Chapter 12

Stability and Control of Aerial Movements

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When a cat falls from a height, it inevitably lands on its feet. For more than a century cats and rabbits have participated in experiments in which they are dropped in an inverted position from which they execute a half twist in midair (Marey 1894). Gymnasts execute similar movements during flight to make a safe landing when a dismount has not gone according to plan. The requirement of such control in aerial movements is not confined to the correction of errors. A gymnast who maintains a fixed configuration in a straight double somersault is unstable and will perform an unwanted half twist in the second somersault. This effect arises from the mechanical characteristics of rotating rigid bodies rather than from an error of the gymnast. Thus, midair control is needed to ensure that twist does not occur. In more complex movements involving multiple twists and somersaults, control is required in order for exactly the correct amounts of somersault and twist rotations to be reached at the time of landing. Strategies for controlling such movements are considered in this chapter.

Statement of the Problem

In aerial sports such as diving, trampolining, and gymnastics, the basic movements comprise somersaults with and without twist. For successful execution of a twisting somersault the athlete must ensure that the required number of twists are completed and for a nontwisting somersault that no twist is seen to occur. Theoretical analyses have shown that a rigid body is stable for rotations about the principal axes corresponding to maximum and minimum moments of inertia but unstable for rotations about the principal axis corresponding to the intermediate moment of inertia (Hinrichs 1978; Marion 1965). This instability arises because rigid body motions fall into two general modes centered on motions about the maximum and minimum principal axes and appear as either wobbling somersaults or twisting somersaults (Yeadon 1993a). Rotations about the intermediate principal axis lie near the boundary separating the two different modes of motion (Yeadon 1993a). For example, a pike (hips flexed) somersault about the lateral axis, corresponding to

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maximum moment of inertia, will appear to be a pure somersault since the angular velocity vector will remain close to this principal axis throughout the movement. In the case of a layout (nominally straight) somersault about the lateral axis, corresponding to the intermediate principal moment of inertia, any slight deviation of the angular velocity vector from this principal axis will eventually lead to a substantial buildup of twist sufficient to change backward rotation into forward rotation (Yeadon 1993a). Figure 12.1 shows a computer simulation of a double somersault in which the body maintains a fixed configuration with 1° of asymmetry in the arm abduction angles. In the first somersault there is very little twist while in the second somersault a half twist occurs. This surprising phenomenon can be reproduced practically by trying to throw a video cassette or a teddy bear about its intermediate axis without it twisting. Inevitably the cassette or teddy bear will perform an unwanted half twist that seems to start in the second somersault. The twist rate increases until a quarter twist is reached and then decreases. This means that there is a very slow twist during the first somersault and a rapid twist in the second somersault. This gives rise to the impression that the twist starts in the second somersault. Since gymnasts and trampolinists perform double somersaults in the straight position without twisting, they must have found some means of preventing the buildup of twist. The problem addressed in this chapter is to identify strategies that can be demonstrated to be capable of controlling the instability.

In this study three alternative strategies for controlling nontwisting somersaults using changes of body configuration are investigated. The three strategies comprise (a) arm abduction, (b) arching of the body, and (c) asymmetrical arm adduction/abduction.

Primary Concepts

One possibility of controlling the layout somersault is to adopt a fixed body configuration for which the somersault is stable. This may be accomplished by arching (or flexing) at the hips and spine sufficiently so that the lateral axis corresponds to the largest principal moment of inertia. If a large amount of arching is needed to accomplish this, there may be a problem in that the body may no longer be regarded as being straight and the gymnast's performance will be judged accordingly.

Another possibility is to make in-flight adjustments to prevent the twist from building up. Such corrections could be made with the arms so that when the body starts twisting to the left the arms move in such a way as to produce a twist to the right. If the time delay in the control system is too large it may not be possible for such control to be successful.

Elaboration of Concepts

Various strategies for controlling nontwisting somersaults are investigated and their ability to control twisting somersaults are considered.

