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Evaluation of a torque driven simulation model of tumbling

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Abstract

The use of computer simulation models in studies of human movement is now widespread. Most of these models, however, have not been evaluated in a quantitative manner in order to establish the level of accuracy that may be expected. Without such an evaluation little credence should be given to the published results and conclusions. This paper presents a simulation model of tumbling takeoffs which is evaluated by comparing the simulation output with an actual performance of an elite gymnast. A five segment planar model was developed to simulate tumbling takeoffs. The model comprised rigid foot, leg, thigh, trunk + head and arm segments with two damped linear springs to represent the elasticity of the tumbling track / gymnast interface. Torque generators were included at the ankle, knee, hip and shoulder joints in order to allow each joint to open actively during the takeoff. The model was customised to the elite gymnast by determining subject specific inertia and torque parameters. Good agreement was found between actual and simulated tumbling performances of a double layout somersault with 1% difference in the linear and angular momenta at takeoff. Allowing the activation timings of the four torque generators to vary resulted in an optimised simulation which was some 0.32 m higher than the evaluation simulation. These simulations suggest that the model is a realistic representation of the elite gymnast since otherwise the model would either fail to reproduce the double layout somersault performance or would produce a very different optimised solution.

Keywords : Muscle modelling, isokinetic dynamometer, subject specific, torque parameters, simulation modelling

Introduction

Computer simulation models of human movement may be used to give insight into the mechanics of a recorded movement or to make predictions about hypothetical movements. In order to achieve these goals the model must be a “good” representation of the biomechanical system being studied. If the model is inappropriate then any insight gained will be into the mechanics of the model rather than the mechanics of the biological system. Additionally any predictions made by the model may have little relevance to the real system.

In order to assess the level of confidence that may be placed in the results obtained from simulation it is necessary to compare the output of the model with actual performance. The nature of the comparison between simulation and performance should be dictated by the subsequent use of the model. If the aim is to determine the kinematic output for various inputs then a comparison of the kinematics of simulation and performance may be deemed appropriate. On the other hand if the model is to used for estimating forces then a kinetic comparison of simulation and performance will be required.

In order that a quantitative comparison can be made between simulation and performance the model may be customised to an individual subject by determining subject specific parameters. Kinematic and/or kinetic data may then be collected on a performance by the subject and used to drive the simulation model. The model may then be evaluated by comparing simulation output variables with the corresponding values from the data collection.

Twenty years ago there was some concern that simulation models should be evaluated or ‘validated’ in a proper manner (Panjabi, 1979). In more recent times little attention seems to have been given to the ways in which models are evaluated or even whether they are evaluated at all.

Very simple models of human movement are unlikely to give accurate results when simulating a complex activity such as jumping. Even when it is shown that simulation output roughly corresponds to performance data (e.g. Alexander, 1990) there is no guarantee that all conclusions reached will apply to the real situation. While more sophisticated models have the potential to produce accurate simulations the difficulty of evaluating a model increases with model complexity. Hatze (1981) was able to reproduce the ground reaction force in a long jump using a highly complex muscle driven simulation model although the joint movement of the simulation did not appear to be in close agreement with the performance. Angle driven simulation models may be evaluated using kinematic data of actual performances (e.g. van Gheluwe, 1981). Most of the muscle driven models, however, have not been evaluated by comparing simulation and individual performance (e.g. Pandy et al., 1990; van Soest et al., 1993). Instead the output from such models has been compared with group average data and the joint kinematics and muscle activities have been shown to be broadly similar.

The aims of this paper are threefold, namely: to determine subject specific parameters for input to a torque driven simulation model of tumbling takeoff, to carry out a kinematic evaluation of the model and finally to use the model to optimise a double layout somersault.

Methods

A computer simulation model was developed for the takeoff phase in tumbling and was customised to an elite gymnast through the determination of subject specific inertia and torque parameters. The simulation model was evaluated by comparing simulations with a tumbling takeoff performed by the same gymnast and was then used to optimise the performance of a double layout somersault in tumbling. The gymnast gave informed consent for the procedures which were carried out in accordance with the protocol approved by the Loughborough University Ethical Advisory Committee.

