maximise the release window were carried out for each gymnast involving no perturbations, 10 ms perturbations and 20 ms perturbations in the timing of the shoulder and hip joint movements prior to release. It was found that the optimisations robust to 20 ms perturbations produced release windows similar to those of the actual performances whereas the windows for the unperturbed optimisations were up to twice as large. It is concluded that robustness considerations must be included in optimisation studies in order to obtain realistic results and that elite performances are likely to be robust to timing perturbations of the order of 20 ms.

Keywords: gymnastics, simulation, release window, angular momentum

Introduction
Backward giant circles on the asymmetric bars (a-bars) in Women’s Artistic Gymnastics are used to generate the necessary angular momentum and flight for both release / re-grasp skills and dismounts. This is also true for male gymnasts competing on the high bar. A common dismount performed by both groups of gymnasts is the double somersault in the layout position (Figure 1). The most striking difference between the techniques used in the backward giant circles of male and female gymnasts is the female gymnast’s need to avoid the lower bar (Figure 1). The gymnast can either straddle the legs to avoid the lower bar or increase the angle of hip flexion (Witten et al., 1996).

It has been shown that female gymnasts use less (normalised) angular momentum than their male counterparts to perform a double layout somersault dismount (Arampatzis and Brüggemann, 1999; Hiley and Yeadon, 2005a). On average the male gymnasts from the 2000 Olympic high bar final had sufficient angular momentum to perform 1.65 straight somersaults during flight (Hiley and Yeadon, 2003a) compared to 1.52 straight somersaults for the female gymnasts (Hiley and Yeadon, 2005a). From the graphics sequences in Figure 1 it is to be expected that a female gymnast uses less normalised angular momentum than her male counterpart since a hyper-extended configuration is usually adopted in flight. However, as the complexity of female dismounts increases more somersault angular momentum will be required, since the addition of twists requires the gymnast to be straight for a longer period of the flight.
Hiley and Yeadon (2005a) calculated the margin for error when timing the release in terms of the release window during which time the gymnast has suitable linear and angular momentum for performing the double layout dismount from the a-bars. If the gymnast releases at any point within this window she will have sufficient angular momentum and flight time to complete the dismount. The margin for error is defined as half the release window time. For consistency of performance it is necessary that the margin for error in timing the release is large enough to encompass the timing precision of a gymnast. By definition there are consequences of failing to release the bar within the release window: early and late releases result in unacceptable and in some cases dangerous performances (Sands et al., 2004). The release windows for the female gymnasts from the 2000 Olympics averaged 69 ms (Hiley and Yeadon, 2005a) and were generally smaller than those of the male gymnasts which averaged 114 ms (Hiley and Yeadon, 2003a). It is to be expected that gymnasts with larger margins for error are able to land their dismounts more consistently and consequently a large release window is desirable. Hiley and Yeadon (2005a) speculated that female gymnasts may be able to produce larger release windows if they could achieve more hip hyper-extension in the giant circle. This would produce a technique similar to the male gymnasts although it
was not clear whether such hyper-extension would be possible due to the constraint of the lower bar.

Hiley and Yeadon (2005b) optimised the backward giant circle technique for male gymnasts on the high bar in order to produce a maximal dismount. Using this approach they were able to develop a new dismount that had not been performed in major competition. Although the dismount was shown to be possible in terms of the gymnast’s ability to generate sufficient angular momentum whilst maintaining a sufficiently large release window there was no indication of the sensitivity of the technique to errors in timing the hip and shoulder joint movements during the giant circle. A technique that requires precise timing to produce a large release window is of little use unless a reasonable release window is obtained when the gymnast makes small deviations from this optimal performance. In other words for consistent performance, technique needs to be robust to small perturbations in timing.

The aim of this study was to determine whether the technique in the backward giant circle prior to dismount of female gymnasts at the Sydney 2000 Olympic Games could be improved in terms of generating more angular momentum and producing larger release windows for double layout dismounts. It was also the aim to determine the effect of requiring the optimised technique of the backward giant circle technique to be robust to perturbations in the timing of joint angle changes.

**Methods**

Subsections in Methods describe the protocol used to optimise the backward giant circle technique for female gymnasts. A simulation model was used to obtain matching simulations of the actual performances in order to obtain joint angle time histories that could be manipulated during the optimisations of a gymnast’s technique.

