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Optimisation of high bar circling technique for consistent performance of a triple piked somersault dismount

Michael J. Hiley and Maurice R. Yeadon

School of Sport and Exercise Sciences, Loughborough University, Loughborough, UK

Abstract

The dismount from the high bar is one of the most spectacular skills performed in Men's Artistic Gymnastics. Hiley and Yeadon (2005) optimised the technique in the backward giant circle prior to release using a computer simulation model to show that a gymnast could generate sufficient linear and angular momentum to perform a triple piked backward somersault dismount with a sufficiently large release window (the period of time during which the gymnast could release the bar and successfully complete the dismount).

In the present study it was found that when the timing of the actions at the hip and shoulder joints from the optimum simulation were perturbed by 30 ms the resulting simulation could no longer meet the criteria for sufficient aerial rotation and release window. Since it is to be expected that a gymnast's technique can cope with small errors in timing for consistent performance, a requirement of robustness to timing perturbations should be included within the optimisation process. When the technique in the backward giant circle was optimised to be robust to 30 ms perturbations it was found that sufficient linear and angular momentum for a triple piked dismount could be achieved with a realistic release window.

Keywords : gymnastics, simulation, robust, giant circle

Introduction

In Men's Artistic Gymnastics the most common dismounts performed from the high bar in elite competition are double somersaults with one or more twists, performed in a straight (layout) body configuration. A smaller number of gymnasts perform a triple tucked somersault dismount and fewer still perform a triple piked somersault dismount (Figure 1). In the 2000 Olympic Games out of the 100 competitors in the qualifying competition 68 performed a double layout dismount (with or without twist), three performed a triple tucked dismount and none performed a triple piked dismount. Since the Code of Points (FIG, 2006) recognises this dismount as being in the E category, only the second most difficult of skills, why is it rarely seen in elite competition?

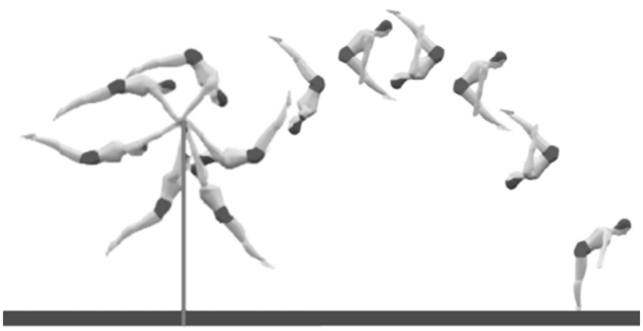

Figure 1. A triple piked backward somersault dismount from the high bar. (Additional horizontal spacing during flight has been used to separate the images).

It has been shown that those dismounts where the gymnast maintains a straight configuration for two somersaults require the greatest angular momentum (Kerwin et al., 1990; Brüggemann et al., 1994). However, Kerwin et al. (1990) found one performance of a triple tucked somersault dismount that had normalised angular momentum comparable to one of the poorer examples of the double layout somersault dismount. It may be speculated that a triple piked somersault dismount will require more angular momentum than a double layout somersault dismount.

Hiley and Yeadon (2005) used computer simulation to show that one of the major limiting factors to producing angular momentum was related to the gymnast's ability to time the release from the high bar. As the amount of angular momentum produced by the backward giant circle increased, the size of the release window (within which a successful dismount could be performed) decreased. If the gymnast were to release at any point within the release window he would have (by definition) sufficient angular momentum and flight time to complete the dismount. Although the model was capable of producing enough linear and angular momentum for a triple layout somersault dismount, the corresponding release window was unrealistically small. When the model was constrained to produce a simulation with a release window comparable to those obtained from double layout performances (mean of the eight 2000 Olympic high bar finalists, 110 ms), the linear and angular momentum generated were sufficient to perform a triple piked dismount.

In addition to producing sufficient angular momentum, flight time and release window, the gymnast's technique must also be robust to small errors in timing of the joint actions at the hip and shoulder. Hiley and Yeadon (2007) demonstrated that the introduction of small timing errors to optimised backward giant circle technique on the asymmetric bars produced simulations with unrealistically small release windows. It was found that release windows of similar magnitudes to actual performances were obtained when optimisations included the requirement for the technique to be robust to 20 ms perturbations. Since a gymnast's technique must be capable of coping with small errors in timing, the concept of robustness should be included in the process of optimisation.