Arm Abduction

Nigg (1974) suggested that the arms could be extended laterally in a straight somersault in order to minimize the influence of the instability. While it might be possible that extending the arms could reduce the twist rate since the moment of inertia about the longitudinal axis is greater, the problem of instability still remains and the proposed strategy at best can only delay the inevitable buildup of twist. If the buildup of appreciable twist does not occur until after the completion of two somersaults, then instability would not present a practical problem for a gymnast. If the buildup of twist becomes noticeable after one somersault, then instability would only present a problem for multiple somersaults. If the buildup of twist were noticeable before the completion of one somersault, then instability would pose a problem in all nontwisting straight somersaults. Thus it is of great relevance to determine the amount of somersault at which the twist becomes apparent.

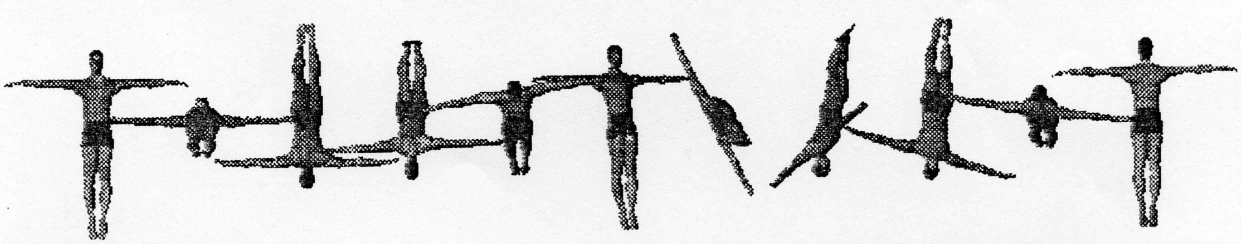

Figure 12.1 A rigid configuration with only 1° of asymmetry in arm abduction angles produces almost a half twist after two somersaults in the straight position.

In order to investigate this strategy for controlling the buildup of twist in straight somersaults, a computer simulation model of aerial movement was used (Yeadon, Atha, and Hales 1990). This model comprised 11 segments representing chest and head, thorax, pelvis, upper arms, lower arms, upper legs, and lower legs. Inertia parameters were calculated from anthropometric measurements of an elite trampolinist using a mathematical inertia model of the human body (Yeadon 1990b). Input to the simulation model comprised (a) initial conditions in the form of the components of angular momentum about the mass center and initial values of three angles defining body orientation, together with (b) time histories of 14 angles defining body configuration. Output of the model comprised the time histories of the angles of somersault, tilt, and twist, which define the orientation of the body in space (Yeadon 1990c).

To determine the effect of arm abduction for somersaults in a straight body configuration, three simulations were first carried out with the arms adducted close to the body. Angular momentum was used, which produced nontwisting double somersaults for symmetrical body configurations. A small perturbation was introduced into each simulation by specifying an initial asymmetry in arm abduction angles. These asymmetries had magnitudes 0.1°, 1°, and 10°. Subsequently three more simulations were carried out in which each arm was approximately perpendicular to the midline of the trunk. Initial arm asymmetries of 0.1°, 1°, and 10° were again used to perturb the motion. A rigid configuration was maintained throughout each simulation.

The introduction of small perturbations into simulations of straight double somersaults resulted in substantial amounts of twist even when the arms were abducted. The twist after one somersault was small when the initial arm asymmetry was 0.1° or 1.0° but was large for an asymmetry angle of 10° (see table 12.1). After two somersaults the twist was large in each of the six simulations. Although separate simulations were carried out for rigid body configurations with arms adducted or abducted, the arms may be considered to have been initially in an adducted position in all cases and to have been instantaneously abducted immediately after takeoff in three of the six simulations. Using the abducted arm configuration did not result in reduced twist. On the contrary, the instability was more evident when the arms were wide. This is because the instability about the intermediate axis is dependent on the three princi-

Table 12.1 Twist After One and Two Somersaults as a Function of Arm Symmetry

		Twist	
Somersault	Arm symmetry	Arms adducted	Arms abducted
1	0.1°	0.00	0.01
1	1.0°	0.02	0.07
1	10.0°	0.23	0.35
2	0.1°	0.22	0.41
2	1.0°	0.46	0.49
2	10.0°	0.50	0.52

Somersault and twist values are in revolutions.

pal moments of inertia. In the case of a body that is symmetrical about the longitudinal axis (e.g., a pencil) the buildup of twist remains slow with a constant twist rate, and there is no sudden half twist. As the two large principal moments of inertia become more different, the twist rate changes more with time so that when the arms are abducted as in figure 12.1 the half twist occurs earlier and faster than when the arms are held close to the body. For an initial arm asymmetry of 1° the movement appeared to be a somersault with little twist followed by a somersault with a half twist (see figure 12.1).

