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Incorporating aspects of motor control in the optimisation of human performance [Intégrer les aspects du contrôle moteur dans l'optimisation de la performance humaine]

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Incorporating aspects of motor control in the optimisation of human performance

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ABSTRACT

Computer simulation modelling is a powerful tool that allows the Sports Biomechanics researcher to investigate the underlying mechanics of technique. Once the underlying mechanics have been established technique may then be optimised. Three case studies from gymnastics are presented which highlight the importance of choosing the appropriate optimisation criterion and including aspects of motor control when investigating limiting performances. In everyday activities minimising effort or joint torque is often used as the basis of the optimisation score, however, in the field of sport effort is often maximised in order to achieve the performance outcome. Although realistic strength characteristics should be incorporated in simulation models aspects of motor control such as coordination and timing precision are just as important in certain limiting situations.

INTRODUCTION

Computer simulation modelling is a powerful tool in Sports Biomechanics as it allows the researcher to investigate the underlying mechanics of technique. Once the underlying mechanics have been established technique may be optimised, which may be used to reduce injuries or to improve performance. When optimising technique, minimising effort or joint torque is often used as the basis of the score (or cost function). Many tasks in everyday life may be based on minimising such variables, however, in the field of sport it is often the case that effort is maximised in order to achieve the desired aspect of technique or to achieve the performance outcome. Therefore, optimisation criteria must reflect the performance outcome rather than the amount of effort required. It is acknowledged that realistic strength characteristics should be incorporated in to simulation models so as to be representative of the athlete, however, strength should not be considered the only limit to maximal performance. Aspects of motor control such as coordination and timing precision are as, if not more, important in certain limiting situations.

The aim of this paper is to demonstrate how computer simulation modelling may be used to gain an insight into the important aspects of gymnastics swinging techniques and the importance of including aspects of motor control when investigating limiting movements. The paper presents 3 case studies to outline the above issues.

Case study 1 – The undersomersault on parallel bars

INTRODUCTION

In gymnastics there is often more than one technique used to perform the same skill. In these situations the question is “Which is the best technique?”. The ‘best’ technique will depend on many factors including the age and preparation of the gymnast and the long term plan of the coach (i.e. which technique will allow the development of more complex skill variations). Simulation modelling and optimisation can be used to help answer such questions. Two techniques were identified in the coaching literature (Davis, 2005) for the undersomersault to handstand on parallel bars (Figure 1). Although the majority of senior gymnasts adopt the ‘stoop stalder’ technique (Figure 1b), Davis (2005) recommended the ‘clear circle’ technique (Figure 1a) be adopted in the early stages of learning the skill. The aim of the study was investigate the effect of cost function on optimum technique for the swing phase of the undersomersault.

Figure 1. The (a) Clear Circle and (b) Stoop Stalder techniques used in the undersomersault to handstand on parallel bars (adapted from Hiley and Yeadon, accepted).

METHODS

Two male gymnasts each performed nine undersomersaults from handstand to handstand while data were recorded using an automatic motion capture system. The highest and lowest scoring trials of each gymnast, as determined by four international judges, were chosen for further analysis. The technique of the gymnasts was optimised using a three-segment planar model of swinging movement on the parallel bars (Hiley & Yeadon, 2003a) and the simulated annealing algorithm (Goffe et al., 1994). The gymnast model included arm, torso, and leg segments which were given subject specific inertia parameters. As flexing of the elbow or knee would lead to deductions from the judges, a single segment was sufficient to represent straight arms and another to represent straight legs. The elastic properties of the bars and gymnast were modelled as damped linear springs (Figure 2). The spring at the shoulder represented the stretch at the shoulder and any extension of the spine. 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 (Begon, Wieber & Yeadon, 2008). The model was

driven using the joint angle time histories at the shoulder and hip (Figure 2, α and β , respectively) in the form of Fourier series.

Figure 2. Three segment simulation model of the gymnast and parallel bars with bar spring and shoulder spring (adapted from Hiley et al., 2009).

