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Maximising somersault rotation in tumbling

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ABSTRACT

Performing complex somersaulting skills during the flight phase of tumbling requires the generation of linear and angular momenta during the approach and takeoff phases. This paper investigates how approach characteristics and takeoff technique affect performance with a view to maximising somersault rotation in tumbling. A five-segment planar simulation model, customised to an elite gymnast, was used to produce a simulation which closely matched a recorded performance of a double layout somersault by the elite gymnast. Three optimisations were carried out to maximise somersault rotation with different sets of initial conditions. Using the same initial linear and angular momentum as the double layout somersault and varying the joint torque activation timings allowed a double straight somersault to be performed with 19% more rotation potential than the actual performance. Increasing the approach velocity to a realistic maximum of 7 ms^{-1} resulted in a 42% reduction in rotation potential when the activation timings were unchanged but allowed a triple layout somersault to be performed with an increase of 31% in rotation potential when activation timings were re-optimised. Increasing also the initial angular momentum to a realistic maximum resulted in a 4% reduction in rotation potential when the activation timings were unchanged but allowed a triple straight somersault to be performed with a further increase of 9% in rotation potential when activation timings were re-optimised. It is concluded that the limiting factor to maximising somersault rotation is the ability to generate high linear and angular velocities during the approach phase coupled with the ability to adopt consonant activation timings during the takeoff phase.

Keywords : tumbling, gymnastics, simulation model, optimisation

INTRODUCTION

Tumbling is a dynamic activity performed by gymnasts and tumblers from an elastic takeoff surface. In Artistic Gymnastics, gymnasts perform tumbling sequences on a sprung floor which has a diagonal length of 17 m whereas in tumbling there is a 26 m sprung track with an additional 11 m run-up. As a consequence tumblers are able to generate more linear and angular momenta during the approach phase. A typical tumbling sequence starts with an approach run where linear momentum is generated, followed by a round-off and flic-flac, during which angular momentum is produced, and culminates in a somersaulting skill. During the somersault takeoff phase the gymnast is able to change the linear and angular momenta by applying muscular torques. The performance of the somersaulting skill is dependent on the linear and angular momenta at takeoff and the configuration changes used by the gymnast during flight. The two most important factors for successful performance are the vertical velocity of the mass centre and the angular momentum about the mass centre at

takeoff (Brüggemann, 1983, 1987; Hwang et al., 1990) since the product of these two factors dictates how much somersault rotation can be achieved.

The characteristics of the approach are obviously important for a successful performance in tumbling. For example Brüggemann (1987) showed that the angular momentum and horizontal velocity at touchdown were closely related to the height achieved in the flight phase ($r = 0.81$). For the maximisation of somersault rotation it might be expected that a faster approach will be better, since this will result in more energy at touchdown and the potential to have more energy at takeoff. However upper limits for the generation of angular momentum and horizontal approach velocity have not been quantified.

The technique used by the gymnast or tumbler during the takeoff phase is also clearly important for a successful performance with gymnasts spending years learning the techniques required to perform a given tumbling movement. However, little is known about the relationship between muscle activation timings and subsequent performance.

The purpose of this paper is to investigate how approach characteristics and takeoff technique affect performance with a view to maximising somersault rotation in tumbling.

METHOD

A computer simulation model of the takeoff phase in tumbling was developed and customised to an elite gymnast through the determination of subject specific inertia and strength parameters. A simulation was produced which matched an actual performance of a double layout somersault by the elite gymnast. The simulation model was then used to maximise somersault rotation by varying the technique used during the takeoff phase for three sets of initial conditions at touchdown with the tumbling track.

