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THE SIMULATION OF AERIAL MOVEMENT - IV. A COMPUTER SIMULATION MODEL

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Abstract

A computer simulation model of human airborne movement is described. The body is modelled as 11 rigid linked segments with 17 degrees of freedom which are chosen with a view to modelling twisting somersaults. The accuracy of the model is evaluated by comparing the simulation values of the angles describing somersault, tilt and twist with the corresponding values obtained from film data of nine twisting somersaults. The maximum deviations between simulation and film are found to be 0.04 revolutions for somersault, seven degrees for tilt and 0.12 revolutions for twist. It is shown that anthropometric measurement errors, from which segmental inertia parameters are calculated, have a small effect on a simulation, whereas film digitization errors can account for a substantial part of the deviation between simulation and film values.

INTRODUCTION

Investigations of human airborne movement can attempt to explain why a certain phenomenon such as twisting occurs and what the outcome would be if the subject made different segmental movements. Such investigations may be experimental and/or theoretical in approach. In both approaches, the idea is to determine the result of varying just one element, such as the arm movement.

The strength of the experimental approach is that data is gathered from actual performances rather than from hypothetical situations. The weakness of such an approach is that it is difficult to change one aspect of technique without introducing other changes. Control of a subject's movements can be achieved using physical restraints (Moorse, 1966). While such a procedure can overcome the problem of unwanted changes to some extent, it is not possible to draw conclusions about unrestrained movements. On the other hand, if data is collected on free movements as in Winter (1966) and Van Gheluwe and Duquet (1977), the conclusions that may be made regarding technique are limited unless there is an accompanying theoretical analysis.

The strength of a theoretical model is that it is possible to determine the result of varying just one aspect of technique. The weakness of this approach is that often neither the model nor the hypothetical movements are shown to be adequate representations of actual performances, as in Pike (1980) and Ramey and Yang (1981).

The limitations of the two approaches may be overcome when a theoretical model is evaluated using data taken from actual performances and when the hypothetical movements are based upon real data, as in Dapena (1981) and Van Gheluwe (1981).

This paper describes a computer simulation model of aerial movement, which may be used to analyse techniques used in twisting somersaults. The model is evaluated using data taken from film of nine performances of twisting somersaults.

THE HUMAN BODY MODEL

The human body model used for computer simulations of aerial movement is the same as the model used in the calculation of the angular momentum in part III of this series (Yeadon, 1990c). In part III the angular momentum was calculated from a knowledge of the somersault, tilt and twist angles. In the case of the computer simulation model, described below, the angular momentum is taken as known and the time histories of the somersault, tilt and twist angles are calculated.

In the following sections an explanation of the level of detail in the model is given and the procedure for solving the angular momentum equation is described.

Segmentation

The body is modelled as 11 linked rigid segments as described and depicted in parts II and III of this series (Yeadon, 1990b,c).

The model is designed for the analysis of twisting somersaults. For good performances of such movements, the head should remain in alignment with the chest, the hands should continue the lines of the forearms and the ankles should be plantar flexed. Thus, in the model, it is assumed that the head maintains a fixed orientation relative to the chest and that no movement occurs at the wrists and ankles. In performances where ideal form is not maintained it may be expected that the above assumptions introduce only small errors since it is not possible for the head, hands and feet to move far from their ideal positions.

The segmental inertia parameters of the left and right limbs are assumed to be equal. The reasons for this are that such an assumption is expected to produce only small errors and that the results of hypothetical simulations should be independent of such body asymmetries if generalizations are to be drawn concerning particular twisting techniques.

Orientation

Details of the orientation angles used in the model are provided in parts I and III of this series (Yeadon, 1990a,c). In this section a qualitative description of the model's freedom of movement is given.

The orientation of the whole body in space is described by three external orientation angles corresponding to somersault, tilt and twist. The body configuration is specified by 14 internal orientation angles which permit the following relative movements of segments.

