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Coping with perturbations to a layout somersault in tumbling

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Abstract

Tumbling is a dynamic movement requiring control of the linear and angular momenta generated during the approach and takeoff phases. Both of these phases are subject to some variability even when the gymnast is trying to perform a given movement repeatedly. This paper used a simulation model of tumbling takeoff to establish how well gymnasts can cope with perturbations of the approach and takeoff phases. A five segment planar simulation model with torque generators at each joint was developed to simulate tumbling takeoffs. The model was customised to an elite gymnast by determining subject specific inertia and torque parameters and a simulation was produced which closely matched a performance of a layout somersault by the gymnast. The performance of a layout somersault was found to be sensitive to the approach characteristics and the activation timings but relatively insensitive to the elasticity of the track and maximum muscle strength. Appropriate variation of the activation timings used during the takeoff phase was capable of coping with moderate perturbations of the approach characteristics. A model of aerial movement established that variation of body configuration in the flight phase was capable of adjusting for takeoff perturbations that would lead to rotation errors of up to 8%. Providing the errors in perceiving approach characteristics are less than 5% or 5° and the errors in timing activations are less than 7 ms, perturbations in the approach can be accommodated using adjustments during takeoff and flight.

Keywords : tumbling, gymnastics, simulation model

Introduction

Tumbling is a dynamic activity performed by gymnasts from an elastic takeoff surface. A typical tumbling sequence starts with an approach run where linear momentum is generated, followed by a round-off and backward handspring (flic-flac) during which angular momentum is produced culminating in a somersaulting skill (Boone, 1976). During the somersault takeoff phase the gymnast is able to change the linear and angular momenta by applying muscular torques. The flight phase 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. For any given skill there will be a range of linear and angular momenta at takeoff which will allow a skill to be performed since the gymnast can make adjustments to body configuration during flight. The two most important factors for successful performance during flight are the vertical velocity of the mass centre and the angular momentum about the mass centre at takeoff from the floor (Brüggemann, 1983 and 1987; Hwang, Seo and Liu, 1990) since the product of these two factors dictates how much somersault rotation can be achieved.

The approach characteristics, track elasticity, muscle activation timings and muscle strength are all important for a successful tumbling performance. In particular the angular momentum and horizontal velocity at touchdown have been found to be closely related ($r = 0.81$) to the height achieved in flight (Brüggemann, 1987). The elasticity of a tumbling track or gymnastics floor depends on the manufacturer and it has been suggested that as the stiffness of the tumbling track increases so should the angle of the body at touchdown (Toderov and Cooper, 1989). The technique (joint angle changes / muscle activations) used by the performer during the takeoff phase will also affect performance although little is known about the relationship between activation timings / muscle strength and performance (Brüggemann, 1983). Small perturbations of the approach characteristics, floor elasticity, activation timings and muscle strength will occur and will affect the linear and angular momenta at takeoff and consequently the amount of somersault that can be produced during flight.

Gymnasts need to be able to control the amount of somersault produced during flight and therefore they need to be able to perceive and cope with perturbations in the approach characteristics, floor elasticity, activation timings and muscle strength. There are two possible strategies that could be employed by a gymnast to accommodate such perturbations. Firstly, a gymnast could adjust the activation timings during the takeoff phase, as this would alter the joint torques used and therefore change the linear and angular momentum at takeoff. Secondly, adjustment of the body configuration during the flight phase (within the bounds of the given skill) could cope with some variation in the linear and angular momenta at takeoff.

The purpose of this paper is to investigate the sensitivity of performance to perturbations of the approach characteristics, floor elasticity, activation timings and muscle strength, and to determine the effectiveness of the two strategies that can be used to cope with these perturbations.

Methods

A computer simulation model of the takeoff phase in tumbling was developed and was 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 layout somersault by the elite gymnast. The simulation model was then used to determine the sensitivity of tumbling performance to changes in the approach and takeoff phases.