Ninety-five anthropometric measurements of the elite gymnast were taken and segmental inertia parameters were calculated using the mathematical model of Yeadon (1990b). One double layout somersault by the gymnast was recorded using a Locam 16mm cine camera operating at 200 Hz and two 50 Hz Hi8 video cameras. The Locam and one video camera were oriented perpendicular to the tumbling track and the other video camera was positioned behind the landing area. Fifteen body landmarks (wrist, elbow, shoulder, hip, knee, ankle and toe on both sides of the body plus the centre of the head) were digitised throughout the movement from both camera views. Quintic splines were fitted to the digitised data (Wood and Jennings, 1979). The closeness of fit at each point was based on the difference between the data and a pseudo data set that was generated by averaging the digitised data from the two adjacent times. DLT reconstructions (Abdel-Aziz and Karara, 1971) were then carried out to synchronise the digitised data (Yeadon and King, 1999) and obtain 3D co-ordinate time histories of each body landmark at 0.005 s time intervals for the takeoff phase and 0.020 s time intervals for the flight phases. The 3D data were then used to calculate orientation and configuration angles (Yeadon, 1990a) which were fitted with quintic splines (Wood and Jennings, 1979) in order to obtain angle and angular velocity estimates. Error estimates were again obtained using pseudo data sets. The mass centre location was calculated from the 3D data and the segmental inertia parameters of the gymnast. The mass centre locations at the start and end of the flight phases before and after contact with the tumbling track were used to determine the horizontal and vertical mass centre velocities at touchdown and takeoff using equations of constant acceleration. The whole body angular momentum about the mass centre at touchdown and takeoff from the tumbling track were calculated as the mean angular momenta values during each flight phase (Yeadon, 1990c).

Maximal isovelocitv extension torque data were collected for the gymnast using a two repetition concentric-eccentric protocol at preset crank angular velocities ranging from 20°s^{-1} to 250°s^{-1} for the ankle, knee, hip and shoulder using an KinCom 125E dynamometer. The joint torque data obtained were fitted using an 18 parameter exponential function of angular velocity and angle (King and Yeadon, 2002). The 18 torque parameters for each joint were calculated by minimising the sum of squares of differences between the measured torque values and the exponential function using Simulated Annealing (Goffe et al., 1994). The gymnast gave informed consent for these procedures in accordance with the protocol approved by the Loughborough University Ethical Advisory Committee.

A planar five-segment model consisting of a foot, shank, thigh, trunk + head, and arm + hand segments was developed for simulating the takeoff phase of tumbling (Figure 1). The elastic properties of the tumbling track were represented by massless damped linear springs which applied horizontal and vertical forces at the toe and vertical forces at the ankle when the toe and/or heel were in contact with the tumbling track. The model had four torque generators T_a , T_k , T_h and T_s (Figure 1) which opened (increased) the ankle, knee, hip and shoulder joint angles a_a , k_a , h_a and s_a (extension at the ankle, knee and hip; flexion at the shoulder). At a given moment in time the torque exerted at a joint was the product of the maximum attainable torque at given joint angle / angular velocity and the torque activation level at that time (between zero and one). Each torque generator was allowed to have an initial torque value corresponding to a maximum of 50% of full activation and to remain at this level for a period of time before ramping up to the final level (less than or equal to full activation). The ramping function increased from zero to the final level over a time period greater than or equal to 50 ms (King and Yeadon, 2003). A rotational elastic component with a stiffness value of $465 \text{ Nm}\cdot\text{rad}^{-1}$ was included in series with the torque generator at the ankle joint. This stiffness value was based upon an elastic element of length 0.314 m in the muscle-tendon complex of the tricep-surae muscle group with a moment arm of 0.046 m (Jacobs et al., 1996) and a maximum stretch of the elastic element of 4% at maximum torque (Bobbert and van Ingen Schenau, 1990).

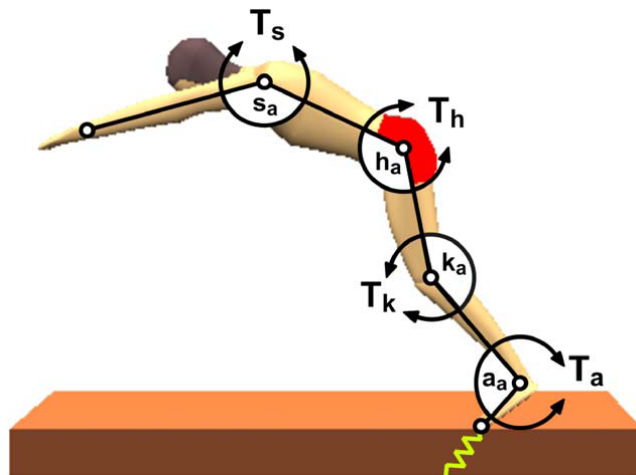


Figure 1. The five-segment simulation model of tumbling takeoff. Four torque generators (T_a , T_k , T_h , T_s) open the ankle, knee, hip and shoulder joint angles a_a , k_a , h_a and s_a and two springs allow for horizontal and vertical movement of the tumbling track.