The shoulder joints each have three degrees of freedom permitting elevation, abduction and medio-lateral rotation of the upper arms. The elbow joints each have one degree of freedom so that only elbow flexion is allowed.

The movement of the chest-head segment **C** relative to the thorax **T** is described by two angles. One of these angles describes spinal torsion. It is assumed that this torsion occurs entirely at the junction of segments **C** and **T** whereas, in reality, such movement occurs along the length of the spine. The other angle describes relative movement of the shoulders in the frontal plane together with any lateral spinal flexion. For simplicity it is assumed that the chest-head segment **C** moves as a single unit in this plane.

Movement of the thorax **T** relative to the pelvis **P** is governed by two angles which permit flexion in the sagittal and frontal planes. Torsion of the thorax relative to the pelvis is not permitted. The relative movement is assumed to be a function of the pike and hula angles described in part III (Yeadon, 1990c).

At the hip joints, flexion and abduction of the thighs are permitted. It is assumed, however, that the thighs have equal flexion angles since for good form in twisting somersaults such symmetry is required. The movement of the line joining the midpoints of knee and hip centres is assumed to be a function of the pike and hula angles as described in part III. Relative abduction of the thighs is permitted since such movement will change the moment of inertia about the longitudinal axis and affect the twist rate.

Only flexion is permitted at the knee joints and it is assumed that the two knee angles are equal since this is consistent with the requirements of good form in twisting somersaults.

Movement between two adjacent segments is assumed to take place around a single common point which is fixed in each segment.

Angular momentum

In part III (Yeadon, 1990c) the angular momentum of the system about its mass centre was obtained as:

$$\begin{aligned} \mathbf{h} = & \mathbf{h}_{\omega_{fi}} + \mathbf{h}_{\omega_{pf}} + \mathbf{h}_{\omega_{tp}} + \mathbf{h}_{\omega_{ct}} \\ & + \mathbf{h}_{\omega_{a_1c}} + \mathbf{h}_{\omega_{b_1c}} + \mathbf{h}_{\omega_{a_2a_1}} + \mathbf{h}_{\omega_{b_2b_1}} \\ & + \mathbf{h}_{\omega_{j_1p}} + \mathbf{h}_{\omega_{k_1p}} + \mathbf{h}_{\omega_{j_2j_1}} + \mathbf{h}_{\omega_{k_2k_1}} \end{aligned} \quad (1)$$

where \mathbf{h} is the total momentum, $\mathbf{h}_{\omega_{fi}}$ is the angular momentum due to movement of the body as a whole and the remaining terms are the angular momenta due to internal movement. Equation (1) may be written in the form:

$$\mathbf{I}_{ff}\boldsymbol{\omega}_{fi} = \mathbf{h} - \mathbf{h}_{\text{rel}} \quad (2)$$

where \mathbf{h}_{rel} is the angular momentum due to relative movements of body segments, \mathbf{I}_{ff} is the whole body inertia tensor and $\boldsymbol{\omega}_{fi}$ is the angular velocity of the system frame f relative to the non-rotating frame i .

Simulation

If air resistance is negligible, the motion of the centre of mass in an airborne movement is a parabola and is determined by the initial velocity of the centre of mass. The present simulation model is concerned only with the rotational movement of the system and does not consider the translational movement of the mass centre.

If air resistance can be neglected then there is no net torque about the mass centre of the system during an airborne movement and the angular momentum of the system about the mass centre remains constant. Van Gheluwe (1979) has estimated the effect of air resistance in aerial movements to be of the order of 1% and so it is reasonable to assume that angular momentum is conserved.

The simulation model requires the following input:

- (a) The angular momentum \mathbf{h} (assumed to be constant).
- (b) The segmental inertia parameters.
- (c) The initial whole body orientation angles ϕ_0 , θ_0 and ψ_0 .
- (d) The time histories of the 14 internal orientation angles which describe body configuration.