Anthropometric measurements of the elite gymnast were taken and segmental inertia parameters were calculated using a mathematical inertia model (Yeadon, 1990b). Two layout somersault and three double layout somersault performances by the gymnast were recorded using a Locam 16mm cine camera operating at 200 Hz and a 50 Hz video camera. 15 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 movements. A DLT reconstruction (Abdel-Aziz and Karara, 1971) was then carried out to synchronise the coordinate data (Yeadon and King, 1999) and obtain 200Hz 3D co-ordinate time histories of each digitised body landmark. The co-ordinate data were then used to calculate the orientation and configuration angles of the gymnast throughout each movement along with the mass centre velocity and whole body angular momentum about the mass centre (Yeadon, 1990a, c). The complete time histories of the orientation and configuration angles were fitted using quintic splines (Wood and Jennings, 1979). The closeness of fit at each point was based on the difference between the data and a pseudo data set which was generated by averaging the two angles from the two adjacent times. The torque parameters for extension at the ankle, knee, hip and shoulder joints of the gymnast were calculated from isovelocity torque / angle / angular velocity data collected at each joint (King and Yeadon, submitted). Before using the torque parameters in the simulation model two modifications were carried out.

Firstly the torque / angular velocity relationship was scaled so as to produce zero torque at the average maximum joint velocity ω_{max} obtained from the five tumbling performances. This was done since the isovelocity data was restricted to joint angular velocities below 200°s^{-1}. The modified torque T' for a concentric joint angular velocity of ω was given by:

$$T'(\omega) = T(\omega') - \frac{\omega}{\omega_{max}} 0.01T_{max} \tag{1}$$

where $\omega' = \frac{\omega_{1\%}}{\omega_{max}} \omega$ and $T(\omega_{1\%}) = 0.01T_{max}$.

Secondly the angle range of the isovelocity torque data at each joint was extended from the common (minimum) isovelocity range of all trials (King and Yeadon, submitted) to the average isovelocity range. For those trials where it was necessary to extrapolate the raw isovelocity data to span the average isovelocity angle range, the torque was set to be equal to the torque value for the last angle of the isovelocity range. For example at the knee joint the angle range was extended from 151°-169° (minimum isovelocity range) to 136°-179° (average isovelocity range). The corresponding surface fit to the extended data set had a RMS difference of 13% of maximum torque. If a simulation required a torque value for a joint angle lying outside the extended range then the torque value on the surface edge at the closest angle was used.

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 of the tumbling track. The model had four torque generators which opened the ankle, knee, hip and shoulder joints. Each torque generator was allowed to change from zero activation to maximum activation once and then remain at maximum activation. The ramp times were constrained to be greater than 50ms for all four joints and the start of the ramping was constrained so that the initial activation at the start of the simulation was less than 50% of maximum. A rotational elastic component was included in series with the torque generator at the ankle joint with a stiffness value of 465 Nm.rad^{-1}. 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 (Jacobs et al., 1996), 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).

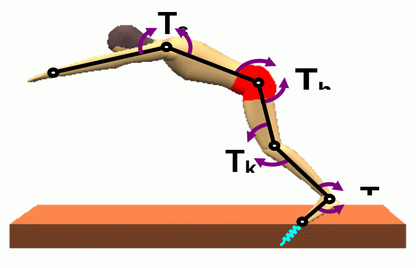

Figure 1. The five segment simulation model of tumbling takeoff. Four torque generators (T_a, T_k, T_h, T_s) open the ankle, knee, hip and shoulder joints, and two springs allow for horizontal and vertical movement of the tumbling track.

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). Input to the simulation model comprised the motion of the system just prior to the initial contact 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 and the ramp time. The output from the model comprised time histories of the whole body angular momentum about the mass centre, the mass centre velocity, the orientation and angular velocity of each segment during the contact phase. The postflight performance of the model was then determined using an 11 segment model of aerial movement (Yeadon et al., 1990) with the model using the same configuration changes as the actual performance.