The aim of this study is to determine whether it is possible for a gymnast to generate sufficient angular momentum, flight time and release window from backward giant circling to perform a triple piked somersault dismount using technique that is robust to perturbations in the timing of the joint movements at the hip and shoulder.

Methods

Subsections in Methods describe the protocols used to optimise the backward giant circle technique. A *simulation model* of a gymnast and high bar was used to vary technique within each *optimisation*.

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, 2003a). The high bar and the gymnast's shoulder were modelled as damped linear springs (Figure 2). In addition to the shoulder spring, there was a parameter that governed the extent to which the torso segment lengthened as the shoulder elevation angle increased. 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, 2003a).

Figure 2. The four segment gymnast - high bar simulation model with damped springs representing bar and shoulder elasticity.

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 with the property that angle changes are effected with zero velocity and acceleration at the endpoints (Hiley and Yeadon, 2003a). The joint angle time histories at the hip and shoulder were defined by consecutive quintic functions allowing the joints to open and close. 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 ϕ (the angle from the upward vertical of the line joining the neutral bar position to the mass centre).

The "rotation potential" was calculated as the product of angular momentum and flight time divided by 2π times the moment of inertia of the body when straight 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.

Optimisation

A simulation model of aerial movement (Yeadon et al., 1990) was used to determine the minimum amount of rotation potential (expressed in straight somersaults) required to perform a triple piked somersault dismount from the high bar. The inertia parameters used in both the high bar – gymnast model and the model of aerial movement were calculated from the mean anthropometric measurements taken on seven elite gymnasts and were scaled using segment lengths calculated from video analysis of the 2000 Olympic high bar champion using the inertia model of Yeadon (1990).

The gymnast – high bar model was implemented within the Simulated Annealing algorithm (Goffe et al., 1994), which was used to manipulate the parameters that defined the joint angle time histories of the hip and shoulder joints. The simulations performed during the optimisations were started at a rotation angle of 90° (body horizontal), with linear and angular momentum taken from video analysis of the Olympic high bar champion (Hiley and Yeadon, 2003b). The simulation of the bar contact phase ended once the model had rotated through approximately 540°. There were four phases in each simulation during which the angles were allowed to change. These corresponded to successively opening, closing, opening and finally closing where opening involved hip extension and shoulder flexion and closing involved hip flexion and shoulder extension (Figure 3). 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 the specified minimum amount of rotation potential, landed with the mass centre between 1.4 m and 3.4 m from the bar and had a flight time of at least 1.2 s (Hiley and Yeadon, 2005). Penalties were imposed for joint angle time histories in which the joint torques exceeded the maximum voluntary joint torque at each joint angular velocity (Hiley and Yeadon, 2007; King and Yeadon, 2002). Joint torques were measured for a male National Team gymnast during eccentric-concentric trials using an isovelocity dynamometer to give a function which expressed maximum voluntary torque in terms of joint angular velocity (King and Yeadon, 2002). This function was scaled up for the Olympic Champion using the maximum percentage of the peak joint torque used in a matching simulation of a recorded performance (Hiley and Yeadon, 2005).

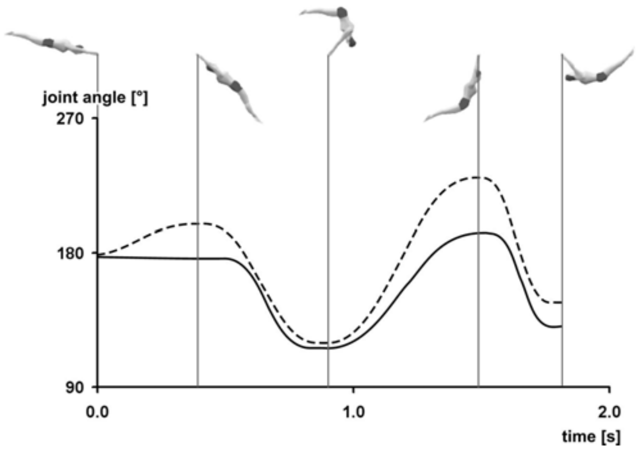

Figure 3. Graphic showing the piecewise quintic functions which define the joint angle time histories at the shoulder (solid line) and hip (dashed line) joints.