Two cost functions, minimisation of peak joint torques and production of a vertical mass centre path and were used to optimise the gymnasts' technique during the swing phase of the undersomersault (starting from the position shown in Figure 2 and ending at bar release). In both optimisations only the coefficients that defined the joint angle time histories were allowed to vary, all other model parameters remained fixed. The upper and lower bounds for the Fourier series coefficients were allowed to vary by $\pm 25\%$ from the initial values which were obtained from a match of the gymnasts' joint angle time histories.

The first optimisation minimised a cost function based on the peak joint torque at the hip and shoulder joints whilst seeking an improved undersomersault performance through the use of penalties. The optimum technique was required to produce sufficient vertical velocity at release to achieve a mass centre height in flight of at least 90% of the final handstand position measured above the bars. The vertical velocity required to reach 90% of handstand was calculated from the height of the mass centre at release using the equations of motion under constant acceleration. The simulation incurred penalties if the horizontal velocity and normalised angular momentum at release exceeded the range spanned by the video analysis of the 18 trials of the gymnasts. The second optimisation effectively minimised horizontal velocity so as to produce a vertical path of the mass centre during the upward swing to release. A root mean squared (rms) difference was calculated between the angle of the resultant mass centre velocity and the upward vertical from a rotation angle of 225° until release (0° corresponds to handstand at the start of the skill, Figure 1). In addition the same penalties were used to produce an improved undersomersault performance as in the first cost function.

RESULTS AND DISCUSSION

In the first set of optimisations, where the peak joint torques were minimised, the model was able to achieve sufficient vertical velocity at release whilst satisfying the criteria for a successful performance. This represents an improvement in performance of 25% and 36% in terms of the height achieved by the mass centre for each gymnast, respectively. As expected the peak joint torques were lower than in the actual performances (Figure 3a). The technique in the first set of optimised simulations (Figure 4b) differed from the technique of the gymnasts (Figure 4a) and more closely resembled the clear circle technique (Figure 1a).

Figure 3. Time histories of joint torque at the hip (circles) and shoulder (crosses) for the gymnast trial and optimised simulations (solid line) of (a) Gymnast 1 from the first optimisation and (b) Gymnast 2 from the second optimisation (adapted from Hiley and Yeadon, accepted).

The second set of optimisations, in which the path of the mass centre was encouraged to be vertical, was still able to achieve sufficient vertical velocity at release whilst satisfying the criteria for a successful. Although the peak joint torques did not exceed the limits set from the actual performances they were considerably higher than those obtained from the first set of optimisations (Figure 3b). The technique from the second set of optimisations (Figure 4c) closely resembled the technique of the two gymnast performances (Figure 4a).

Figure 4. Graphical sequences of (a) the gymnast's technique and optimum simulations (b) minimising joint torques and (c) producing vertical mass centre path for Gymnast 2 (adapted from Hiley and Yeadon, accepted).

The minimisation of joint torques may be an appropriate optimisation criterion where the gymnast strength limits are approached during the movement. When minimising the joint torques a technique similar to the backward clear circle technique was obtained. This finding supports the coaching recommendation that

the clear circle technique is adopted in the initial stages of learning, as it is physically less demanding. In the case of the stoop stalker technique it is clear that minimising peak joint torques is not the goal of the gymnast, rather the production of a vertical mass centre path. The advantages of such a mass centre path are as follows: firstly the direction of the mass centre velocity changes less near to release leading to a more consistent performance. That is, if the release is mistimed slightly the mass centre will still be moving in the correct direction (Hiley & Yeadon, 2003b). Secondly, the undersomersault to handstand forms the basis of more complex skills: the undersomersault to handstand with a half or full twist. Having a vertical mass centre velocity while the body is twisting will reduce the complexity of the hand grasp changes.

The identification of an appropriate criterion for a given skill is not always a simple matter since the over-riding factor might be strength (optimisation 1), skill development (optimisation 2), or something else such as timing (Hiley & Yeadon, 2003b). Indeed it may not always be possible to explain technique in terms of a single optimisation criterion since sometimes there may be a number of competing factors that are relevant and important.

Case study 2 – The triple layout somersault dismount from high bar

INTRODUCTION

In elite Men's Artistic Gymnastics competitions the majority of dismounts from the high bar comprise a double somersault with a straight (layout) body configuration with one or more twists (Figure 5). Less common alternatives include the triple tucked and the triple piked somersault dismounts, however, no one has yet performed a triple layout somersault in competition. What then are the limiting factors to performing the triple layout somersault dismount? Perhaps the limiting factor in performing a triple layout is the gymnast's ability to produce sufficient angular momentum during the final backward giant circle.