The backward giant circles from three double layout dismount performances from the Sydney 2000 Olympic games were chosen for investigation. The method for calculating the release windows for these performances is described in Hiley and Yeadon (2005a). The performances were chosen as they represented a (A) small, (B) average and (C) large release window. A set of anthropometric measurements of a "mean" elite female gymnast was obtained as the mean measurements taken from eight Romanian international gymnasts. These mean values were then scaled to each of the three competitors using segment lengths and widths obtained from video digitisation (Hiley and Yeadon, 2005a) and inertia parameters were calculated using the model of Yeadon (1990).

**Simulation Model**

A four segment planar model of a gymnast comprising arm, torso, thigh and lower leg segments was used to simulate the movement around the bar (Hiley and Yeadon, 2003b). The upper bar and the gymnast's shoulder structure were modelled as damped linear springs (Figure 2). The spring at the shoulder represented the increase in length of the gymnast between the wrist and the hip (i.e. not just the stretch at the shoulder joint). In addition to the shoulder spring, there was a parameter that governed the extent to which the torso segment lengthened (representing scapular rotation) as the shoulder elevation angle increased.
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 angular velocity of the arm, the initial orientation of the arm and the joint angle time histories in the form of stepwise quintic functions. In changing a joint angle $\theta$, from $\theta_1$ to $\theta_2$ between times $t_1$ and $t_2$, the time history was given by:

$$\theta(t) = \theta_1 + (\theta_2 - \theta_1)q(x)$$

where $x = (t - t_1)/(t_2 - t_1)$ and $q(x) = x^3(6x^2 - 15x + 10)$. It should be noted that $q(x)$ is a quintic function with the properties $\dot{q}(0) = \ddot{q}(0) = \dddot{q}(0) = 0$ so that angle changes are effected with zero velocity and acceleration at the endpoints. The joint angle time histories at the hip and shoulder were defined by consecutive quintic functions allowing the joints to close, open and close again before release. 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 upward vertical to the line joining the neutral bar position and 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 (Hiley and Yeadon, 2003b). The angular momentum of the body about its mass centre at release was normalised by dividing by $2\pi$ times the moment of inertia of the body about its mass centre when straight and multiplying by the flight time to give the equivalent number of straight somersaults in the flight phase. The time of flight of a simulation was calculated from the release and landing heights of the mass centre and the vertical velocity at release using the equation for constant acceleration under gravity.

Matching Simulations

In order to manipulate the technique of the gymnasts using the simulation model a close match between the simulated and recorded performances was required. The simulation model was implemented with the Simulated Annealing optimisation algorithm (Goffe et al., 1994). A cost function $F$ was established to measure the difference between the recorded performance and a simulation of this performance as defined in equation (2):

$$F = \phi + \alpha + \beta + 80(x_b + z_b) + 20(h + \dot{x}_{cm} + \dot{z}_{cm}) + 5\phi_0$$

where $\phi =$ root mean squared (rms) difference in degrees between recorded and simulated rotation angle, $\alpha, \beta =$ rms differences in degrees between the recorded joint angle time histories at the hip and shoulder and the consecutive quintic functions used to drive the model, $x_b, z_b =$ the rms differences between recorded and simulated bar displacements, $h =$ absolute difference in normalised angular momentum at release between simulation and actual performance, $\dot{x}_{cm}, \dot{z}_{cm} =$ absolute differences in linear
velocity at release between simulation and actual performance, \( \phi_0 = \text{absolute difference in initial rotation angle between simulation and actual performance} \). The method for obtaining the data from the actual performances is detailed in Hiley and Yeadon (2005a). The weightings of the cost function \( F \) shown in equation (2) were chosen so that each of the seven components made approximately equal contributions in a matching simulation since they were considered to be of equal importance.