A number of optimisations were performed using the gymnast – high bar model. The first optimisation maximised the release window based on the minimum rotation potential required to successfully perform a triple piked somersault dismount. Initial estimates of the parameters defining the joint angle time histories, these were based on the circling technique of the Sydney Olympics high bar champion prior to release for a double layout somersault dismount with two twists (Hiley and Yeadon, 2005). To investigate the sensitivity of the optimum solution to perturbations, the last two shoulder and hip actions (i.e opening and closing prior to release) were perturbed by 30 ms. Five different perturbation combinations were used: no perturbation, shoulder and hip both early, shoulder and hip both late, shoulder early with hip late, and shoulder late with hip early. For each of the five simulations the release window was calculated.

To investigate the effect of a requirement for robustness on optimal technique, the timings of the last two shoulder and hip actions (i.e opening and closing prior to release) were perturbed by 10 ms. For each step of this second optimisation the five different perturbation combinations described above were used, the score returned to the optimisation routine being the smallest release window obtained from the five simulations. The solution to the first optimisation was used to provide the initial estimates of the joint angle time histories for this second optimisation.

The third, fourth and fifth optimisations were similar to the second except that the technique was required to be robust to 20 ms, 30 ms and 40 ms perturbations, respectively. Each of these optimisations was started from the optimal simulation from the previous optimisation.

Finally, all optimisations were repeated with the mean voluntary maximum joint torque data not scaled to the Olympic Champion's performance. This was done to represent a gymnast working within his strength characteristics or a gymnast who was not as strong as the Olympic Champion.

Results

The minimum rotation potential required to perform a good triple piked somersault dismount was found to be 1.78 straight somersaults, compared to 1.72 straight somersaults for the 2000 Olympic high bar champion's double layout somersault dismount with two twists. The scaling of the maximum voluntary joint torque data to allow the Olympic Champion to perform his dismount without exceeding the torque limits was 2:1 at the shoulder and 1:1 at the hip.

The first optimisation which maximised the release window, subject to a rotation potential of 1.78 straight somersaults, produced a release window of 156 ms. Some of the release windows obtained when the optimal solution was perturbed by 30 ms were very small (Figure 4a). The five bars correspond to (1) the unperturbed simulation, (2) shoulder and hip actions 30 ms early, (3) shoulder and hip actions 30 ms late, (4) shoulder 30 ms early with hip 30 ms late, and (5) shoulder 30 ms late with hip 30 ms early. The release windows of simulations 2, 3 and 5 were very small since the perturbed simulations were terminated once the joint torque limits were exceeded and this limited the end time of the release window.