Body Arching

Hinrichs (1978) determined the directions of the principal axes during tucked, pike, and layout somersaults from a trampoline. In the tucked and pike somersaults the principal axis corresponding to maximum moment of inertia remained close to the angular momentum vector, while for the layout somersault the intermediate principal axis remained close to the angular momentum vector. This apparent stability about the intermediate axis led Hinrichs to speculate that the trampolinist must have made adjustments during flight to prevent the buildup of twist. On the other hand, it has been shown that small asymmetries do not led to substantial twist in a straight single somersault (see table 12.1) and so in-flight corrections may not have been required. In a straight double somersault, however, even small asymmetries will lead to a half twist. It would be of interest to determine, therefore, the extent to which various amounts of arching of the body can delay the buildup of twist in a double layout somersault. If the strategy of arching is not capable of limiting the effects of instability, the remaining possibility is that in-flight corrections are made to reverse any buildup of twist.

To determine the effect of arching on the stability of layout somersaults, simulations were carried out in which the angle between upper trunk and thighs remained constant. These angles ranged from 120° for an arched configuration to 180° for a straight body. Perturbations were introduced using initial arm asymmetries of 0.1°, 1°, and 10°, and a fixed configuration was maintained throughout each simulation. The results of these simulations established the extent to which arching of the body could limit the buildup of twist during a double somersault.

The adoption of an arched body configuration enabled the effects of instability to be reduced and even eliminated. Adopting an angle of 132° between upper trunk and thighs resulted in stable wobbling somersaults with little twist when the initial arm asymmetry was 0.1° or 1.0°. For an initial arm asymmetry of 10° a body arch of 129° was required in order for the motion to follow the stable wobbling somersault mode. Although in this case the motion was in a technically stable mode, the twist angle oscillated slowly with an amplitude of 0.24 revolutions and reached 0.14 revolutions after two somersaults. From table 12.2 it can be seen that arching provides a progressive improvement in controlling the buildup of twist.

In the simulation shown in figure 12.2 the abduction angle of the left arm is 1° more than that of the right arm so that the principal axes are tilted through a small angle. During the first one and a half somersaults there is a body arch of 145° and a knee angle of 160°. This phase of the motion is unstable but the buildup of twist is slow since the two large principal moments of inertia are approximately equal. In the last half somersault the body moves through the straight position into a stable pike somersault with a body flexion angle of 130°. Thus it is possible to perform an open double back somersault without appreciable buildup of twist providing the body arch is not less than that shown in figure 12.2.

Table 12.2 Twist After Two Somersaults as a Function of Body Arch and Arm Asymmetry

Body arch	Twist	Twist	Twist	Somersault
Arm asymmetry	0.1°	1°	10°	
120°	0.00 W	0.00 W	0.02 W	Stable
130°	0.00 W	0.01 W	0.16 T	Stable
140°	0.01 T	0.07 T	0.41 T	402°
150°	0.03 T	0.27 T	0.48 T	253°
160°	0.11 T	0.42 T	0.49 T	200°
170°	0.22 T	0.46 T	0.50 T	177°
180°	0.22 T	0.47 T	0.50 T	170°

Twist values are in revolutions. W = wobbling somersault; T = twisting somersault. During the stated somersault angle, the buildup of twist increases by a factor of 10.

Control Using Asymmetrical Arm Movements

In a twisting somersault asymmetrical arm movements may be used to alter the tilt angle to produce twist or to stop or reverse the twist (Yeadon 1993c). It should be possible, therefore, to ensure that the twist angle remains small during an unstable straight somersault by making corrective arm movements. In a backward somersault abduction of the left arm will produce a twist to the right while abduction of the right arm will produce a twist to the left.

To evaluate the capabilities of asymmetrical arm abduction for correcting the buildup of twist, the equations of motion of a model comprising two arms and one body segment were first linearized by assuming that perturbations remained small. This permitted an analytical consideration of the prospective control strategies for arbitrarily small perturbations.