The stiffness and damping parameters of the elastic interface between the simulation model and the tumbling track were determined for one of the layout somersault performances by minimising the difference between the actual and simulated performance in terms of strategy used (val_s), elasticity of the track (val_e) and takeoff components (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. The elasticity component consisted of contact time, the maximum and final depressions of the tumbling track horizontally and vertically. The takeoff component comprised the horizontal and vertical velocity of the mass centre and the whole body angular momentum at takeoff. In general the weightings for each variable in val_t and val_e were set in proportion to the inverse of the value of each variable from the actual performance. The exceptions were the weightings for the final track displacements which were set equal to the weightings for the maximum track displacements. The effect of using these weightings was that val_t and val_e represented the average percentage error between the simulated and actual performance in terms of the tumbling track movement, the velocity and angular momentum at takeoff, and the contact time (equation (2)). For the calculation of val_s each joint was given an equal weighting and the trunk was given a weighting equal to the total weighting of the joint angles as the trunk angle represented the whole body orientation whereas the joint angles defined the configuration (equation (3)). val_s, therefore measured the difference in the strategy used between the simulated and actual performance in degrees.

$$\text{Takeoff score } val_t \text{ and elasticity score } val_e = 100\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{s_i - a_i}{a_i}\right)^2\right]^{½} \qquad (2)$$

Strategy score $\mathrm{val_s}$ $$= \left[\sum_{i=1}^{n} w_i (s_i - a_i)^2 \Big/ \sum_{i=1}^{n} w_i \right]^{½} \qquad (3)$$

where i denotes the different variables, n = the number of variables, s_i = the value of variable i from a simulation, a_i = the value of variable i from the actual performance and w_i = weighting for variable i.

Equations (2) and (3) were combined to give an overall score for a simulation $\mathrm{val_{tes}}$. $\mathrm{val_t}$, $\mathrm{val_e}$ and $\mathrm{val_s}$ were equally weighted as 10% for $\mathrm{val_t}$ or $\mathrm{val_e}$ was considered to be comparable with 10° for $\mathrm{val_s}$:

$$\mathrm{val_{tes}} = \left[\tfrac{1}{3} (\mathrm{val_t^2} + \mathrm{val_e^2} + \mathrm{val_s^2}) \right]^{½} \qquad (4)$$

The initial conditions for the simulation were estimated from the video analysis of the layout somersault performance and corresponded to the time of initial contact with the tumbling track. The 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 sixteen other parameters were varied in the matching optimisation. Twelve of these parameters defined the activation time histories of the four torque generators and four parameters governed the characteristics of the elastic tumbling track. The Simulated Annealing algorithm (Goffe, et al., 1994) was used to vary the twenty-one parameters until the best match was found ($\mathrm{val_{tes}}$ minimised). The stiffness and damping parameters obtained were then fixed and used as independent estimates for the evaluation of the simulation model using one of the double layout somersault performances.

The simulation model was evaluated using the objective function $\mathrm{val_{ts}}$ by comparing a simulation of a double layout somersault with the actual performance by the elite gymnast. $\mathrm{val_{ts}}$ was calculated from $\mathrm{val_t}$ and $\mathrm{val_s}$ with both parts equally weighted. The initial conditions at the start of the simulation were estimated from the video analysis of the double layout somersault and corresponded to the time of initial contact with the tumbling track (angular velocities allowed to vary by $\pm 50°.s^{-1}$). Seventeen parameters were then varied using the Simulated Annealing algorithm until $\mathrm{val_{ts}}$ was minimised.

The optimum double layout somersault simulation was found by allowing the twelve parameters that defined the activation profiles to the four torque generators to vary. The optimum solution was defined as the simulation with the correct amount of rotation potential (flight time × angular momentum) that maximised the peak height during the postflight phase. This optimisation demonstrated how the model could be applied and also indicated whether the torque and activation functions used were reasonable.

Results

Subject specific parameters were determined for the elite gymnast used in the study. The inertia parameters consisted of the mass, mass centre location, length and moment of inertia of each of the five segments in the model (Table 1). The maximum strength at each joint was defined using a surface function which expressed the maximum torque that could be produced at a joint as a function of the joint angle and angular velocity (e.g. Figure 2). In addition independent estimates of the stiffness and damping parameters for the tumbling track / gymnast interface were determined for a layout somersault. The horizontal and vertical stiffness were calculated as 57052 $N.m^{-1}$ and 75528 $N.m^{-1}$ and the corresponding damping values were 226 $N.s.m^{-1}$ and 124 $N.s.m^{-1}$.