Figure 5. A double straight (layout) somersault dismount with two twists along with the preceding $\frac{3}{4}$ backward giant circle (adapted from Hiley and Yeadon, 2007).

In addition to producing angular momentum and flight the backward giant circle can also have an effect on the timing of release from the bar. Hiley and Yeadon (2003b) defined the “release window” as the period of time during which the gymnast

has sufficient angular momentum and flight to successfully complete the desired dismount. It may be argued that the larger the release window the gymnast has the easier it is to time the release correctly and the more consistent the performance will be. For the eight high bar finalists at the 2000 Olympic games the average release window was calculated to be approximately 110 ms (Hiley and Yeadon, 2003b). Prior to release for a triple layout dismount it might be expected that the gymnast will be rotating faster than for a double layout and this will reduce the size of the release window. If the release window becomes too small the timing of the release becomes critical, which may be a limiting factor.

The aim of the study was to determine whether it is possible for a gymnast to generate sufficient angular momentum during backward giant circles to perform a triple layout somersault dismount. The release window will be determined for the optimised accelerated backward giant circle technique to determine the feasibility of the dismount.

METHODS

A planar computer simulation model of a gymnast and high bar (Hiley and Yeadon, 2003a) was used to optimise the technique in the $1\frac{3}{4}$ backward giant circles prior to release for the dismount. The model comprised four rigid segments representing the arm, torso, thigh and lower leg, with the bar and the gymnast's shoulder structure modelled as damped linear springs. Model input included 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 of the shoulder, hip and knee joints in the form of piecewise quintic functions (Hiley and Yeadon, 2003a). To avoid joint angle time histories that exceeded the strength characteristics of a gymnast, parameters defining the strength capabilities of the gymnast were determined by collecting isovelocity dynamometer data and fitting a surface which expressed maximum torque as a function of angle and angular velocity (King and Yeadon, 2002). The muscle surfaces were scaled to individuals using body mass (Zatsiorsky, 1995). Inertia parameters were calculated using the inertia model of Yeadon (1990a). The spring parameters were calculated from a combination of static loading experiments and optimisation (Hiley and Yeadon, 2003a).

Output from the model comprised the time histories of the horizontal and vertical bar displacements, the location and velocity of the mass centre of the model, the rotation angle, the joint torques and the angular momentum of the body about its mass centre. The rotation angle was defined as the angle made by the line joining the mass centre of the model to the neutral bar position with the vertical. The angular momentum was normalised by dividing by 2π 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 that could be performed in the subsequent flight phase.

The simulation model was implemented with 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 optimisation procedures were started with the mass centre of the model directly above the neutral bar location (rotation angle of 0°). Each simulation was started using the initial angular momentum about the mass centre obtained from

video analysis of accelerated giant circles prior to a double layout somersault dismount (Hiley and Yeadon, 2003b). The simulation finished once the model had rotated through 650°. 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. The optimisation algorithm manipulated the magnitude and the start and end times of the actions at the hip and shoulder joints in order to maximise the release window.

The release window was defined as the period of time for which the model possessed a specified minimum amount of angular momentum, landed with the mass centre between 1.4 m and 3.4 m from the bar and had a time of flight of at least 1.2 s. Penalties were imposed for joint angle time histories which exceeded the maximum joint torque possible at each joint angle and angular velocity. The maximum release window for a double layout dismount was determined. The minimum angular momentum requirement (1.49) was based on the mean normalised angular momentum of the eight high bar Olympic finalists (Hiley and Yeadon, 2003b).

To determine how much normalised angular momentum could be produced whilst maintaining a sufficiently large release window, the optimum joint angle time histories from the first optimisation were used as the initial estimates for a second optimisation. The upper and lower bounds on the parameters being optimised were extended and the lower limit on the angular momentum defining the release window was increased. The process of increasing the lower limit of the angular momentum and using the solution from the previous optimisation as the initial estimate for the next release window maximisation was continued until the model had sufficient angular momentum to perform a triple layout somersault dismount (approximately 2.60 straight somersaults). The above process was repeated with maximum joint torques given by the muscle surfaces reduced by 25%. This was done in order to determine the effect of strength on the optimum technique.