The equations of motion for an asymmetrical arm abduction controller may be derived as follows. Suppose that abduction of one arm is accompanied by adduction of the other so that the sum

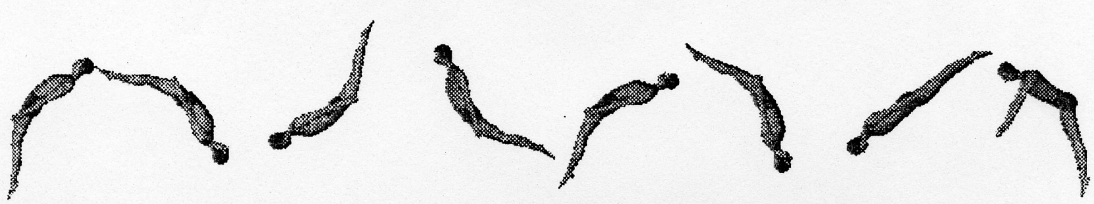

Figure 12.2 A double backward somersault with sufficient body arch to limit the buildup of twist.

$\varepsilon_a + \varepsilon_b$ of the abduction angles of the left and right arms from the midline of the trunk remains constant.

Let $\dot{\varepsilon} = -\dot{\varepsilon}_a = \dot{\varepsilon}_b$ be the rate of change of arm abduction angles. As shown in Yeadon (1990c) the equation of motion will be

$$h = I\omega + h_{rel} \qquad 12.1$$

where

h is the total angular momentum about the mass center,

I is the whole body inertia tensor about the mass center,

ω is the angular velocity of the system, and

h_{rel} is the angular momentum corresponding to internal movements.

The equation may be written as

$$\begin{bmatrix} h \cos\theta \cos\psi \\ -h \cos\theta \sin\psi \\ h \sin\theta \end{bmatrix} = \qquad 12.2$$

$$\begin{bmatrix} B\,0\,0 \\ 0\,A\,0 \\ 0\,0\,C \end{bmatrix} \cdot \begin{bmatrix} \dot{\phi} \cos\theta \cos\psi + \dot{\theta} \sin\psi \\ -\dot{\phi} \cos\theta \sin\psi + \dot{\theta} \cos\psi \\ \dot{\phi} \sin\theta + \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ I_a\dot{\varepsilon} \\ 0 \end{bmatrix}$$

where

$A > B > C$ are the principal moments of inertia of I,

$I_a\dot{\varepsilon}$ is the angular momentum associated with the arm movement, and

ϕ, θ, and ψ are Cardan angles for somersault, tilt, and twist corresponding to successive rotations about lateral, frontal, and longitudinal principal axes.

Equation 12.2 gives rise to

$$h = B\dot{\phi} + B\dot{\theta} \sec\theta \tan\psi \qquad 12.3$$

$$-h \sin\psi = -A\,\dot{\phi} \sin\psi + A\dot{\theta} \sec\theta \cos\psi + I_a\,\dot{\varepsilon} \sec\theta \qquad 12.4$$

$$h \sin\theta = C\,\dot{\phi} \sin\theta + C\,\dot{\psi}. \qquad 12.5$$

Eliminating $\dot{\phi}$ from equations 12.3 and 12.4 gives

$$h\,(A - B) \sin\psi = AB\,\dot{\theta}\,(\sec\theta \cos\psi + \sec\theta \sin^2\psi \sec\psi) + I_a\,B\,\dot{\varepsilon} \sec\theta. \qquad 12.6$$

Eliminating $\dot{\phi}$ from equations 12.3 and 12.5 gives

$$BC\,\dot{\psi} = h(B - C) \sin\theta + BC\,\dot{\theta} \tan\theta \tan\psi. \qquad 12.7$$

If the tilt and twist angles θ and ψ are assumed to be small and the controlling angular velocity $\dot{\varepsilon}$ is small, then equations 12.6 and 12.7 imply that $\dot{\theta}$ and $\dot{\psi}$ will also be small. The approximations $\sin\theta = \theta$, $\cos\theta = 1$, $\sin\psi = \psi$, $\cos\psi = 1$ are used in equations 12.6 and 12.7 and small quantities of the third order are neglected. Equation 12.6 becomes

$$h\,(A - B)\,\psi = AB\,\dot{\theta} + I_a B\dot{\varepsilon}. \qquad 12.8$$

Equation 12.7 becomes

$$BC\,\dot{\psi} = h(B - C)\,\theta. \qquad 12.9$$

Differentiating equation 12.9 and using equation 12.8 gives

$$\ddot{\psi} = k^2\,\psi - m\dot{\varepsilon} \qquad 12.10$$

where $k^2 = h^2(B - C)\,(A - B)/AB^2C$, and $m = hI_a(B - C)/ABC$.