Anthropometric measurements of an elite gymnast were taken and segmental inertia parameters were calculated using the mathematical model of Yeadon (1990b). One layout somersault and one double layout somersault performed by the gymnast from a tumbling track onto a landing mat in a safety pit were recorded using a Locam 16mm cine camera operating at 200 Hz and a 50 Hz video camera. 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 manually throughout the movements. A DLT reconstruction (Abdel-Aziz and Karara, 1971) was then carried out to synchronise the digitised data (Yeadon and King, 1999) and obtain 3D co-ordinate time histories of each digitised body landmark. The co-ordinate data were then used to calculate mass centre location and orientation and configuration angles to which quintic splines were fitted (Wood and Jennings, 1979) in order to obtain whole body angular momentum about the mass centre (Yeadon, 1990a, c). Mass centre velocity at touchdown / takeoff were calculated from the displacement data over the flight phase assuming constant acceleration. Strength measurements were taken during eccentric-concentric movements using an isovelocity dynamometer (KinCom 125E), with crank angular velocities ranging from $20^{o}s^{-1}$ to $250^{o}s^{-1}$, in order to express torque as a function of joint angle and angular velocity at the ankle, knee, hip and shoulder joints (King and Yeadon, 2002). 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 foot contact phase of tumbling (Figure 1). The elastic properties of the tumbling track were represented by two massless damped linear springs which allowed for horizontal and vertical movement. The model had four torque generators which opened the ankle, knee, hip and shoulder joint angles a_a, k_a, h_a and s_a (Figure 1). Each torque generator was allowed to have an initial value of up to 50% of full activation and to remain at this level for a period of time before ramping up to some upper limit (less than or equal to full activation). The ramping function increased from zero to the upper limit over a time period greater than or equal to 50 ms. A rotational elastic component was included in series with the torque generator at the ankle joint (King and Yeadon, 2002).

The FORTRAN code implementing the model was generated using the Autolev software package (Kane and Levinson, 1985). Subject specific model parameters comprised the previously obtained segmental inertias and joint torque parameters. Input to the simulation model comprised the motion of the system just prior to the initial contact with the tumbling track (mass centre velocity, orientation of each segment, angular velocity of each segment) and parameters for each torque generator (initial activation, onset time, ramp time, level of maximum activation). 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. These data at takeoff were used as the initial conditions for an 11 segment simulation model of aerial movement (Yeadon et al., 1990) so that the somersault rotation during flight could be determined. The aerial model required time histories of the configuration throughout flight. Over the first 100 ms the configuration at takeoff was merged into the configuration used in the actual performance which was then used for the remainder of the flight. The flight phase ended when the mass centre was the same height as the actual performance at landing.

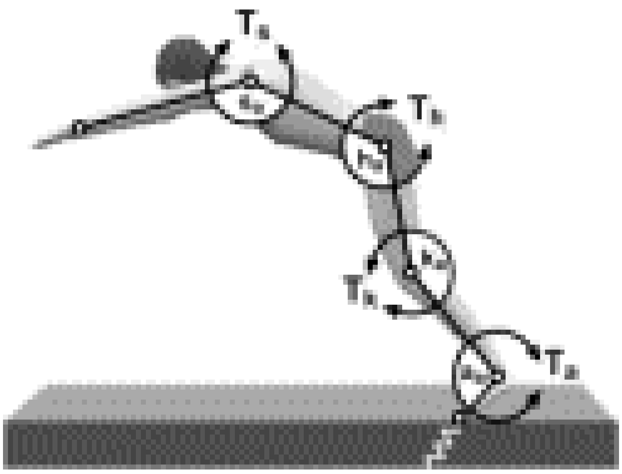

Figure 1. The five segment simulation model of tumbling takeoff. Four torque generators (T_a, T_k, T_h, T_s) open the ankle, knee, hip and shoulder joint angles a_a, k_a, h_a and s_a and two springs allow for horizontal and vertical movement of the tumbling track.

The simulation model has previously been evaluated by comparing simulations with an actual double layout somersault performance by the elite gymnast. Good agreement was demonstrated with an average difference of 5° in the joint angles during the contact phase and an average difference of 1% in linear and angular momenta at takeoff (Yeadon and King, 2002).

The Simulated Annealing algorithm (Goffe, et al., 1994) was used to obtain a matching simulation which was in close agreement with the image analysis of the actual layout somersault performance by minimising a cost function based on the difference between a simulation and the actual performance in terms of strategy (val_s) and takeoff (val_t). The strategy component consisted of the four joint angles at takeoff, the trunk angle at takeoff and the minimum ankle and knee angles during the takeoff phase. 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. For the calculation of val_s each joint angle describing body configuration was given an equal weighting and the trunk angle describing whole body orientation was given a weighting equal to the total weighting of the joint angles. val_s therefore measured the difference in the strategy used between a simulation and the actual performance in degrees. The score (cost function) for a simulation was then calculated by summing val_t and val_s with equal weighting given to val_t, and val_s as 10% for val_t was considered to be comparable with 10° for val_s.