RESULTS AND DISCUSSION

As the lower limit of the angular momentum defining the release window was increased the size of the maximised release window decreased (Table 1). When the lower limit on the angular momentum was sufficient to perform a triple layout dismount (2.60 straight somersaults) the maximised release window had dropped to 57 ms. With a constraint of maintaining a sufficiently large release window (at least 110 ms) the model was able to produce enough angular momentum for 2.10 straight somersaults. When the optimisation protocol was repeated with the maximum strength at the hip and shoulder joints reduced by 25%, the size of the release windows decreased (Table 1). With the constraint of maintaining a sufficiently large release window (at least 110 ms) the model was able to produce enough angular momentum for 1.90 straight somersaults.

Table 1. Release windows from the optimal simulations as the lower limit on the normalised angular momentum was increased, for both full and reduced joint torque limits

lower limit angular momentum (ss)	100% joint torque		75% joint torque	
	release window (°)	release window (ms)	release window (°)	release window (ms)
1.49	64	187	62	186
1.60	66	189	61	178
1.70	66	185	50	156
1.80	63	178	43	141
1.90	54	155	34	111
2.00	47	140	29	97
2.10	33	108	25	86
2.20	31	98	22	75
2.30	25	83	17	66
2.40	22	80	9	39
2.50	20	75	-	-
2.60	15	57	-	-

The results showed that for the strength and inertia parameters used it is possible to produce sufficient linear and angular momentum for a triple layout somersault dismount. This may not be the case for all gymnasts, with different strength and inertia characteristics. The release window for the triple layout dismount was relatively small (57 ms) in comparison to the actual performances of double layout dismounts from the Olympic Games (110 ms). With such a small margin for error (± 28 ms) timing the release from the bar may be critical and help to explain why the dismount has not been performed in competition. The consequence of releasing late is collision with the bar and so this movement must be considered to be of high risk. When the maximum joint torque values were reduced the model was not capable of producing sufficient angular momentum for the triple layout dismount. With a lower limit on the angular momentum of 2.10 straight somersaults and a release window of approximately 110 ms the model would have been capable of producing a new dismount in the subsequent flight phase, the lay-full-full (Figure 6). The dismount was still possible with a lower limit of 1.90 straight somersaults, but required more knee and hip flexion during the tucked phase.

Figure 6. A triple backward somersault dismount with two twists (lay-full-full) performed from the maximum strength optimum backward giant circle (adapted from Hiley and Yeadon, 2005).

Although the triple layout is theoretically possible it is unlikely that a gymnast would perform this dismount in competition. A gymnast performing a dismount at the end of their routine is more likely to choose a dismount where they are able to work within themselves and easily time the release (i.e. have a large release window).

Case study 3 – The Tkatchev release and regrasp on high bar

INTRODUCTION

The Tkatchev release and regrasp on high bar is performed from a backwards rotating giant circle. During release the direction of rotation must be reversed so that the gymnast rotates forwards in flight while travelling backwards over the bar to regrasp (Figure 7). The gymnast adopts a straddled configuration in flight to reduce the moment of inertia about the lateral axis through the mass centre.

Figure 7. The Tkatchev release and regrasp on high bar (adapted from Hiley et al., 2007).

When a gymnast performs the same skill a number of times it might be expected that he is attempting to use the same technique. However, it is also to be expected that within each attempt there will be some variability in the technique used (Newell and Corcos, 1993). The term coordination precision will be used here to refer to the level of variability in the timings and angles of the movement when the gymnast performs the same skill a repeated number of times. A gymnast's technique should therefore be robust so that it can produce similar results (e.g. production of linear and angular momentum) despite the level of variability present (i.e. the gymnast's coordination precision).