The FORTRAN code implementing the model was generated using the Autolev software package which is based on Kane's method of formulating the equations of motion (Kane and Levinson, 1985). Subject specific model parameters comprised the previously

determined segmental inertias and joint torque parameters. Input to the simulation model comprised the motion of the system just prior to touchdown of the model with the tumbling track (mass centre velocity, orientation of each segment, angular velocity of each segment) and for each torque generator: the initial activation, the onset time, the ramp time and the final (greatest) activation level. The output from the model comprised whole body angular momentum about the mass centre, mass centre velocity, orientation and angular velocity of each segment at the time of takeoff from the tumbling track. The simulated performance during flight was then determined using a three-dimensional 11-segment model of aerial movement (Yeadon et al., 1990) which used configuration angles as input.

A matching procedure was used to obtain a simulation that was in close agreement with the recorded double layout somersault performance. The Simulated Annealing algorithm (Goffe, et al., 1994) was used to obtain the best match by minimising a cost function which was based on the difference between a simulation and the actual performance in terms of strategy used (val_s) and takeoff (val_t). The strategy component consisted of the four joint angles at takeoff, the trunk segment angle at takeoff and the minimum ankle and knee angles during the takeoff phase. For the calculation of val_s each joint (ankle, knee, hip and shoulder) was given a weighting of 1/8 and the trunk angle was given a weighting of 1/2 (equal to the total weighting of the joint angles) since the trunk angle represented the whole body orientation whereas the joint angles defined the configuration. val_s therefore measured the difference in the strategy used between a simulation and the actual performance in degrees. The takeoff component comprised the horizontal and vertical velocity of the mass centre and the whole body angular momentum at takeoff. The weightings for each variable in val_t were set in proportion to the inverse of the value of each variable from the actual performance. The effect of using these weightings was that val_t represented the average percentage difference between a simulation and an actual performance in terms of the velocity and angular momentum at takeoff. The cost function for a simulation was then calculated by averaging val_t and val_s since 10% for val_t was considered to be comparable with 10° for val_s .

The initial conditions for the matching simulation were estimated from the video analysis of the actual performance and corresponded to the time of touchdown with the tumbling track. The mass centre velocity and the segment angles were fixed at the values estimated from the video analysis as these were considered to be sufficiently accurate. The five initial segment angular velocities, however, were allowed to vary by $\pm 50^\circ/\text{s}$ in the matching optimisation as these estimates were not considered to be very accurate. In addition 20 other parameters were varied in the matching optimisation. Sixteen of these specified technique by defining the activation time histories of the four torque generators (initial activation, the time that the activation changes from the initial level, the ramp time and the final (greatest) activation level) and four parameters governed the characteristics of the elastic tumbling track. The Simulated Annealing algorithm (Goffe et al., 1994) was used to vary the 25 parameters until the cost function was minimised and the best match was found. The optimisation routine was run with different initial conditions for the parameters to guard against the routine becoming stuck in a local minimum. A typical optimisation evaluated up to 20,000 simulations and took 24 hours to run.

Values for the horizontal approach velocity and whole body angular velocity at the start of the takeoff phase were calculated for an elite male tumbler who performed one double straight somersault and one triple twisting double straight somersault. The maximum values obtained were then increased by 10% to give realistic limiting values for the horizontal velocity and angular momentum at touchdown.