Equation (2) may then be used to calculate the components of the angular velocity $\boldsymbol{\omega}_{fi}$ in the system frame f at any time.

In part III (Yeadon, 1990c) it was shown that in frame f :

$$[\boldsymbol{\omega}_{fi}]_f = \mathbf{R}_\omega \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

where

$$\mathbf{R}_\omega = \begin{bmatrix} \cos \theta \cos \psi & \sin \phi & 0 \\ -\cos \theta \sin \psi & \cos \phi & 0 \\ \sin \theta & 0 & 1 \end{bmatrix}$$

Equation (2) may now be written as:

$$\mathbf{I}_{ff}\mathbf{R}_\omega \begin{bmatrix} \dot{\phi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^T = \mathbf{h} - \mathbf{h}_{\text{rel}} \quad (3)$$

Equation (3) comprises three first order differential equations for the whole body orientation angles ϕ , θ and ψ . These equations are integrated numerically using Merson's form of the Runge Kutta method (Lambert, 1973).

The output of the simulation model comprises the time histories of the orientation angles ϕ , θ and ψ .

Assumptions

The following assumptions have been made:

- (1) Air resistance may be neglected.
- (2) The inertia values of the left and right limbs are equal.
- (3) The body segments are rigid bodies.
- (4) Adjacent segments are connected at a single point.
- (5) The head, hands and feet do not move relative to their adjacent segments.
- (6) The flexion angles of the thighs are equal.
- (7) The left and right knee angles are equal.

In reality not one of the above assumptions is true. The extent to which they are reasonable assumptions for the model may be evaluated by how close the agreement is between the output angles of the model and the angles obtained from film data.

EVALUATION OF THE MODEL

In order to evaluate the model, nine twisting somersaults executed from a trampoline were filmed. The movements were performed by three subjects of varied ability. Subject A was a novice trampolinist, subject B was an experienced springboard diver, and subject C was an elite competitive trampolinist. The movements performed ranged from a single somersault with one twist to a double somersault with two twists.

Prior to filming, anthropometric measurements were taken on each subject so that segmental inertia parameters could be calculated using the inertia model described in part II (Yeadon, 1990b). The movements were filmed using two cameras, the films were digitized and quintic spline coefficients of the orientation angles were calculated as described in part I (Yeadon, 1990a). Using the segmental inertia values and the time histories of the 17 orientation angles, the angular momentum values for each movement were calculated as described in part III (Yeadon, 1990c).

For each movement, the whole body angular momentum, the segmental inertia parameters, the initial values of the three external orientation angles, and the time histories of the 14 internal orientation angles were input into the computer simulation model. The simulation model calculated the time histories of the three external orientation angles.

Table 1: Maximum deviations between simulation and film values of the somersault, tilt and twist angles

Subject	Total somersault (revolutions)	Total twist (revolutions)	Somersault deviation (revolutions)	Tilt deviation (degrees)	Twist deviation (revolutions)
A	1	1	0.02	3	0.05
A	1	$1\frac{1}{2}$	0.01	4	0.03
B	1	1	0.02	3	0.07
B	1	$1\frac{1}{2}$	0.03	5	0.08
C	1	1	0.01	2	0.09
C	1	1	0.01	1	0.02
C	2	1	0.03	7	0.05
C	2	$1\frac{1}{2}$	0.04	6	0.12
C	2	2	0.03	6	0.05

Table 1 lists the maximum absolute deviations of the simulation values of the three external orientation angles from, the corresponding film values for each of the nine filmed movements. Overall, the

maximum deviations are:

somersault deviation:	0.04 revolutions
tilt deviation:	7 degrees
twist deviation:	0.12 revolutions.