A successful Tkatchev is one in which the gymnast regrasps the bar. For a successful performance the gymnast must have sufficient linear and angular momentum at release to place the gymnast in a position to regrasp the bar at the end of the flight phase. Hiley et al. (2007) determined the release timing window of the preceding giant circle for 10 successful and 10 unsuccessful Tkatchev attempts. In order for the gymnast to regrasp the bar a sufficiently large release window is required. The release windows for the successful trials ranged from 9 – 74 ms (mean 29 ± 21 ms). The release windows for the unsuccessful trials, as might be expected, were much smaller (mean 3 ± 4 ms).

Many competitive gymnasts are able to perform release and regrasp skills on high bar with a success rate higher than 90% (a measure of consistency). Other gymnasts are unable to achieve such consistency. The reasons for this may include the use of inappropriate technique, lack of coordination precision, or lack of strength. The aim of this study is to investigate to what extent a given gymnast with an established coordination precision may be able to improve consistency of performance from changes in technique, and strength.

METHODS

The coordination precision was determined from the kinematic data collected by Hiley et al. (2007) from 20 performances of the Tkatchev. One senior male gymnast competing at national level (mass = 64 kg, height 1.63 m) performed 60 Tkatchev release and regrasps which were captured using nine Vicon M2 cameras operating at 100 Hz. The 10 successful trials and the 10 nearest misses of the bar were chosen for initial analysis. Arm orientation and joint configuration angles were calculated (Yeadon, 1990b) and quintic splines (Wood and Jennings, 1979) were used to fit joint angle time histories so that the data could be interpolated.

To calculate the timing and angle variability of the gymnast the instants of maximum and minimum hip and shoulder flexion and extension angles (Figure 8) were determined from the quintic splines (i.e. determine the start time, end time and magnitude of a joint flexion/extension). The mean and standard deviation were calculated for each measure.

Figure 8. Joint angle time histories of the hip and shoulder with the maximum and minimum flexion/extension angles indicated along with a graphical representation of the gymnast.

A four segment simulation model, which included damped linear springs for the elastic structures of the gymnast and high bar, was used (Hiley and Yeadon, 2005). Input to the model comprised the initial conditions (initial spring displacements, model configuration and velocities) and the joint angle time histories of the shoulder, hip and knee in the form of piecewise quintic functions (Hiley and Yeadon, 2003a). In order to define a joint angle time history the start time, end time and magnitude of each angle change must be specified. Output from the model comprised the whole body rotation angle and the linear and angular momentum about the mass centre of

the model. The model incorporated subject-specific inertia data (Yeadon, 1990a) and strength characteristics scaled from data on an elite male gymnast using an isovelocity dynamometer (King and Yeadon, 2002; King et al., 2009).

The parameters defining the joint angle time histories of the shoulder, hip, and knee were varied in order to maximise the number of successful performances produced when the technique was randomly perturbed to the level of the variability measured in the gymnast performances (i.e. increase the consistency of performance). The parameters included the start and end time of each joint flexion/extension and the magnitude of the angle change (Hiley and Yeadon, 2003a). Simulations were penalised if the joint angle time histories resulted in joint torques which exceeded those determined from the subject-specific strength characteristics.

The release window was defined as the period of time for which the model possessed normalised angular momentum (Kerwin et al., 1990) within the range of the 10 successful trials $\pm 10\%$ of that range (Hiley et al., 2007) and linear momentum to place the model in a position to regrasp the bar. In order for the model to be within successful catching distance of the bar, the mass centre had to lie within a sector defined by the range of actual catch positions and those that would be anatomically feasible.

To investigate the effect of variability in the timing and angles of the shoulder and hip actions, perturbations were added to the start time, end time and angle parameters of the joint angle time histories up to the maximum standard deviation levels of 12 ms and 2.3° (obtained from the analysis of the 20 performances). A random number generator with a normal distribution was used to add variability to the parameters of the joint angle time histories to the specified level. For each set of joint angle time history parameters produced by the genetic optimisation algorithm (Carroll, 2001) 500 randomly perturbed simulations were performed. From Hiley et al. (2007) the critical size of release window for a successful Tkatchev was approximately 10 ms. The perturbed simulations were given a score based on the size of the release window produced:

score = 0, if release window = 0 ms
score = 1, if 0 ms < release window < 10 ms
score = 2, if release window ≥ 10 ms

The sum of scores for the 500 simulations was maximised using a parallelised genetic optimisation algorithm. The optimal solution was subsequently used to produce 1000 randomly perturbed simulations in order to test its robustness.