A value for I_a/A was obtained using a simulation under conditions of zero angular momentum with the model of Yeadon, Atha, and Hales (1990). The arms were moved through a small angle ε and the change in the tilt angle of the longitudinal principal axis was noted. When $h = 0$, equation 12.8 gives $I_a/A = \dot{\theta}/\dot{\varepsilon}$ and so θ/ε was used as an approximation to I_a/A.

In equation 12.10 ψ is the output variable, which should remain small if the buildup of twist is to be prevented, and $\dot{\varepsilon}$ is the control variable. When no control is exercised and a fixed body configuration is maintained $m = 0$ and equation 12.10 has solution

$$\psi = \psi_0 e^{kt}. \qquad 12.11$$

This demonstrates the exponential buildup of twist for rotations initially close to the intermediate principal axis. If ψ is small the somersault rate will be $\dot{\phi} = h/B$ and kt may be expressed as $p\dot{\phi}t = p\phi$ so that equation 12.11 may be written as

$$\psi = \psi_0 e^{p\phi} \qquad 12.12$$

where $p^2 = (B - C)\,(A - B)/AC$.

For a given body configuration ψ will increase by a factor 10 when $p\phi$ increases by ln(10). For arms by the sides of the body this corresponds to 170° of somersault while for arms abducted as in figure 12.1 it requires 163° of somersault. For arched configurations the latent periods for the buildup of twist range from 170° when straight to 402° for a body arch of 140° (see table 12.2). This buildup delay becomes infinite for a body arch of 133°.

In the case where control using asymmetrical arm movement was attempted, proportional plus integral plus derivative (PID) solutions of the form

$$\dot{\varepsilon}(t) = K_p\,\psi(t-T) + K_i \int \psi(t-T) + K_d\,\dot{\psi}(t-T) \qquad 12.13$$

were sought where K_p, K_i, and K_d are constants and T is the delay in the feedback loop. Thus corrections were based on the state of the system at an earlier time.

Using an analytical solution to the problem of such control for arbitrarily small perturbations, it was found that proportional plus derivative (PD) control was necessary and sufficient to provide stable operation for nonzero time delays (Yeadon and Mikulcik 1996). In other words the best value for the constant K_i was zero. Stable control was possible for a range of values of K_p and K_d providing that the time delay T in the system was not greater than 0.28 somersaults. Figure 12.3 shows that there is a set of controller values that maximizes the time delay T that can be accommodated. Alternatively, it may be stated that for each set of controller values, there is a value of time delay beyond which stable control is not possible. The larger the time delay, the narrower the range of allowable controller parameters, and therefore the greater the difficulty in maintaining stable control.

Control of Finite Perturbations

The above analytical treatment assumes that the perturbations of the system are arbitrarily small. In reality we may have arm asymmetries where the arm abduction angles differ by as much as 10°, and the control system must be able to cope with such disturbances for the duration of a double somersault. On the other hand, stable control may not be necessary since the duration of the movement is limited. Proportional plus derivative control was

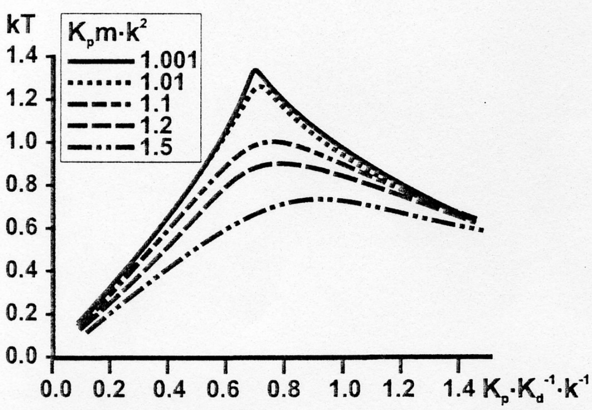

Figure 12.3 The time delay T that can be accommodated for PD parameters K_p and K_d. There are values of K_p and K_d that maximize T. For delays greater than this value of T, stable control is not possible.