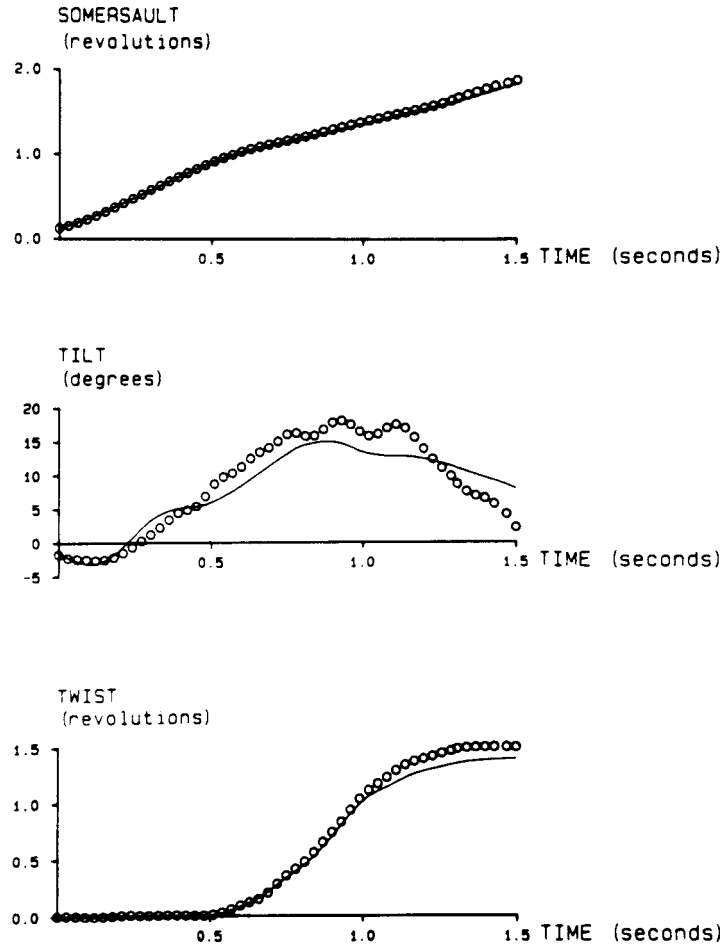


Figure 1: Comparison of simulation and film values for the somersault tilt and twist angles (continuous line = simulation values; circles = film values).

Figure 1 compares the time histories of the somersault, tilt and twist angles obtained from simulation and film of a double somersault with $1\frac{1}{2}$ twists. Graphics film and simulation sequences for this movement were generated using the SAMMIE man model (Kingsley et al., 1981). Figure 2 presents a comparison of these graphics sequences.

This movement was selected for the comparison between simulation and film since both the rotational absolute deviations and relative deviations are high. Even so, the agreement between simulation and film is good. In Figure 2 the sequences depicting the first half of the movement are indistinguishable and it is only in the second half that the differences are visible.

DISCUSSION

The simulation values of the twist angles show the greatest deviations from the film values. These maximum deviations range from 3% to 9% of the total twist. It is of interest to determine how much deviation arises from measurement errors.

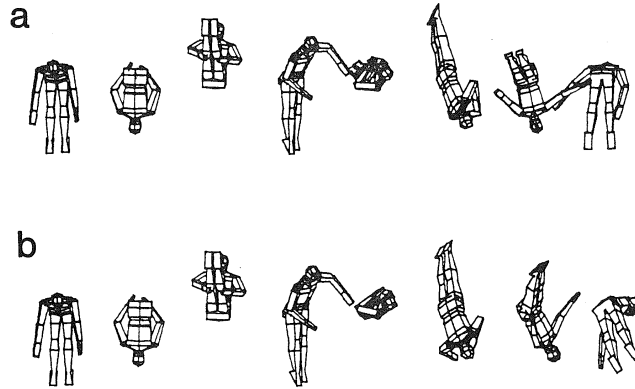


Figure 2: Comparison of graphics sequences of a double somersault with $1\frac{1}{2}$ twists: (a) film sequence, (b) simulation sequence.