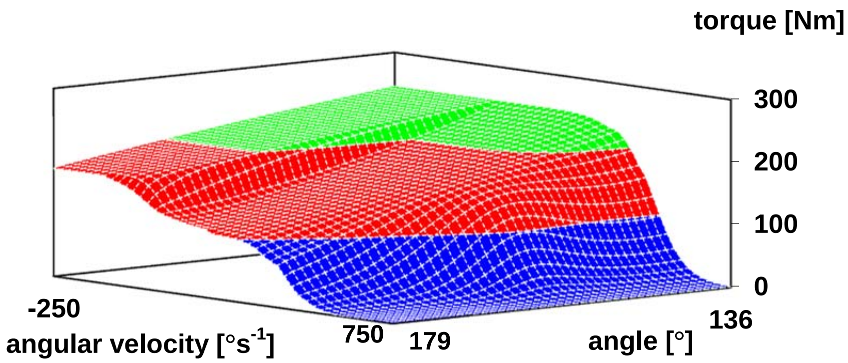

Figure 2. The surface showing torque as a function of knee angle and knee angular velocity for the extrapolated knee angle range with a scaled angular velocity profile.

Table 1. Segmental inertia parameters used in the simulation model

segment	segment length [m]	CM location [m]	mass [kg]	moment of inertia [$kg.m^2$]
foot	0.150	0.076	1.59	0.0048
shank	0.397	0.169	6.53	0.0761
thigh	0.403	0.171	15.41	0.2123
trunk + head	0.515	0.351	34.45	1.6158
arm + hand	0.735	0.295	7.80	0.2519

Note: Since the model has single segments representing both feet, lower legs, upper legs and arms the values given are the combined values of both limbs.

Good agreement was found between the double layout somersault performance and the evaluation simulation (val_{ts} = 3.8 which was calculated from val_t = 1%, and val_s = 5°). The initial conditions for the simulation were estimated from the video analysis (Table 2) and the twelve activation parameters were varied until the best comparison was found (Table 3). During the takeoff phase the overall comparison between the actual performance and the evaluation simulation was good with the model behaving in a similar manner to the actual performance (Figure 3, average RMS difference during the takeoff phase was 5° for joint and trunk angles and 0.01m for mass centre location). At takeoff from the tumbling track the difference in the mass centre velocities was 1%, the difference in angular momenta was 1%, and the average difference in the segment angles was 6° (third graphic in Figure 4a and 4b and Table 4). The effect of these differences in takeoff conditions is shown in the last four graphics of each sequence (Figure 4b).

The optimisation of postflight performance for the same initial kinematics as the double layout somersault performance produced a simulation which rose 0.32m higher than the simulation of the actual performance (Figure 4c). The main differences between the optimised activation profiles and those of the evaluation simulation were at the ankle and shoulder joints (Table 4). The initial activation at the ankle in the evaluation simulation was 50% of maximum whereas in the optimised solution it was 5% of maximum. For the optimised solution the shoulder was almost maximally activated throughout the takeoff phase whereas in the evaluation simulation very little shoulder torque was used. The hip and knee activation profiles were similar for the evaluation and optimised simulations with the hip activation very high throughout both simulations and the knee starting at around 20% of maximum and reaching maximum activation for the last 40% of both simulations.