Three optimisations were carried out to maximise rotation potential (flight time \times angular momentum at takeoff) for various initial conditions. The flight time was constrained

to be greater than 1.05 s (that of the actual double layout somersault performance) to ensure that the optimum simulations were not unrealistically fast and low. For each optimisation 21 parameters were varied, 16 of which defined the activation time histories for the four torque generators, while the remaining five parameters defined the initial body configuration and orientation. The difference between the three optimisations was in the initial linear and angular momenta (at touchdown) input to the simulation model. For the first optimisation (Optimisation 1) the linear and angular momenta at touchdown were fixed at the values obtained for the actual double layout performance. For the second optimisation (Optimisation 2) the initial horizontal velocity at touchdown was allowed to vary (up to the limiting value) and in the third optimisation (Optimisation 3) the initial angular momentum at touchdown was allowed to vary as well (up to the limiting value). In addition to the three optimisations, two single simulations were performed to establish the effect of changing the initial conditions without re-optimising the technique used. The first single simulation used the technique from Optimisation 1 with the optimised horizontal velocity at touchdown from Optimisation 2. The second single simulation used the technique from Optimisation 2 with the optimised angular momentum at touchdown from Optimisation 3. The simulation model of Yeadon et al. (1990) was used with the results of each simulation of the takeoff phase to determine how much somersault rotation could be achieved during the flight phase. Two configuration strategies were used during the flight phase, one corresponding to the layout configuration used by the gymnast in the actual double layout somersault and the other corresponding to a straight configuration with the arms by the sides and the body extended. The lower moment of inertia for the layout configuration permits more rotation than the straight configuration.

RESULTS AND DISCUSSION

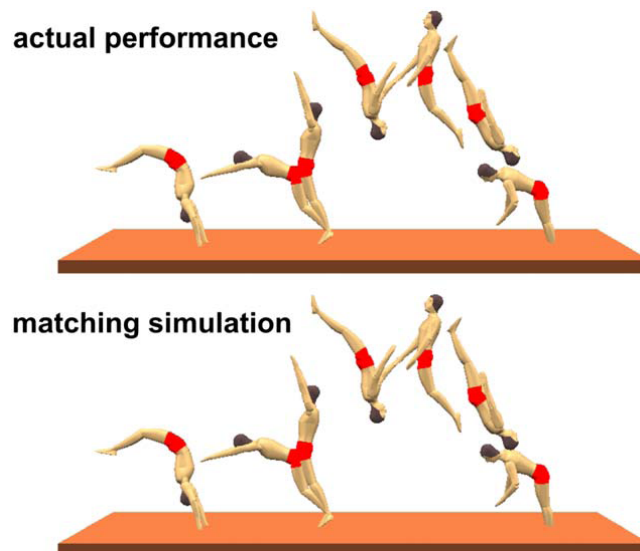


Figure 2. Comparison of actual performance and matching simulation of a double layout somersault (the gymnast approaches from the left with a backward handspring).

By optimising the initial segment angular velocities (Table 1), the activation timings (Table 2) and the stiffness / damping parameters for the tumbling track (horizontal stiffness: $131,361 \text{ Nm}^{-1}$, vertical stiffness: $56,732 \text{ Nm}^{-1}$, horizontal damping: 0 Nsm^{-1} , vertical damping: 148 Nsm^{-1}) close agreement was obtained between the actual double layout somersault

performance and the matching simulation (Figure 2). The average difference in linear and angular momenta at takeoff from the tumbling track was less than 1%, and the average difference in segment angles at takeoff was less than 1° (Table 3). It would therefore appear that using a simple activation profile defined by four parameters is able to approximate the activation profile at each joint. In the future it would be useful to compare the activations timings used to EMG data collected during tumbling movements. More complex activation profiles could have been used in the study and this may have improved the agreement in the joint angle changes (Figure 3). This, however, would have required many more parameters to be varied. The overall agreement between actual performance and the matching simulation was considered to be sufficiently close to allow the simulation model to be used to investigate how changing the approach characteristics and technique affects the production of rotation potential during the takeoff phase.

Table 1. Initial conditions at touchdown for the matching double layout simulation and the three optimisations

variable	matching	Opt 1	Opt 2	Opt 3
u_g [ms^{-1}]	4.83	4.83	7.00	7.00
v_g [ms^{-1}]	-0.27	-0.27	-0.27	-0.27
a_a	100°	111°	113°	96°
k_a	144°	146°	145°	141°
h_a	116°	114°	130°	131°
s_a	148°	135°	125°	140°
tr_a	17°	13°	23°	20°
cm_a	57°	54°	51°	47°
a_ω	-821°s ⁻¹	-821°s ⁻¹	-821°s ⁻¹	-821°s ⁻¹
k_ω	-278°s ⁻¹	-278°s ⁻¹	-278°s ⁻¹	-278°s ⁻¹
h_ω	715°s ⁻¹	715°s ⁻¹	715°s ⁻¹	715°s ⁻¹
s_ω	-157°s ⁻¹	-157°s ⁻¹	-157°s ⁻¹	-157°s ⁻¹
tr_ω	931°s ⁻¹	955°s ⁻¹	924°s ⁻¹	1005°s ⁻¹