Repeated anthropometric measurements were used to produce two sets of segmental inertia parameters for subject C. Each set of inertia parameters was used in conjunction with the film data of the movement shown in Fig. 2a to produce a simulation. The maximum deviations between the twist angles obtained from simulations and film were 0.11 and 0.12 revolutions, while the deviation between simulation values was 0.01 revolutions. This indicates that anthropometric measurement errors have a small effect on the accuracy of simulations.

In order to determine the effect of film digitization error on simulations, the following procedure was adopted. In the simulation shown in Fig. 2b, the internal orientation angles obtained from film data were based on the mean of four estimates obtained by repeated digitization. These four estimates were obtained using the four combinations of film data which arise from the two digitizations of two films. Each combination of film data was used to obtain estimates of the time histories of the orientation angles. Each of the four sets of angle values was used to produce a simulation of movement shown in Fig. 2a. The maximum deviations between the twist angles obtained from the four simulations and the twist angles obtained from film were 0.03, 0.08, 0.12 and 0.14 revolutions. This indicates that a substantial part of the deviation between simulation and film arises from errors associated with film digitization.

As a consequence of this, the errors arising from the assumptions inherent in the model may be somewhat less than those indicated in Table 1. However, whenever the simulation model is used to predict the amount of twist produced by a particular technique, the accuracy of the result should be taken to be 10% since none of the twist deviations in the nine comparisons exceeded this value.

The simulation model provides a powerful method for the analysis of twisting somersaults. A filmed performance can first be simulated using the orientation angles calculated from the film digitizations in order to check the accuracy of the simulation. The orientation angles may then be modified to remove all arm asymmetry. The simulation based upon the modified angles may then be compared with the original simulation in order to determine how much asymmetrical arm movement contributes to the twist. The contributions of other aspects of technique to the production and control of twist can be determined in a similar manner.

In addition to providing a means of evaluating twisting techniques which are in use, the simulation model can also be used to evaluate hypothetical movements with a view to obtaining general results and to determining optimum techniques. Such applications of the simulation model will be considered in future articles.

References

- Dapena, J. (1981). Simulation of modified human airborne movements. *Journal of Biomechanics*, 14:81–89.
- Kingsley, E. C., Schofield, N. A., and Case, K. (1981). SAMMIE: a computer aid for man machine modelling. *Computer Graphics*, 15:163–169.

- Lambert, J. D. (1973). *Computational Methods in Ordinary Differential Equations*. Wiley, New York.
- Moorse, A. C. (1966). A cinematographical analysis of a full twisting backward somersault. *Modern Gymnast*, 8:12–13.
- Pike, N. L. (1980). *Computer simulation of a forward, full twisting dive in a layout position*. PhD thesis, Pennsylvania State University.
- Ramey, M. R. and Yang, A. T. (1981). A simulation procedure for human motion studies. *Journal of Biomechanics*, 14:203–213.
- Van Gheluwe, B. (1979). *A biomechanical simulation model of the airborne twist somersault [in Dutch]*. PhD thesis, Free University of Brussels.
- Van Gheluwe, B. (1981). A biomechanical simulation model for airborne twist in backward somersaults. *Journal of Human Movement Studies*, 7:1–22.
- Van Gheluwe, B. and Duquet, W. (1977). A cinematographic evaluation of two twisting theories in the backward somersault. *Journal of Human Movement Studies*, 3:5–20.
- Winter, F. W. (1966). A photographic analysis of selected twisting dives. Master's thesis, Springfield College.
- Yeadon, M. R. (1990a). The simulation of aerial movement - I. The determination of orientation angles from film data. *Journal of Biomechanics*, 23:59–66.
- Yeadon, M. R. (1990b). The simulation of aerial movement - II. A mathematical inertia model of the human body. *Journal of Biomechanics*, 23:67–74.
- Yeadon, M. R. (1990c). The simulation of aerial movement - III. The determination of the angular momentum of the human body. *Journal of Biomechanics*, 23:75–83.