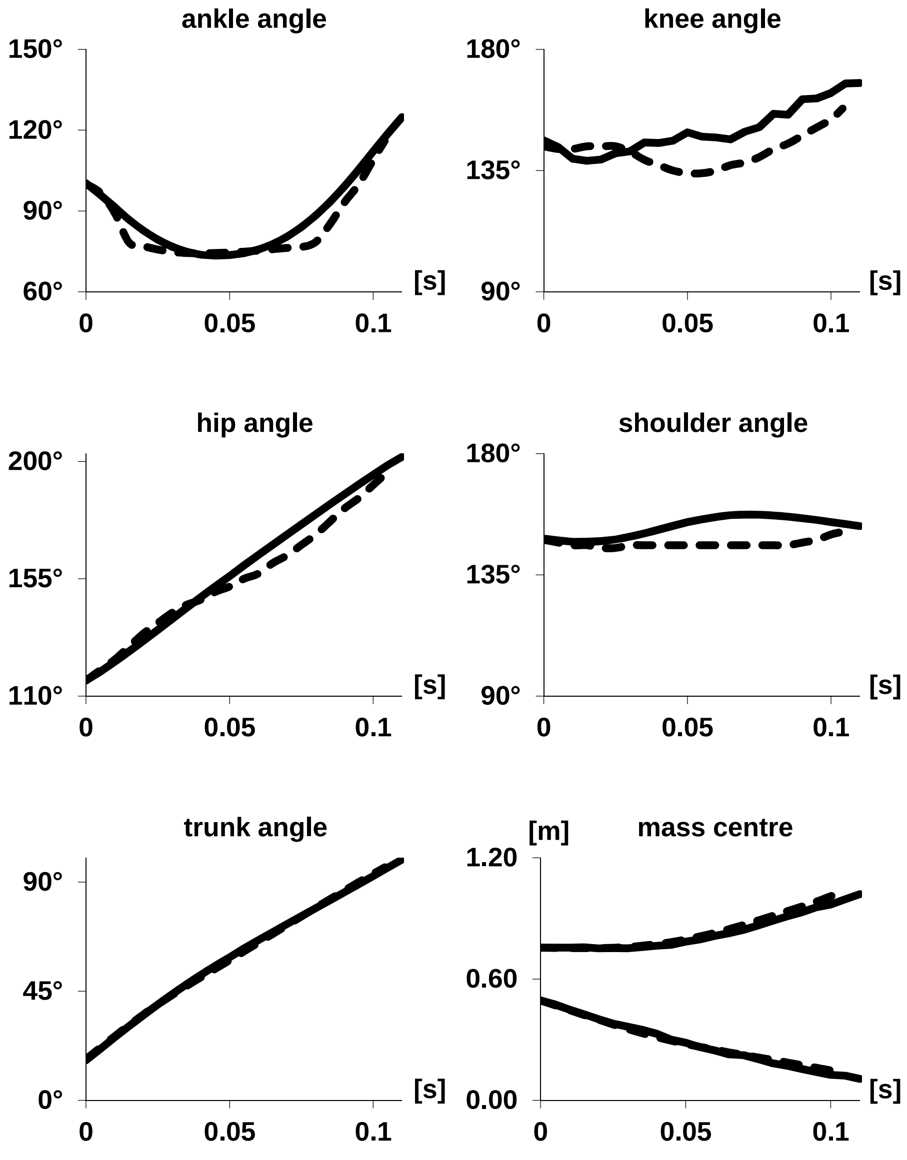

Figure 3. Comparison of key kinematic variables during the contact phase (solid line - actual performance data, dashed line - evaluation simulation data).