The initial conditions for each simulation were estimated from the image analysis of the actual performance and corresponded to the time of initial contact with the tumbling track (Table 1). The initial mass centre velocity and segment angles were fixed at the values estimated from the video analysis as these were considered to be sufficiently accurate. However, the initial segment angular velocities were allowed to vary somewhat ($\pm 50°s^{-1}$) in the matching optimisation as these estimates were not considered to be so accurate. In addition 20 other parameters were varied in the matching optimisation. Sixteen of these defined the activation time histories of the four torque generators (Table 2) and four parameters governed the characteristics of the elastic tumbling track. The Simulated Annealing algorithm was used to vary the 25 parameters within realistic limits until the best match was found.

Table 1. Initial conditions at touchdown with the tumbling track for the matching layout somersault simulation

variable	layout simulation
u_g	4.46 ms^{-1}
v_g	-0.67 ms^{-1}
a_a	108°
k_a	157°
h_a	110°
tr_a	5°
s_a	152°
a_ω	-503°s^{-1}
k_ω	-657°s^{-1}
h_ω	344°s^{-1}
tr_ω	932°s^{-1}
s_ω	-221°s^{-1}

Note: a_i, k_i, h_i, tr_i and s_i = the ankle, knee hip, trunk and shoulder angles (i = a) and angular velocities (i = ω) at touchdown, u_g and v_g = the horizontal and vertical velocity of the mass centre 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.

Some variation in the rotation potential (takeoff angular momentum × time of flight) can be coped with by modifying the configuration during the flight phase. The simulation model of aerial movement (Yeadon et al., 1990) was used to determine the range in rotation potential associated with a layout somersault. The configuration changes used were allowed to vary within the bounds of an acceptable layout somersault (hip flexion / extension was limited to 20° and arms were no higher than shoulder level during the middle phase of flight).

The first part of the sensitivity analysis investigated the effect of perturbations in the approach and takeoff phases on performance, while keeping the technique parameters (activation profiles) fixed at the values obtained in the matching simulation. Fourteen separate perturbations were made to the approach and takeoff phases: ±10° change in whole body orientation, ±10° change in body configuration (at each joint), ±10% change in horizontal velocity of the mass centre and ±10% change in whole body angular momentum at touchdown; ±10% change in stiffness and damping parameters for the elastic interface; ±10% change in the maximum strength possible at each joint and ±10 ms change in activation timings for each torque generator. In addition the magnitude of each perturbation was then adjusted until the rotation potential just lay within the acceptable bounds for a layout somersault while keeping the activation profiles fixed.

The second part of the sensitivity analysis investigated whether a layout somersault could be achieved for each of the initial perturbations if the activation profiles were changed during the takeoff phase. The optimisation procedure varied the 16 parameters which defined the activation profiles until the difference between the rotation potential of a simulation and that of the layout somersault was minimised. In order to investigate the sensitivity of performance to activation timings, the activation profiles were varied during the takeoff phase to determine whether a double layout somersault could be achieved for the approach characteristics of the layout somersault. The required linear and angular momenta at takeoff and the appropriate configuration during flight were determined from a double layout somersault performance by the elite gymnast. The 16 parameters which defined the activation profiles to the four torque generators were then varied until the difference between the rotation potential of a simulation and that of the double layout somersault was minimised.

Results

Using appropriate activation timings (Table 2) close agreement was found between the actual layout somersault performance and the matching simulation (Figure 2). The average change in the initial estimates (Table 1) of the segment angular velocities was 29°s^{-1} (corresponding to individual changes of 18°s^{-1}, -53°s^{-1}, -31°s^{-1}, 3°s^{-1} and 47°s^{-1} in the ankle, knee, hip, trunk and shoulder angular velocities). The average difference between the matching simulation and the actual performance in terms of linear and angular momenta at takeoff was less than 1%, and the average difference in segment angles at takeoff was less than 1° 9Table 3).