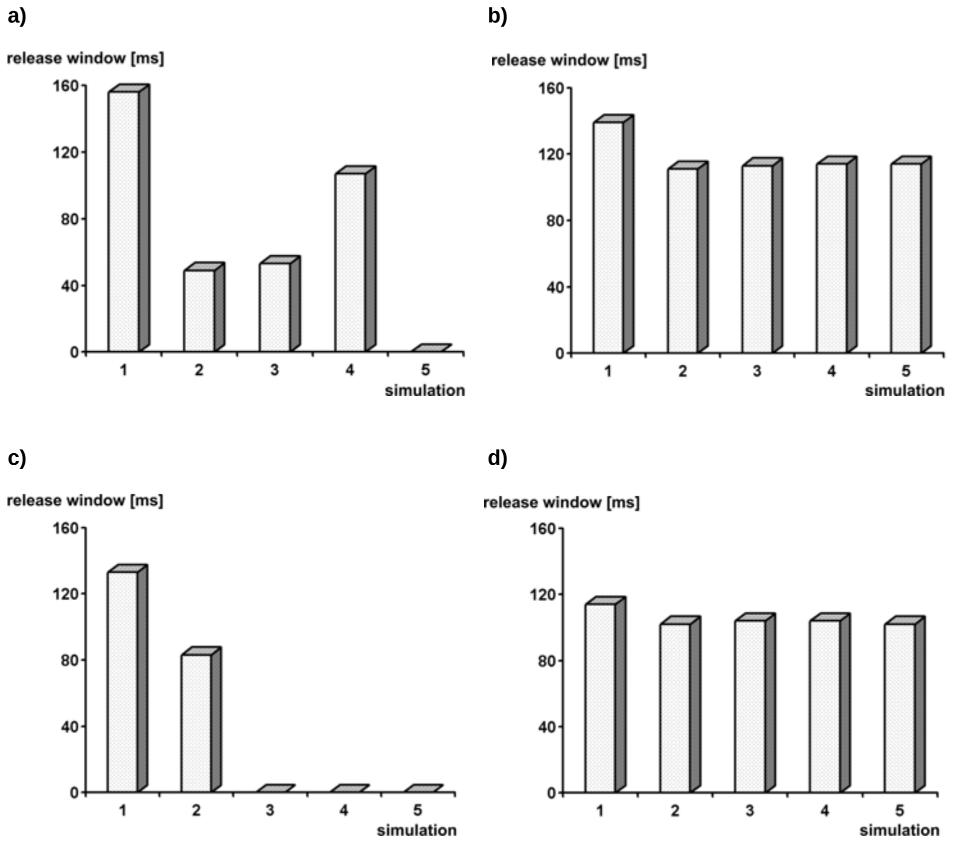

Figure 4. The size of release window when the (a) maximised and (b) robust to 30 ms simulations are perturbed by 30 ms using the five different perturbation combinations – [1] the unperturbed simulation, [2] shoulder and hip actions early, [3] shoulder and hip actions late, [4] shoulder early with hip late, and [5] shoulder late with hip early. Charts (c) and (d) are the equivalent data for the reduced strength data robust to 20 ms and then perturbed by 20 ms.

The release windows of the optimisations required to be robust to 10, 20, 30 and 40 ms perturbations decreased with increasing perturbations (Table 1). The kinematics of the three circling techniques corresponding to (a) the actual performance of the double layout somersault dismount, (b) the simulated triple piked somersault dismount with maximised release window and (c) the optimisation robust to 30 ms perturbations were similar (Figure 5). The joint angle and joint torque histories corresponding to the graphic sequences in Figure 5 are presented in Figure 6.

Table 1. Release windows for optimisations robust to timing perturbations

strength	perturbation size				
	0 ms	10 ms	20 ms	30 ms	40 ms
champion	156	146 - 151	136 - 144	111 – 139	88 - 121
reduced	133	115 - 124	102 - 114	89 - 102	80 - 101

Note : The range of release windows in each robust optimisation corresponds to the five perturbation combinations.

a)

b)

c)

Figure 5. The last ¾ giant circle prior to release for (a) the gymnast's double layout somersault (b) triple piked somersault with maximised release window and (c) optimised triple piked somersault robust to 30 ms perturbations.