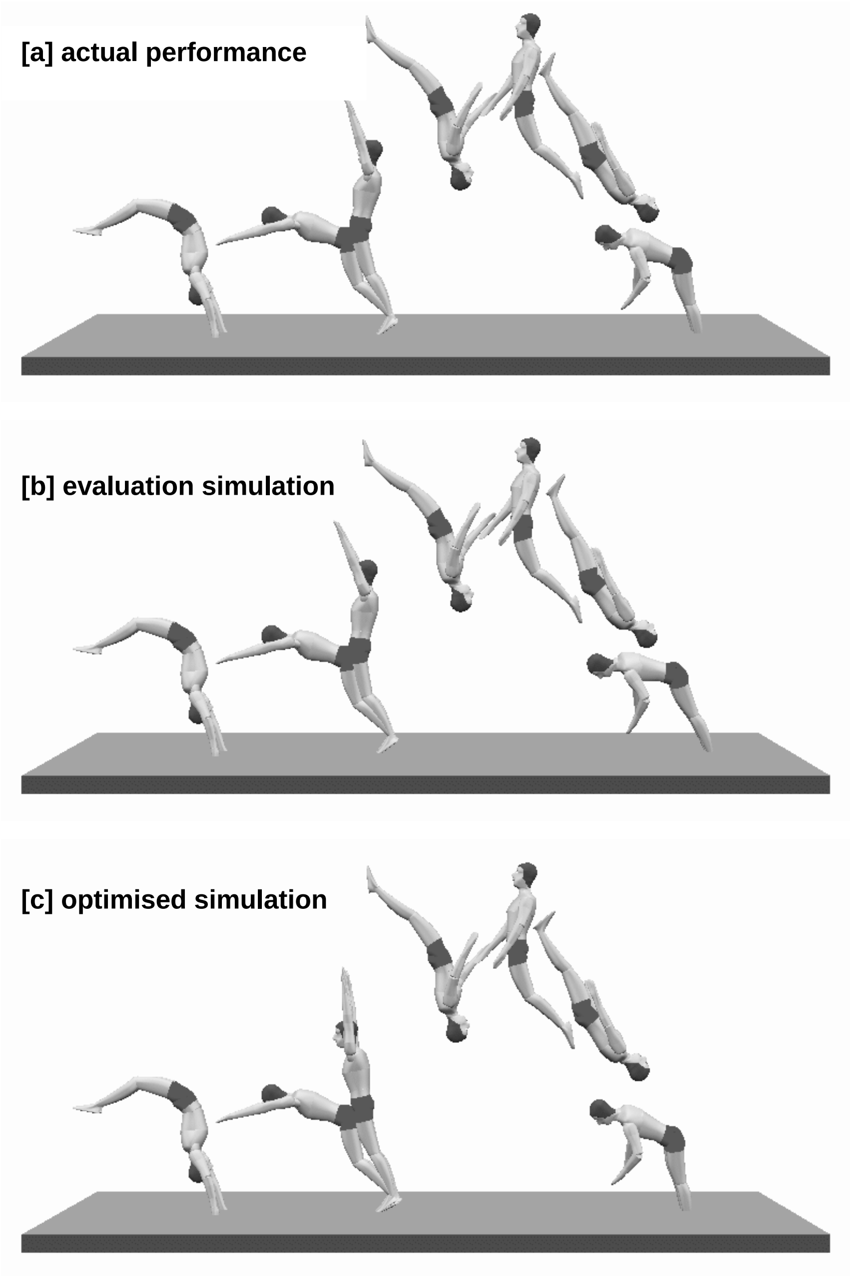

Figure 4. Comparison of [a] actual performance, [b] evaluation simulation and [c] optimised simulation (maximum height) of a double layout somersault.

Table 2. Initial conditions at touchdown with the tumbling track

variable	matching layout	double layout evaluation
u_g	4.46 $m.s^{-1}$	4.83 $m.s^{-1}$
v_g	-0.67 $m.s^{-1}$	-0.27 $m.s^{-1}$
a_a	108°	100°
k_a	157°	144°
h_a	110°	116°
tr_a	5°	17°
s_a	152°	148°
a_ω	-514 $°.s^{-1}$	-823 $°.s^{-1}$
k_ω	-604 $°.s^{-1}$	-278 $°.s^{-1}$
h_ω	314 $°.s^{-1}$	731 $°.s^{-1}$
tr_ω	917 $°.s^{-1}$	946 $°.s^{-1}$
s_ω	-206 $°.s^{-1}$	-208 $°.s^{-1}$

Note: a, k, h, tr and s refer to ankle, knee hip, trunk and shoulder, the subscripts a and ω refer to angle and angular velocity at touchdown, u_g and v_g = the horizontal and vertical velocity of the mass centre at touchdown.

Table 3. Activation timings for the four torque generators

parameter	matching layout simulation	evaluation double layout simulation	optimised double layout simulation
i_a	50%	50%	5%
i_k	28%	18%	20%
i_h	5%	49%	43%
i_s	5%	5%	49%
t_a	-0.025 s	-0.025 s	0.020 s
t_k	-0.015 s	0.019 s	-0.010 s
t_h	0.022 s	-0.025 s	-0.024 s
t_s	0.098 s	-0.017 s	-0.025 s
r_a	0.050 s	0.050 s	0.050 s
r_k	0.074 s	0.051 s	0.087 s
r_h	0.060 s	0.050 s	0.051 s
r_s	0.413 s	0.197 s	0.050 s

Note: i_j = the initial activation expressed as a percentage of maximum, t_j = the time that the activation changes from the initial level and r_j = the corresponding ramp time [for j = a (ankle), k (knee) h (hip), s (shoulder)].