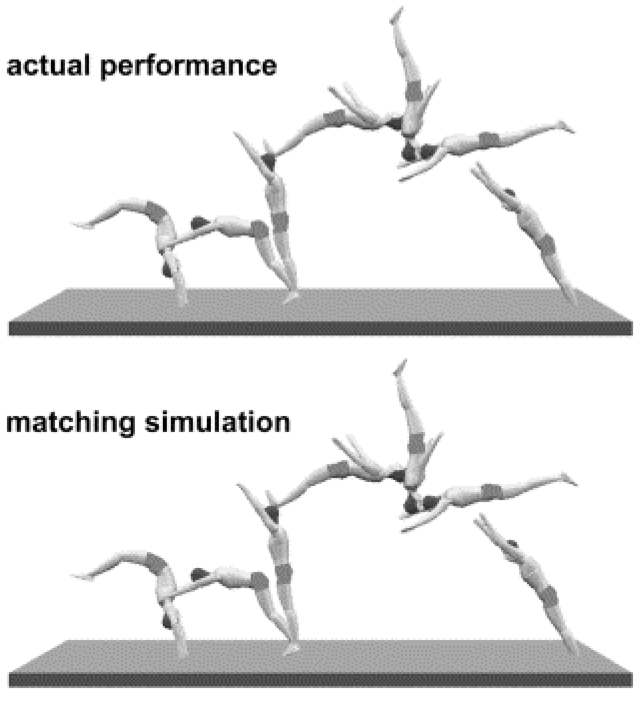

Figure 2. Comparison of actual performance and matching simulation of a layout somersault. In both sequences the approach is from the left: the first graphic shows the gymnast during the backward handspring, the second and third graphics show the touchdown and takeoff and the remainder show the subsequent flight phase where a layout somersault is performed. The close agreement indicates that the model is sufficiently accurate to investigate mechanisms for coping with perturbations in the approach and takeoff phases.

Table 2. Activation parameters for the four torque generators

parameter	matching layout simulation	double layout simulation
i_a	32%	5%
i_k	26%	29%
i_h	5%	8%
i_s	5%	50%
t_a	0.126 s	0.084 s
t_k	0.068 s	0.190 s
t_h	0.192 s	0.049 s
t_s	0.270 s	0.194 s
r_a	0.128 s	0.054 s
r_k	0.071 s	0.115 s
r_h	0.177 s	0.058 s
r_s	0.180 s	0.087 s
max_a	100%	100%
max_k	93%	85%
max_h	62%	100%
max_s	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 maximum, r_j = the corresponding ramp time and max_j = maximum activation reached in a simulation as a percentage of full activation.

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

variable		actual layout performance	matching layout simulation	double layout simulation
u_g	[ms^{-1}]	2.75	2.75	1.93
v_g	[ms^{-1}]	5.06	5.06	5.37
h_g	[$kgm^2.rads^{-1}$]	56	56	88
a_{amin}	[°]	72	72	72
a_a	[°]	125	127	120
k_{amin}	[°]	143	143	147
k_a	[°]	174	175	174
h_a	[°]	175	174	189
tr_a	[°]	78	79	86
s_a	[°]	154	151	189

Note: For strategy component val_s: a_{amin} and k_{amin} = the minimum ankle and knee angles, a_a, k_a, h_a, tr_a and s_a = the ankle, knee hip, trunk and shoulder 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.

By varying the configuration during flight it was found that it was possible for a layout somersault to be performed for a 16% range in the rotation potential (Figure 3). When the rotation potential lay outside this range, the configuration changes required to keep the total rotation the same rendered an unacceptable performance of a layout somersault.