To investigate the effect of the level of the timing and angle variability on consistency the optimisation was repeated with the level of the perturbations reduced by 25% (i.e. to a standard deviation of 9 ms and 1.7°). To investigate the effect of strength on consistency the above two optimisations were repeated with the joint torques calculated from the joint angle – angular velocity – torque profiles increased by 25%. One further optimisation was performed which maximised the release window without considering variability (i.e. no perturbations added to the joint angle time history parameters).

RESULTS AND DISCUSSION

In the analysed performances the average standard deviation for the joint angles at the same instants was 2.3° (Table 2). The average standard deviation of the start and end points of hip and shoulder flexion/extensions was 12 ms (Table 2). The data for each time were found to be normally distributed. Peak deviations from the mean were obviously larger than the average, over 30 ms for the timings (Figure 9). Using a random number generator with a normal distribution to add variability with a specified standard deviation produced a good match to the variability in the actual performances (Figure 9) both in terms of the average deviation and the peak deviation. When the timing and angle variability is viewed within a joint angle time history it can be seen that the method used produces a comparable envelope of joint angle time histories when compared with the actual performances (Figure 10).

Table 2. Average angle and times ($\pm$ standard deviation) at key points within the joint angle time history of the preceding giant circle

Average (n = 20)	Max hip angle	Max shld. angle	Min hip angle	Min shld. angle
Time [ms]	118 $\pm$ 9	157 $\pm$ 15	483 $\pm$ 11	610 $\pm$ 13
Angle [$^\circ$]	215 $\pm$ 3	193 $\pm$ 2	115 $\pm$ 2	113 $\pm$ 2

Figure 9. Timing variability about the mean at maximum shoulder flexion for the 20 actual performances (white) and 20 perturbations (standard deviation 12 ms) from the random number generator (grey), arranged in ascending order.

Figure 10. Envelopes containing the hip joint angle time histories obtained from (a) the 20 gymnast performances and (b) 20 perturbed simulations based on the optimal solution (standard deviations, 12 ms and 2.3°).

In the present study a more consistent performance, in terms of producing a suitably large release window to allow a successful Tkatchev, was achieved whilst maintaining realistic joint torques at the hip and shoulder. The largest increase in consistency was indeed obtained by altering technique (Table 3). The gymnast's technique only produced a successful performance 17% of the time (when considering all 60 gymnast trials); by modifying the technique the model was able to increase this figure to 69%, a marked improvement. This was achieved by performing the hip flexion and shoulder extension under the bar slightly earlier, flexing the shoulder over a larger range and a slightly later hip extension prior to release. Further gains in consistency were achieved by reducing the amount of variability present in the joint angle time histories and by increasing the strength of the model.

Table 3. Release windows obtained from the optimisations with different variability and joint torque constraints, along with the gymnast performances

Optimisation	Release window	
	Average [ms] (n = 1000)	% > 10 ms (n = 1000)
Variability 100% Torques 100%	34 ± 25	69
Variability 100% Torques 125%	40 ± 25	77
Variability 75% Torques 100%	42 ± 21	84
Variability 75% Torques 125%	49 ± 20	91
Maximised window	14 ± 30	19
Gymnast	7 ± 13*	17*

* Numbers based on the 60 trials from Hiley et al. (2007) assuming similar release windows for the additional 40 unsuccessful Tkatchevs to the 20 analysed

Optimising without variability can produce a significantly larger release window (103 ms) than any of the analysed gymnast performances (Table 3). However, when the solution was randomly perturbed in 1000 simulations the average release window was 14 ms and only 19% resulted in a successful release window (Table 3). It is therefore important that optimisations should include those aspects of human movement which are likely to have a direct impact on the outcome.

A method of optimising technique including variability based on human performances has been presented. The consistency of performance could be improved through changes to technique as well as increases in strength. While a specific gymnastics movement has been studied there are general implications for the study and understanding of human movement. The precision with which movement can be repeated has a marked effect upon consistency and success in a limiting movement. In optimisation studies it is necessary to consider issues of robustness to timing and angle variability and to base such analyses on measured levels of coordination precision.

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