The aim of the matching process was to provide close agreement between the simulation and the actual performance and to provide joint angle time histories in the form of quintic functions (equation 1) which could subsequently be manipulated to optimise the gymnast’s technique. The final giant circle before release starting from approximately 30° past the handstand (above the bar) up to release was simulated. This starting angle was chosen to ensure that all grip changes with turn had been completed. The subject-specific inertia parameters calculated for each gymnast 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 video analysis. 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 and damping coefficients, the stiffness and damping coefficients of the shoulder spring, the masses of the arms and legs, the shoulder elevation parameter and the initial conditions (as described in Hiley and Yeadon, 2005a). The size and duration of the joint movements performed at the hip and shoulder were initially estimated from the video analysis. The joint angles were allowed to vary by up to ± 1.0 radians and the times were allowed to vary by up to ± 0.2 s in order to obtain a close match with the recorded angles.

Optimisation

A number of optimisations were performed. Initially the matched joint angle time histories were manipulated in order to maximise the release window given the normalised angular momentum at release from the actual performances. In order to obtain a solution which was close to the gymnast’s technique the timings were allowed to vary by ± 0.05 s and the angles by ± 0.1 radians for each gymnast. To investigate the effect of a requirement for robustness on optimal technique, the timings of the shoulder and hip joint movements were perturbed by 10 ms for each gymnast. For each step of this second set of optimisations five different perturbation combinations were used: no perturbation, shoulder and hip perturbed together both early and late, shoulder early with hip late, and shoulder late with hip early. The score returned to the optimisation routine was the smallest release window obtained from the five simulations. This procedure was repeated for 20 ms perturbations for each gymnast in a third set of optimisations.

The final three optimisations were carried out on gymnast A who had the smallest release window and were used to maximise the release window with increased angular momentum. The normalised angular momentum at release was increased from the actual performance value (1.52 straight somersaults) to the average obtained from the male gymnasts in the high bar final (1.65 straight somersaults). An optimisation was performed to maximise the release window with the increased angular momentum, then a further two optimisations were carried out in which the optimised technique was required to be robust to 10 ms and 20 ms perturbations, respectively. In both of these optimisations the timings and the angles were allowed to vary further from the gymnast’s original technique (± 0.075 s and ± 0.35 radians). A simulation model of
aerial movement (Yeadon et al., 1990) was used to determine the improvements in the flight phase based on the increased angular momentum at release.

In all of the optimisations to maximise release windows, joint angle time histories were constrained by joint torque limits. The joint torque limits were determined by measuring joint torques during eccentric-concentric trials using an isovelocity dynamometer for a male National Team gymnast and fitting a function which expressed maximum voluntary torque in terms of joint angle and angular velocity (King and Yeadon, 2002). From the matching simulations it was found that the female gymnasts worked within these peak joint torques. In order to maintain solutions that required similar amounts of effort to that of each gymnast’s current technique, the joint torque functions were scaled based on the maximum percentage of the male peak joint torque used in the matching simulation. If a joint torque produced by the simulation model exceeded the peak value, the simulation was given a penalty. In addition joint angle time histories which resulted in the gymnast contacting the lower bar were given a score of zero.

In each release window optimisation, the Simulated Annealing algorithm (Goffe et al., 1994) was used to manipulate the parameters which defined the joint angle time histories of the hip and shoulder joints. The simulations performed during the optimisations were started with the mass centre of the model approximately 30° past the vertical (rotation angle of 0°). Each simulation was started using the initial angular momentum about the mass centre obtained from video analysis (Hiley and Yeadon, 2005a). For simplicity the model kept the knee joint fully extended throughout. The release window was defined as the period of time for which the model possessed ± 10% of the specified normalised angular momentum, landed with the mass centre between 1.0 m and 3.0 m from the bar and had a time of flight at least 90% of the actual flight time. The limits placed on the distance travelled by the mass centre were obtained from the mean landing distances of the nine a-bar performances analysed from the Sydney Olympics (Hiley and Yeadon, 2005a), allowing two standard deviations on either side.