Note: a_i , k_i , h_i , s_i and tr_i = the ankle, knee hip, shoulder and trunk angles ($i = a$) and angular velocities ($i = \omega$) at touchdown; u_g and v_g = the horizontal and vertical velocity of the mass centre at touchdown. cm_a = the angle of the mass centre to toe line relative to the horizontal at touchdown (body orientation at touchdown). The trunk angle tr_a is the angle the trunk makes with the horizontal and the joint angles are shown in Figure 1.

Using torque generators is a potential limitation of the study as the effect of biarticular muscles are not completely accounted for when determining the velocity of shortening during a simulation. However using torque generators does allow subject specific parameters to be determined which includes the torque produced by biarticular muscles. Since the model has

previously been evaluated (Yeadon and King, 2002) and the matching in the current study is good, the effect of neglecting to model biarticular muscles specifically is assumed to be small. The inclusion of a series elastic element at the ankle joint has previously been shown to improve the agreement between actual performance and simulation by less than 2% (Yeadon and King, 2002). Thus any errors arising from the use of data from the literature for the amount of stretch in the series elastic element and the lengths of the contractile and elastic elements will have small effect and will not affect the findings of the study.

An elite tumbler was found to have a horizontal velocity of approximately 6.4 ms^{-1} and a whole body angular velocity of approximately 720°s^{-1} at touchdown when performing a double straight somersault and a triple twisting double straight somersault. Limiting values for the approach velocity and angular velocity were estimated at 7.0 ms^{-1} and 800°s^{-1} . These were considered to be achievable limiting values in that they were 10% higher than the measured velocities.

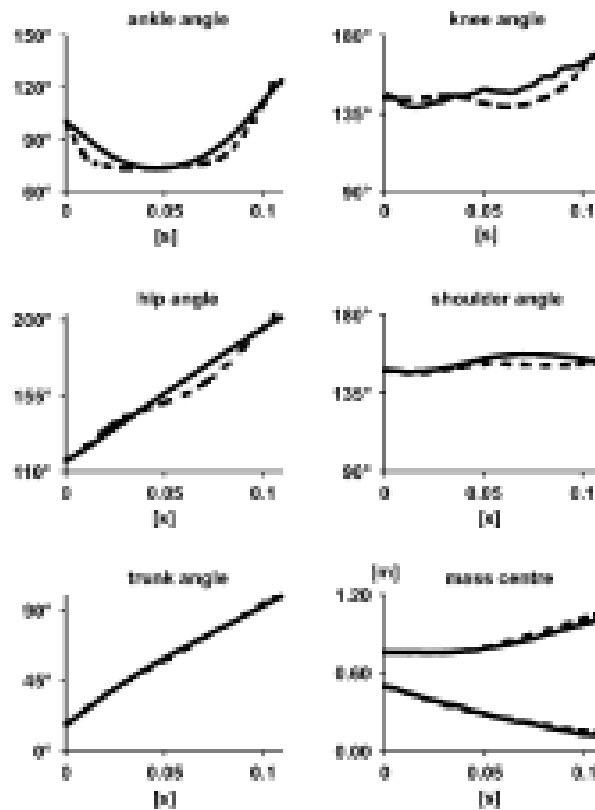


Figure 3. Comparison of key kinematic variables during the takeoff phase; solid line = actual performance, dashed line = matching simulation data.