incorporated into the 11-segment computer simulation model of Yeadon, Atha, and Hales (1990) by making the arm abduction angles change from ε_a to $\varepsilon_a - \delta\varepsilon$ and from ε_b to $\varepsilon_b + \delta\varepsilon$ over a time interval $\delta T = 0.01\ T_f$, where T_f is the flight time and $\delta\varepsilon = (K_p\psi + K_d\dot{\psi})\,\delta T$. A time delay was also introduced by basing the correction $\delta\varepsilon$ upon earlier values of ψ and $\dot{\psi}$ in a simulation.

Simulations of straight double somersaults with perpendicular arms were run for initial arm asymmetries of 0.1°, 1°, and 10° and values of the proportional and derivative constants were found for which the buildup of twist was controlled. The feedback time delay in the control loop was increased to determine the maximum delay for which control was possible and to obtain the corresponding values for the control parameters. These values were then compared with the corresponding results from the theoretical analysis.

The results of the numerical solutions for control using the computer simulation model were in general agreement with the theoretical findings. Increasing the time delay resulted in smaller ranges of suitable parameter values that gave stable control, and this enabled optimum values to be determined. For a time delay equivalent to 0.02 somersaults and an initial arm asymmetry of 10°, the arms moved rapidly to approximately symmetrical positions that changed little during the movement so that the response was stable (see figure 12.4a). When the delay was increased to 0.12 somersaults the twist was controlled although the amplitude of the arm oscillations did not decrease (see figure 12.4b), and the response could be described as (slightly worse than) neutral control. Increasing the delay to 0.24 somersaults resulted in control of the twist although the difference in arm abduction angles became more than 90° (see figure 12.4c), and the response was unstable.

If the original asymmetry in arm angles is reduced from 10° to 1°, then a delay of 0.24 somersaults produces a response similar to figure 12.4b. A further reduction in arm angle asymmetry to 0.1° with a delay of 0.24 somersaults produces a stable response similar to figure 12.4a. Table 12.3 gives the maximum twist and arm asymmetry in each of these five simulations. Note that in the first simulation the arm asymmetry dropped rapidly from 10° to 2° and then remained at that value.

Since the theoretical analysis of PD control gave a limit on the delay equivalent to 0.28 somersaults, the results of the numerical simulation model may be considered to be comparable. The best values for the proportional and derivative constants K_p and K_d were found by running numerous simulations with