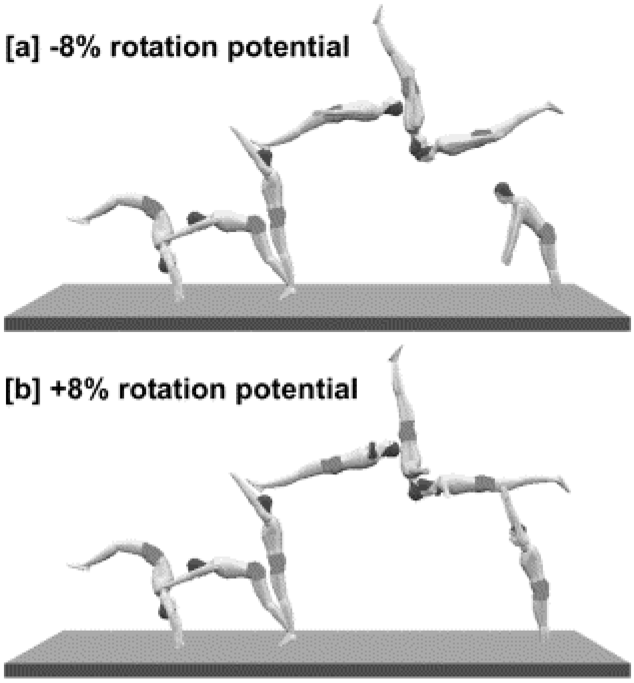

Figure 3. Aerial adjustments that can be made to cope with [a] -8% and [b] +8% change in rotation potential at takeoff from the tumbling track. The configuration changes shown are acceptable in the context of a layout somersault with less than 20° hip flexion / extension during mid-flight in [a] and the arms no higher than shoulder level during mid-flight in [b].

Perturbing the approach characteristics while keeping the activation profiles and timing fixed was found to have the greatest effect on performance, with a layout somersault not being possible for any of the initial perturbations (10% or 10°) as only a ±8% change in the rotation potential could be coped with by making changes to the aerial configuration (upper part of Table 4, Figure 3). In fact if technique was kept fixed during takeoff only small perturbations (less than 5% and 5°) could be coped with using aerial adjustments (lower part of Table 4).

Perturbing the stiffness and damping parameters by ±10% for the tumbling track had the smallest effect with a layout somersault possible for both perturbations even with the takeoff technique fixed. Furthermore a layout somersault was found to be possible for a +105% increase in the stiffness and damping parameters (lower part of Table4).

Perturbing the activation timings to the four torque generators by ±10 ms resulted in large changes in performance (upper part of Table 4), which were sufficient to prevent a layout somersault being achieved. To produce a layout somersault required the activation timings to be perturbed by no more than +4 ms to –7 ms (lower part of Table 4).

The ±10% perturbation in maximum strength at each joint had a small effect on performance with a layout somersault almost possible for both 10% perturbations with the takeoff technique fixed (upper part of Table 4).

Table 4. The effect of perturbations in the approach and takeoff phases on the performance of a layout somersault (activation profiles fixed). The upper part of the table (fixed perturbation) indicates how sensitive performance is to comparable perturbations. The lower part of the table (coping perturbation) indicates the perturbations that can be coped with by changes in aerial configuration.

	percentage changes					
	time of flight		angular momentum		rotation potential	
fixed perturbation	+	-	+	-	+	-
+10° / -10° orientation	-13	6	25	-22	18	-23
+10° / -10° configuration	-24	-34	-12	57	-31	18
+10% / -10% horizontal velocity	2	-4	-19	16	-23	19
+10% / -10% angular momentum	-12	-3	63	-49	67	-56
+10% / -10% stiffness and damping	-6	2	5	3	0	6
+10% / -10% muscle strength	3	-10	-4	19	-3	13
+10 ms / -10 ms activation timings	-16	3	33	-11	23	-12
coping perturbation						
+4° / -4° orientation	-4	3	9	-9	8	-8
+4° / -1° configuration	0	-8	6	14	8	8
+4% / -4% horizontal velocity	1	-2	-7	6	-8	8
+1% / -1% angular momentum	-1	0	7	-7	8	-8
+105% / -13% stiffness and damping	-26	2	24	4	-8	8
+45% / -5% muscle strength	6	-5	-11	10	-8	8
+4 ms / -7 ms activation timings	-5	3	10	-9	8	-8

Note: Angular momentum is about a transverse axis through the mass centre at takeoff and rotation potential = time of flight × angular momentum

For all the initial perturbations (10°, or 10%) there existed activation profiles which resulted in simulations with the correct amount of rotation potential to perform a layout somersault. In addition it was possible to vary the activation profiles to the four torque generators in order to allow a double layout somersault to be performed (Figure 4, Table 2 and Table 3).

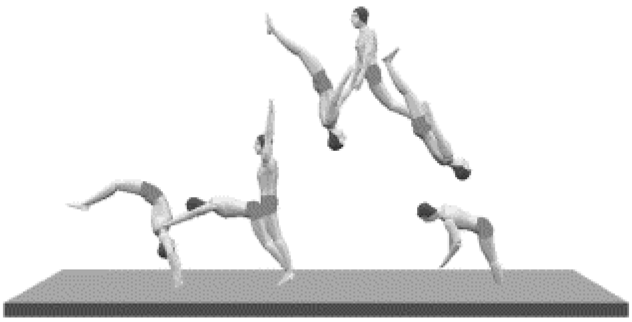

Figure 4. Simulation with activation timings adjusted so as to produce a double layout somersault. The graphics sequence uses the same configuration changes as the actual performance of a double layout somersault by the gymnast. This demonstrates the high sensitivity of performance to activation timings.