Optimisation 1 demonstrated that it was possible to adopt suitable activation timings in order to change the linear and angular momenta at takeoff and produce a double straight somersault (Figure 4). Optimisation 1 had lower activation levels at the knee and greater activation levels at the hip and shoulder compared to the matching simulation (Table 2) resulting in greater knee flexion at takeoff (Table 3). In addition the orientation of the body at touchdown was 3° lower than the matching simulation (Table 1). The optimum simulation had sufficient height and angular momentum to permit a straight body configuration during flight and to land on the tumbling track. This was a significant improvement (19% more rotation potential) on the actual double layout somersault performance which landed on a mat in a foam filled landing pit. The total energy at takeoff for the optimum solution was 1%

more than in the matching simulation which was 4% more than the energy at touchdown. It would therefore appear that optimising the activation profiles is able to change the distribution of linear and angular momenta during takeoff but does not have a large effect on the total energy of the system. As a consequence, maximising somersault rotation appears to require high initial kinetic energy at touchdown along with suitable activation timings during the takeoff phase.

Table 2. Activation parameters for the four torque generators in the matching double layout simulation and the three optimisations

parameter	matching	Opt 1	Opt 2	Opt 3
i_a	5%	5%	5%	5%
i_k	11%	14%	11%	38%
i_h	34%	48%	48%	50%
i_s	18%	50%	49%	50%
t_a	0.118 s	0.077 s	0.072 s	0.066 s
t_k	0.074 s	0.157 s	0.283 s	0.135 s
t_h	0.034 s	0.027 s	0.027 s	0.025 s
t_s	0.281 s	0.415 s	0.025 s	0.025 s
r_a	0.103 s	0.050 s	0.050 s	0.050 s
r_k	0.063 s	0.070 s	0.180 s	0.120 s
r_h	0.057 s	0.051 s	0.051 s	0.050 s
r_s	0.261 s	0.372 s	0.050 s	0.050 s
max_a	100%	100%	100%	100%
max_k	91%	98%	91%	100%
max_h	100%	100%	100%	100%
max_s	100%	100%	100%	100%

Note: i_j = the initial activation expressed as a percentage of full activation for ankle ($j=a$), knee ($j=b$), hip ($j=h$), shoulder ($j=s$), t_j = the time that the activation reaches final (greatest) level, r_j = the corresponding ramp time and max_j = final activation level reached in a simulation as a percentage of full activation.

Optimisation 2 was used to determine the optimum horizontal approach velocity for maximising somersault rotation. The optimum solution was found to use the maximum permitted horizontal velocity of 7.0 ms^{-1} (Table 1) and with a consonant technique during the takeoff phase (Table 2) produced sufficient rotation potential (31% increase above Optimisation 1) to allow a triple layout somersault to be produced with the landing into a pit 9 (Figure 4). Without the changes in activation timings and body configuration and orientation

at touchdown the increase in approach velocity had a detrimental effect with a 42% reduction in the rotation potential at takeoff of Optimisation 1. This demonstrated that an increase in the horizontal velocity at touchdown is only beneficial if it is accompanied by the appropriate activation timings. The differences in the activation profiles between Optimisation 1 and Optimisation 2 were at the knee and shoulder where the knee activation profile was reduced and the shoulder was activated maximally (Table 2) resulting in greater knee flexion at takeoff. These differences allow more angular momentum to be produced during the takeoff phase. The initial orientation of the body (at touchdown) was 3° lower than in Optimisation 1 (Table 1). The total energy at takeoff was within 1% of the energy at touchdown, with the total energy approximately 40% greater at touchdown and takeoff when compared with the double layout performance. Therefore a triple layout somersault requires a much faster approach with more energy generated and appropriate activation timings during the takeoff phase. As a consequence a triple layout somersault could not be performed in Artistic Gymnastics in the floor exercise where the restricted run-up results in approach velocities of around 4.5 ms⁻¹ (Hwang, Seo and Liu, 1990). An additional optimisation was carried out with the upper bound for the horizontal approach velocity removed and an optimum approach velocity of 10.7 ms⁻¹ was found beyond which the knees started to collapse during the takeoff phase.

Table 3. Comparison of the double layout performance with the matching simulation and the three optimisations

variable	actual	matching	Opt 1	Opt 2	Opt 3
u_g [ms ⁻¹]	2.48	2.51	1.91	3.59	2.97
v_g [ms ⁻¹]	4.71	4.72	4.72	5.27	5.62
h_g [kgm ² .rads ⁻¹]	96	97	116	138	143
a_{amin}	74°	73°	73°	73°	71°
a_a	125°	126°	133°	119°	111°
k_{amin}	142°	139°	131°	130°	119°
k_a	168°	169°	142°	136°	123°
h_a	202°	202°	180°	175°	177°
s_a	153°	153°	168°	163°	168°
tr_a	99°	98°	92°	94°	92°

Note: For strategy component val_s: a_{amin} and k_{amin} = the minimum ankle and knee angles; a_a , k_a , h_a , s_a and tr_a = the ankle, knee hip, shoulder and trunk angles at takeoff. For takeoff component val_t: u_g and v_g = the horizontal and vertical velocity of the mass centre at takeoff; h_g = the angular momentum about a transverse axis through the mass centre at takeoff.