Results
Over the three performances the matching simulations were able to match the recorded rotation angle to within 1.5° rms difference (Figure 3a) and the horizontal and vertical displacements of the bar to within 0.014 m rms difference (Figure 3b). The simulations matched the normalised angular momentum and the linear velocities at release to within 1%. For the three performances the mean stiffness coefficient (vertical and horizontal combined) of the bar obtained in the matching procedure was 14160 N.m⁻¹, which lay within the limits as set out by the FIG (2000). There was less than 9% difference in bar stiffness coefficients obtained from the three performances. It was found that on average the bar was 10% less stiff in the horizontal direction. The average damping coefficient for the bar was 91 N.m.s⁻¹. The average lengthening of the torso parameter and the average stiffness and damping of the spring at the shoulder were 0.012 m, 24386 N.m⁻¹ and 3957 N.s.m⁻¹, respectively. The average stretch in the gymnasts from the actual performances and the matched simulations was 0.09 m and 0.08 m, respectively. The matches between the measured joint angle time histories from the video analysis and those determined using the quintic functions were close with an average rms difference of less than 2.1° (Figure 3c).
Figure 3. Typical matches between simulation (solid line) and actual performance (circles/crosses) for (a) whole body rotation angle (b) net bar displacement and (c) joint angle time histories of the hip and shoulder.
Table 1 shows the peak joint torques obtained during the matched simulations. Also presented in Table 1 are the peak joint torques expressed as a percentage of the peak joint torque estimated from the elite male gymnast torque – angular velocity functions.

Table 1. Peak joint torques in the matching simulations

<table>
<thead>
<tr>
<th>gymnast</th>
<th>peak shoulder torque (Nm)</th>
<th>% male peak shoulder torque</th>
<th>peak hip torque (Nm)</th>
<th>% male peak hip torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65</td>
<td>59</td>
<td>69</td>
<td>51</td>
</tr>
<tr>
<td>B</td>
<td>121</td>
<td>75</td>
<td>105</td>
<td>81</td>
</tr>
<tr>
<td>C</td>
<td>87</td>
<td>45</td>
<td>48</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 2. Release windows: actual and maximised

<table>
<thead>
<tr>
<th>gymnast</th>
<th>release windows (ms)</th>
<th>actual performance</th>
<th>maximised</th>
<th>robust to 10 ms</th>
<th>robust to 20 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>58</td>
<td>118</td>
<td>84 - 93</td>
<td>43 - 77</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>69</td>
<td>141</td>
<td>104 - 117</td>
<td>56 - 84</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>76</td>
<td>105</td>
<td>94 - 99</td>
<td>81 - 94</td>
<td></td>
</tr>
</tbody>
</table>

The results from the three sets of optimisations in which the release windows were maximised for the matched angular momentum are presented in Table 2. When the optimised technique was required to be robust to the timing of the hip and shoulder joint movements the release windows produced were smaller. In Table 2 the range of release windows obtained from the five perturbed combinations are presented for each robust optimisation. As the timing perturbations in the robust optimisations increased, the size of the release windows decreased. Graphics sequences of the actual performance, the maximised performance and the optimised performance robust to 10 ms perturbations are shown in Figure 4.

The optimisation where the release window was maximised given a 9% increase in the normalised angular momentum at release produced a window of 125 ms. When the requirement to be robust to 10 ms was introduced the size of the release window was smaller (range 81 – 84 ms) than in the maximised simulation. Graphics sequences of the actual performance including the dismount and the optimised performance robust to 10 ms with the modified dismount are shown in Figure 5. When required to be robust to 20 ms perturbation the size of the release window was again smaller (range 44 – 63 ms).
Figure 4. The last giant circle prior to release for competitor A from (a) the matched simulation (b) the maximised release window simulation and (c) the robust to 10 ms perturbations simulation. The shaded zone represents the release window for each simulation, with the solid lines depicting the rotation angle of the mass centre at the start and end of the release window.
Figure 5. The last giant circle and flight from (a) the actual performance and (b) the increased angular momentum simulation robust to 10 ms. In both cases the images in the flight phase have been given increased separation to highlight changes in body configuration.

Discussion

This study has shown that larger release windows for double layout somersault dismounts from a-bars can be produced using small timing changes to existing techniques. For consistent performances the release window needs to be robust to small variations in technique timing in the giant circle and this leads to somewhat smaller release windows. Greater changes to existing technique can produce greater angular momentum at release while preserving a realistic release window.