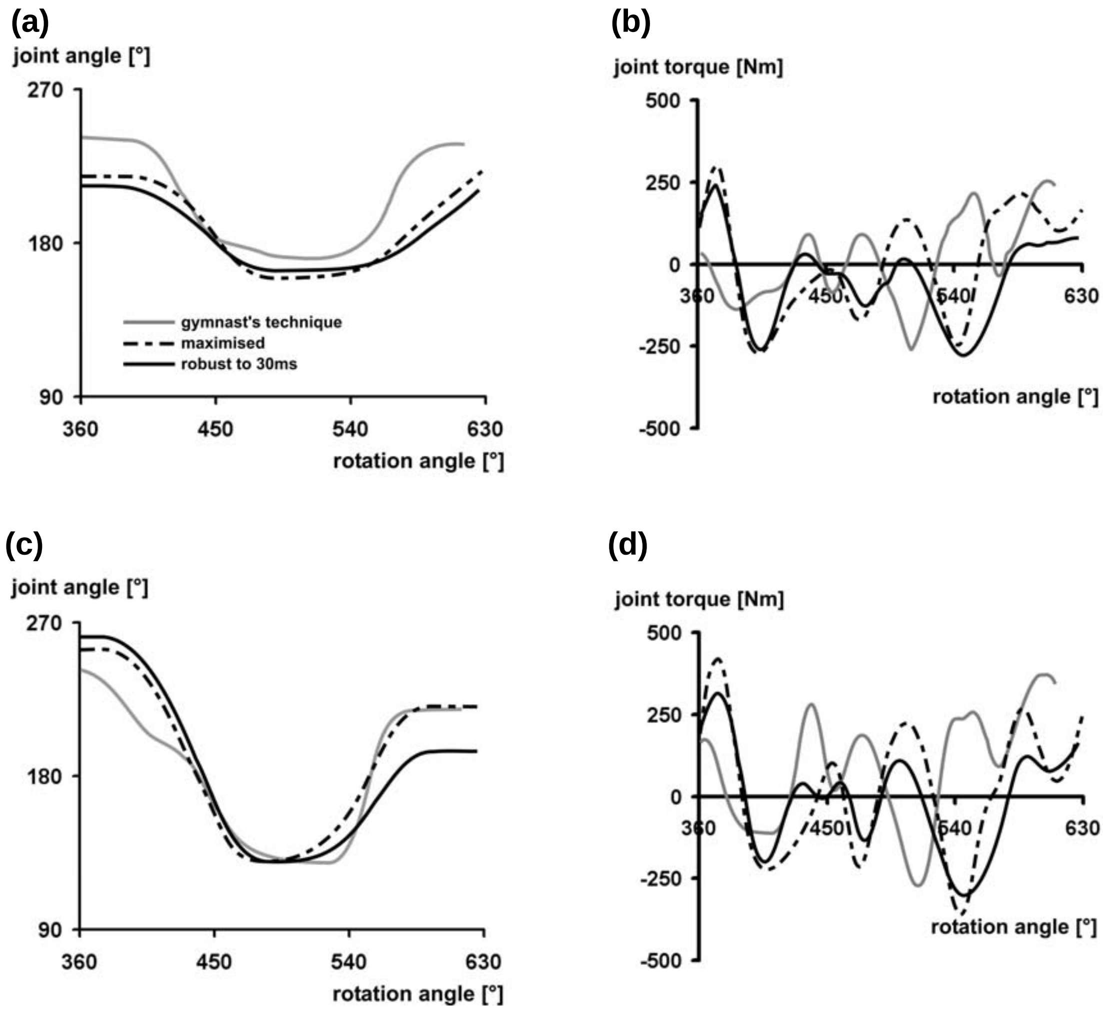

Figure 6. The shoulder and hip (a, c) joint angle and (b, d) joint torque histories corresponding to the graphic sequences in Figure 5 the last ¾ giant circle prior to release for [1] the gymnast's double layout somersault (grey line), [2] triple piked somersault with maximised release window (dashed line), and [3] optimised triple piked somersault robust to 30 ms perturbations (black line).

For the repeated optimisations with the reduced joint torque limits the maximised release window was 133 ms. The release windows of the optimisations required to be robust to 10, 20, 30 and 40 ms perturbations were smaller than the corresponding release windows for the full strength joint torque limits (Table 1).

Discussion

Optimisation is a process that allows the researcher to investigate how technique might be improved. Care must be taken, however, to ensure simulations obtained from such optimisations are not overly sensitive to perturbations. If small deviations from "optimum" technique result in inadequate performances, then the technique can no longer be considered to be optimum. The optimum technique should allow the athlete a certain degree of variability without appreciable effect on the performance. The aim of the present study was to try and find a technique of backward giant circling which produced sufficient rotation potential whilst maintaining a realistically large release window and being robust to perturbations in the timing of the actions at the hip and shoulder joints.

The gymnast's technique was initially optimised to maximise the release window with sufficient rotation potential to produce a triple piked somersault dismount. The minimum rotation potential required was equivalent to approximately 4% more than that of the double layout dismount performed by the champion gymnast. Despite requiring more rotation potential, the optimised technique produced a similarly sized release window (156 ms) to the actual double layout performance (150 ms) found by Hiley and Yeadon (2003b). However, when the timings of the actions at the hip and shoulders were perturbed three of the five simulations produced release windows of 50 ms or less (Figure 4a). It would be unrealistic for a gymnast to rely on such a technique since the smallest measured window was 88 ms (Hiley and Yeadon, 2005). It can be seen that introducing the requirement to be robust to timing perturbations reduced the size of the release windows obtained (Figure 4b), compared with the maximised optimisation (Figure 4a[1]). However, when the 30 ms robust solution was perturbed, a realistic release window (>110 ms) was obtained for each of the perturbation combinations (Figure 4b) and this may be expected to correspond to more consistent performance in a practical situation. As the size of the perturbation in the robust optimisation increased, the size of the release windows decreased (Table 1) but only when the size of the perturbation reached 40 ms, did the smallest release window (88 ms) drop to the size of the smallest window (88 ms) obtained from the eight high bar finalists at the 2000 Sydney Olympics (Hiley and Yeadon, 2003b).