Optimisation 3 found that having greater whole body angular momentum at touchdown (18% increase) was beneficial for the maximisation of somersault rotation so long as a suitable technique could be adopted. The optimum solution possessed 9% more rotation potential than Optimisation 2 and this was sufficient to allow a triple straight somersault to be performed with the landing on the tumbling track (Figure 4). Without the changes in

activation timings and body configuration and orientation at touchdown the increase in angular momentum at touchdown had a detrimental effect with a 4% reduction in the rotation potential at takeoff when compared with Optimisation 2. This demonstrated that an increase in the angular momentum at touchdown is only beneficial if it is accompanied by the appropriate technique. The initial orientation of the body (at touchdown) was 4° lower than in Optimisation 2 (Table 1) and the major difference in the activation timings was at the knee where the activation level was higher. This is probably due to the increased loading on the knee (higher initial angular momentum) requiring a higher knee torque to ensure that the knee extends before takeoff. Again the energy at touchdown and takeoff were similar and were approximately 50% greater than the energy of the actual double layout somersault performance.

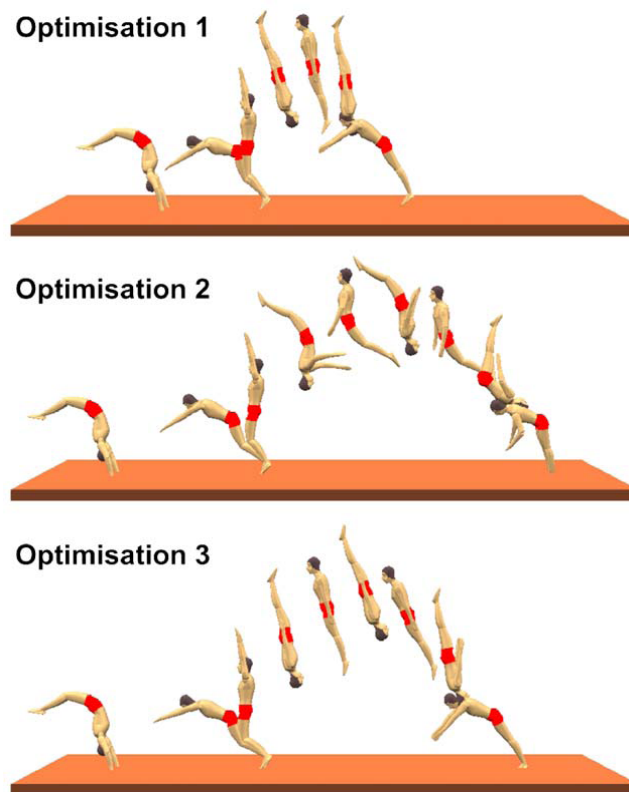


Figure 4. Graphics sequences showing the optimum simulations for maximising rotation with (1) original approach velocities (2) horizontal approach velocity of 7 ms^{-1} (3) angular approach velocity of 800°s^{-1} and horizontal approach velocity of 7 ms^{-1} .

A simple maximisation of somersault rotation was used as an optimisation criterion in this study and the conditions for producing a triple somersault with a straight body were found. It may be concluded that the limiting factor to maximising somersault rotation is the ability to generate high linear and angular velocities during the approach phase coupled with the ability to adopt consonant activation timings during the takeoff phase. In practice a gymnast will adopt an optimisation strategy that produces a robust solution that is also close to optimal in the above narrow sense of maximising rotation potential. In other words small errors in technique will produce only a small reduction in performance. In future analyses such considerations should be included in optimisation criteria since there is evidence that robustness can explain technique in, for example, targeted movements (Harris and Wolpert, 1998).

Acknowledgments

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