Table 4. Comparison of actual performances and simulations

variable	layout performance	matching simulation	double layout performance	evaluation simulation
u_g	2.75	2.66	2.48	2.51
v_g	5.06	4.69	4.71	4.66
h_g	56	57	96	97
t	0.12	0.12	0.11	0.10
q_{1max}	0.04	0.06	0.03	0.07
q_{1end}	0.00	0.00	0.00	-0.01
q_{2max}	0.06	0.06	0.06	0.06
q_{2end}	0.00	0.00	0.00	0.00
a_{amin}	72	73	74	74
a_a	125	134	125	116
k_{amin}	143	131	142	134
k_a	174	177	168	158
h_a	175	169	202	196
tr_a	78	73	99	96
s_a	154	143	153	151

Note: 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. 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, t = the time of takeoff, q_{1max} and q_{2max} = the maximum horizontal and vertical depression of the tumbling track, q_{1end} and q_{2end} = the horizontal and vertical depression of the tumbling track at takeoff.

Discussion

This paper has shown how the method of determining subject specific torque parameters (King and Yeadon, submitted) can be used to personalise a simulation model to an individual. To produce a subject specific simulation model of tumbling required a model with a finite number of parameters which could be determined experimentally. Using torque generators to represent the forces produced by muscles allowed surface functions to be determined for the maximal torque around a joint. The effect of including series elastic components was investigated by including an elastic component around the ankle joint. It was found that this component improved the agreement between the actual performance and the evaluation simulation by less than 2%. Since the agreement between the model and the actual performance was sufficiently good for the purposes required elastic components were not used at other joints. The two modifications to the method used to determine subject specific torque parameters (King and Yeadon, submitted) highlight limitations in using isovelocity data. Since torque data was not obtained at high angular velocities it was necessary to scale the torque / angular velocity profile in order to give a realistic value for ω_{max}. Since the angle range corresponding to the isovelocity torque data was smaller than the range in a tumbling movement, it was necessary to extrapolate the torque / angle data to give a larger joint angle range. Despite these approximations it appears that the method of calculating torque parameters is able to give reasonable estimates of the maximum joint torques that can be produced since the evaluation compares well with the actual performance and the optimised simulation is not greatly different. In the future in may be possible to obtain torque data at higher angular velocities so that better estimates of the torque parameters for the surface function can be calculated and the need for scaling the surface eliminated. In addition a greater angle range of torque data could be obtained at slow angular velocities although there does not appear to be a simple method to increase the range of isovelocity angle data at high angular velocities unless non-isovelocity data is used.

Good agreement has been demonstrated between the simulated and actual tumbling performances with less than 1% difference in the linear and angular momentum at takeoff. The objective function used was heavily weighted towards the takeoff characteristics. A relatively simple activation profile (controlled by three parameters) was used at each joint allowing each joint torque to ramp up from an initial level to maximum once during the simulation. A better comparison between the joint angles used during the takeoff phase would have required a more complex objective function, more complex activation functions and would have therefore resulted in many more parameters to be varied. In movements where the contact time is longer or submaximal activation profiles are used, a more complex profile would be required, but in a maximal dynamic movement a simple profile would appear to approximate the movement patterns quite well.

The optimisation of the double layout somersault for the same initial conditions as the evaluation simulation produced a 0.32 m higher flight phase. The original performance by the elite gymnast was recorded during training and was performed into a landing pit. It is therefore quite likely that the gymnast could have performed a higher double layout somersault.

Both the evaluation simulation and the optimisation simulation imply that the model is a realistic representation of the elite gymnast with realistic subject specific parameters used. If the model strength estimates were too high it might be expected that the optimised simulation would be unrealistic whereas if they were too low then the evaluation would be poor. The subject specific torque driven simulation model may now be used to quantify sensitivity of performance, to determine the limiting factors for performance and also to optimise performance.

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