One of the limitations of the present study was the need to scale a male gymnast’s strength data using performance data of the female gymnasts. As it was not possible to collect individual torque – angular velocity data, this method allowed limits to be set which were close to the joint torques used in the actual performances. The joint torque time histories at the hip and shoulder for each optimisation lay within realistic limits as presented by Sheets and Hubbard (2004). A typical joint torque time history for an optimised technique is presented in Figure 6. It is likely that increasing the torque limits would result in larger release windows but this may have given less insight into the gymnasts’ technique. Similarly in the initial optimisations constraints were imposed to produce simulations close to the gymnasts’ own technique. Larger release windows would have been possible if the joint angle time histories were allowed to vary further.
away from the gymnasts’ original technique. This was demonstrated during the optimisation with increased angular momentum, where the technique was allowed to vary further from the original technique, producing a release window of 125 ms compared to 118 ms for the original optimisation. However, keeping the simulated technique close to the gymnasts’ recorded technique was more appropriate for investigating the effect of errors in timing. Another limitation was that it is not possible to determine how robust a gymnast’s technique is from a single performance, since this may have already suffered some perturbation. However, it was found that introducing the requirement to be robust to perturbations in timings reduced the size of the optimised release windows and that the size of the release windows became smaller as the magnitude of the perturbations increased (Table 2). Optimised release windows comparable with actual performances were obtained with perturbations of 20 ms (Table 2). This result agrees with Yeadon and Brewin (2003) who found that changes in body configurations needed to be timed to within 15 ms to prevent excessive residual swing in the final handstand position, when performing the backward longswing on rings. A delay in the timing of the configurational changes of 30 ms lead to considerable residual swing. Similarly Schmidt and Lee (1999) presented an error in movement time of between 20 and 30 ms for a coincidence timing task. Although this task was not for whole body movements the study provides an indication of the variation in human movement timing.

![Joint torque time history for the shoulder (solid line) and hip (dashed line) during an optimal simulation robust to 10 ms.](image)

The aim of the present study was to try and improve the technique during the backward giant circle in terms of producing more normalised angular momentum whilst maintaining a large release window. However, these two factors alone cannot guarantee that the gymnast will have a successful performance. When perturbations were introduced into a maximised technique, the resulting simulated performance was often incapable of producing the desired results. Figure 7 shows what happened to the optimised simulations, where the sole aim was to maximise the release window, when they were perturbed by 10 ms. The five light bars correspond to the maximised simulation, followed by four simulations where the shoulder and hip joint movements were performed 10 ms earlier or later than in the maximised simulation. It can be seen that when the technique is perturbed the release window can be much smaller than in the maximised simulation. In some cases the model was not able to produce a release window at all when perturbed. This was due to either exceeding the joint torque limits or the model contacting the lower bar. The five dark bars in Figure 7 are the
corresponding simulations from the optimised technique required to be robust to 10 ms. Although all the (perturbed) release windows from the robust solutions are smaller than the unperturbed maximised windows (first light bar), they are sufficiently large for a successful dismount to be performed. It is therefore important to include the requirement for robustness in any optimisation since a gymnast requires a technique that will produce similar results when small errors in timing are made.

Figure 7. The size of release window for each gymnast – (a) gymnast A, (b) gymnast B and (c) gymnast C - when the maximised (light bars) and robust (dark bars) simulations were perturbed by up to 10 ms – (1) no perturbation, (2) shoulder and hip perturbed together both early, (3) both late, (4) shoulder early with hip perturbed both early, (5) shoulder late with hip early.

(a)

(b)

(c)
Hiley and Yeadon (2005) speculated that female gymnasts may be able to produce larger release windows if they could achieve a larger hyper-extension at the hip earlier in the giant circle. Although the hip and shoulder angles were only allowed to vary over a small range so as to produce a technique similar to the gymnasts’ own, it was found that a delayed and slower closing of both the shoulder and hip angles prior to release produced a larger window. The same result was obtained in the optimisation with greater angular momentum at release. Rather than hyper-extending earlier in the giant circle, a delayed and slower closing of both angles prior to release was used. A delayed slower action was found to load the bar in such a way that the release velocity was viable for a longer portion of the giant swing.

It has been shown that introducing the requirement of robustness into optimisations reduces the size of the release window. However, similar release windows to those obtained from actual performances were found when technique was required to be robust to perturbations of 20 ms. The results suggest that elite gymnasts can cope with perturbations of the order of 20 ms.

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