Using the strength characteristics of the National Team gymnast rather than the 2000 Olympic high bar champion produced a similar set of results but in all cases the release windows obtained were somewhat smaller (Table 1). When the non-robust optimisation was perturbed by 20 ms three of the five simulations produced release windows of 0 ms (Figure 4c). When the solution robust to 20 ms was perturbed, a realistic release window (>100 ms) was obtained for each of the perturbation combinations (Figure 4d). At a perturbation of 30 ms the smallest release window obtained dropped to 89 ms, close to the size of the smallest window obtained from the high bar finalists at the 2000 Olympics (88 ms). Reducing the strength of the gymnast reduces the size of perturbation the technique can cope with whilst maintaining a realistic release window.

Since this study is concerned with producing a consistent performance, it is speculated that the Olympic Champion's technique is robust to perturbations of up to 30 ms. However, a more conservative estimate, based on the reduced strength optimisations, would suggest that in general an elite gymnast's technique will be robust to timing perturbations of 20 ms. It is therefore recommended that when optimising simulations of swinging skills a minimum robustness requirement of 20 ms is included. This result is in agreement with Yeadon and Brewin (2003) who found that timing perturbations of 15 – 30 ms to changes in body configurations resulted in the range of residual swing in the final handstand position of elite performances of the backward longswing on rings. Similarly, Hiley and Yeadon (2007) found that release windows comparable to actual performances of asymmetric bar dismounts were obtained from optimisations robust to 20 ms perturbations.

The kinematics of the optimised techniques were very similar to the Olympic Champion's technique for the double layout dismount (Figures 5 and 6). The most striking difference between the optimised techniques and the gymnast's technique was a slightly delayed and slower closing of the shoulder angle (shoulder extension) prior to and through the point of release. It can also be seen that in the optimisation robust to 30 ms perturbations less hip flexion prior to release was used (Figures 5c and 6c), whereas in the optimisation robust to 20 ms similar amounts of hip flexion to the matched and maximised optimisation were used. The slightly delayed shoulder extension has previously been associated with a later peak vertical bar displacement, which affects the path of the mass centre and gives a longer period of time for which the centre of mass velocity is appropriate for the dismount (Hiley and Yeadon, 2007). Although there were only small differences in the joint angle time histories the differences in joint torques were more marked. In the perturbed simulations that resulted in small release windows (Figure 4) the primary limitation was that the joint torque limits were exceeded. This suggests that the robust optimisations produce simulations that would have slightly different activation profiles, had the model been muscle or torque driven. In other words, when the gymnast deviates from the robust optimum technique, the demands do not exceed the strength limits.

One of the limitations of the present study was the assumption that the legs remained straight throughout the giant circles. In reality the knees flex and extend as the gymnast circles the bar. Keeping the knees fully extended throughout the circle will place a greater demand on the hip flexor torques leading up to release, increasing the chance of exceeding the joint torque limit. However, it might be expected that mistiming any knee actions may result in somewhat smaller release windows. Although not expected to have a large effect on the present results, the influence of the knee action could be investigated in future studies. However, it may be argued that constraining the joint angle time histories to four phases of "opening" and "closing" using quintic functions simplifies the gymnast's technique. Using a more flexible/complex method to define the joint angle time histories, such as Fourier series, would be likely to lead to somewhat larger release windows. In the matching simulation the shoulder joint torques exceeded the maximum voluntary joint torque data recorded from a National Team gymnast. In order that these limits were not exceeded the data for the shoulder had to be scaled by 2:1 for the Olympic Champion. Possible reasons for the level of scaling required include the likelihood that the Olympic Champion is indeed stronger than the National Team gymnast and that the National Team gymnast was unable to recreate the shoulder actions (used in high bar swinging) on the dynamometer since on the dynamometer the shoulder was isolated from torso flexion and extension. However, in both scaled and unscaled optimisations similar results were obtained with the introduction of robustness reducing the size of the release window produced.

It has been shown that it is possible to perform a triple piked somersault from high bar with a sufficiently large release window whilst being robust to small perturbations in timing. Why then is this dismount rarely seen in elite competition? For the 2000 Olympic high bar champion an increase of only 4% in rotation potential was required. When compared with the average rotation potential of the high bar finalists (1.65 straight somersaults) this would be an increase of 8%. It is therefore likely that the triple piked somersault dismount (classified E) has insufficient reward compared to the more commonly performed double layout somersault dismount with two twists (also classified E). Until this is recognised by the Code of Points (FIG, 2006), the triple piked somersault dismount is likely to remain a rarity in elite competition.

Conflict of Interest Statement

The authors wish to disclose that they have no financial or personal relationships with any people or organisations that could inappropriately influence this work.

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