Discussion

The first aim of this paper was to investigate how sensitive tumbling performance is to perturbations of the approach characteristics, floor elasticity, activation timings and muscle strength. The performance of a layout somersault was found to be sensitive to the approach characteristics and the activation timings but relatively insensitive to the elasticity of the track and maximum muscle strength. The second aim was to determine the effectiveness of feedforward adjustments during the takeoff phase and feedback corrections during the flight phase. It was found that adjustments in activation timings were capable of coping with moderate perturbations of the approach while adjustments during flight could cope with moderate takeoff perturbations.

The simplicity of the activation profiles used is a potential limitation of the study. Although constraints of 50% and 50 ms were placed on the initial activation level and torque ramp time at each joint, the optimisation procedure chose initial activation levels ranging from 5% to 32% and ramp times ranging from 71 ms to 180 ms for the matching simulation of the layout somersault (Table 2). Since pre-contact EMG levels in drop jumps can be as high as 80% of eccentric values (Kovacs et al., 1999) and ramp times of lower extremity muscles can be as low as 80 ms (Freund and Budingen, 1978) these values may be considered to be reasonable. Even with the simplified activation profiles the model was able to match an actual performance and compensate for approach perturbations. The activation profiles correspond to neural profiles that are more complex than simple band-bang control and so there is some flexibility for matching the profiles of the actual performance. As a consequence these activation profiles may be expected to provide an adequate representation although there remains the possibility that a takeoff strategy is adopted that minimises performance error and that performance is somewhat less sensitive to perturbations than indicated in this study. Elastic components were not used at other joints as the inclusion of a series elastic element at the ankle had previously been shown to only improve the agreement between actual performance and simulation by less than 2% (Yeadon and King, 2002). A single segment foot was used in the model rather than a more complex representation that may have lead to closer agreement between simulation and actual performance. However, the close agreement between the takeoff momenta (1%) and the segment angles (1^{o}) of the matching simulation and actual performance suggests that the model is sufficiently complex to represent the activity.

The first part of the analysis established how sensitive performance was to changes in approach and takeoff phases. Only small perturbations of less than 5° and 5% in the approach characteristics could be coped with when the activation timings were fixed. Tumbling performance was very insensitive to increases in the stiffness of the tumbling track. This was due to increases in the stiffness parameters having opposite effects on the takeoff angular momentum and time of flight so that the rotation potential remained similar for large perturbations (see lower part of Table 4). The insensitivity of performance to perturbations in track elasticity implies that a gymnast should be able to cope with some inconsistency in the tumbling track elasticity without having to adjust technique during the contact phase. This is fortunate since there is probably insufficient time to make adjustments to technique once the gymnast has contacted the tumbling track. In experiments on foot inversion perturbations it was found that at least 126 ms was required before significant muscle tension was developed (Konradsen et al., 1997) whereas the total contact time for the layout somersault was only 120 ms.

Tumbling performance was also found to be insensitive to maximum strength at each joint. However, it may be expected that in a maximal performance (e.g. a double layout somersault) a change in maximum strength would have a larger effect on performance. Perturbations of the activation timings had a large effect on performance with gymnasts having to adopt the required the activation timings within a window of around 10 ms in order to compensate sufficiently during the flight phase.

Varying the activation timings allowed a layout somersault to be performed for all initial perturbations so that, in theory, a gymnast should be able to use feedforward control to compensate for variations in touchdown conditions providing he is able to estimate these accurately prior to touchdown. In practice a gymnast will be able to estimate the expected touchdown conditions and to time activations only within certain limits which this study suggests lie within 5% / 5^o and 7 ms (Table 4). In these circumstances the rotation potential generated will lie within 8% of that required for a layout somersault and, in theory, the gymnast will be able to compensate using configuration changes in the flight phase. Such adjustments may be made using vestibular feedback to provide somersault angular velocity estimates (Wendt, 1951) and visual feedback for information on orientation (Rezzette and Amblard, 1985). Since the time delays associated with the vestibular and visual systems are 185 ms or less (Nashner, 1973; Raab and Fehrer, 1962) and the flight time of a layout somersault is more than 1 s, there is ample time for these systems to respond.

Acknowledgments

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