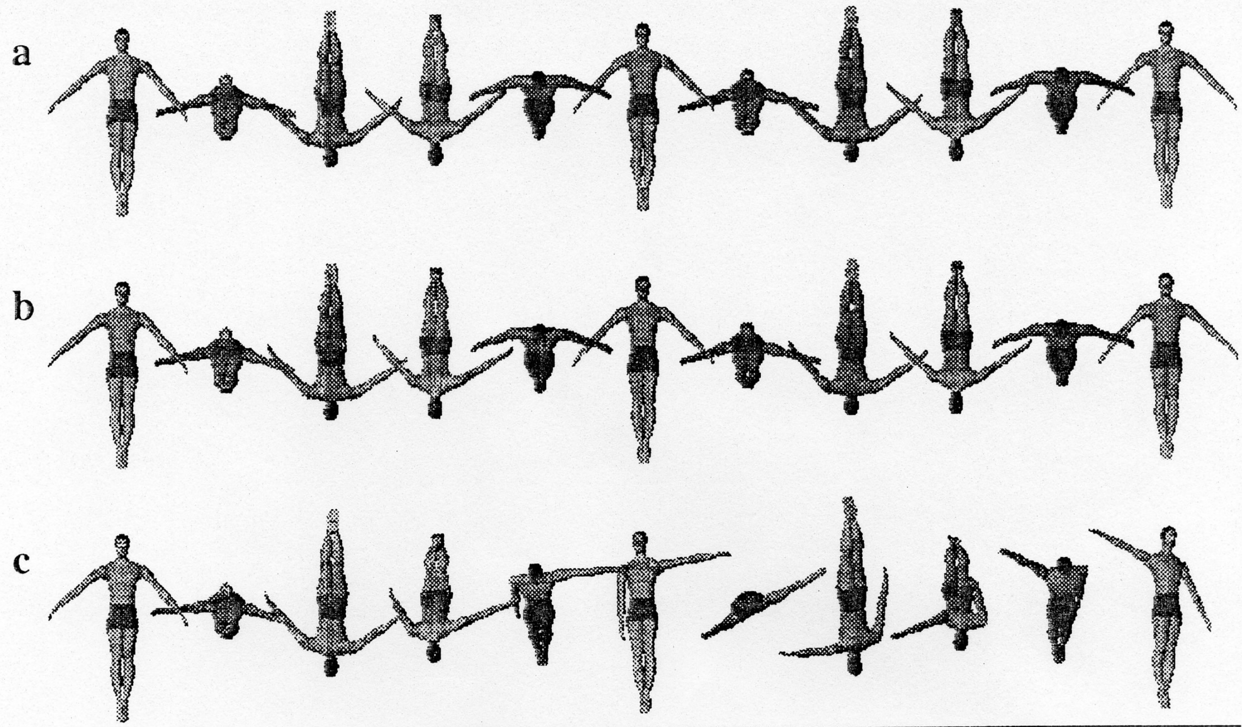

Figure 12.4 Proportional plus derivative control in straight double somersaults with feedback delays of *(a)* 0.02, *(b)* 0.12, and *(c)* 0.24 somersaults.

Table 12.3 Controlling the Twist in Straight Double Somersaults Using Arm Asymmetry

Initial arm asymmetry	Feedback delay (som)	Maximum twist (rev)	Maximum arm asymmetry
10.0°	0.02	0.00	2°
10.0°	0.12	0.01	18°
10.0°	0.24	0.09	143°
1.0°	0.24	0.04	24°
0.1°	0.24	0.00	2°

an initial arm asymmetry of 0.2° and a feedback delay of 0.24 somersaults. The value obtained for $K_p m/k^2$ was 1.01, which agrees well with the analytical result that this parameter should be slightly greater than 1.0 in order to maximize the time delay that can be handled. For a value of 1.01, figure 12.3 indicates a maximum time delay equivalent to 0.26 somersaults for which stable control can be maintained. The value of K_d obtained empirically for the numerical simulations was equal to 0.98 of the optimum value indicated in figure 12.3. It may be concluded that there is good agreement between analytical and numerical results.

Film Analysis

In order to address the question as to whether in-flight corrections are actually used in practice, a straight double somersault performed by an elite trampolinist was filmed using two 16 mm cameras operating at 70 frames per second. In each frame of the flight phase the wrist, elbow, shoulder, hip, knee, and ankle centers were digitized for each camera view and three-dimensional coordinates of these body landmarks were calculated. Orientation and configuration angles were determined (Yeadon 1990a), and segmental inertia parameter values were calculated from anthropometric measurements (Yeadon 1990b).

The orientation of the intermediate principal axis relative to the angular momentum vector was calculated throughout the double somersault in order to determine whether there was sufficient arching or flexing of the body to remove the instability. The film values of the body configuration angles and the initial orientation angles and angular momentum were used as input to the simulation model. This was done in order to establish whether a buildup of twist became noticeable during the simulation. If substantial twist occurred in the simulation this would indicate that the movement was unstable and that the gymnast must have made adjustments during flight, providing that the model was not in error. To demonstrate that such twist occurred as a result of instability rather than due to errors in the model it was necessary to demonstrate that the model could produce a nontwisting double somersault for a body configuration time history within the error limits of the film data. In order to do this, additional simulations were carried out in which the arm abduction angles were modified from the film values using a control strategy with zero delay. It is to be expected that if the simulation model is a close approximation to reality, there exist configuration histories close to those obtained from film for which there is no appreciable buildup of twist in the simulation.

The three-dimensional film analysis of the straight double backward somersault (see figure 12.5a) revealed that the lateral axis through the hips was close to the intermediate principal axis for almost the entire movement. This suggests that control was employed during flight in order to prevent the buildup of twist, although this need not necessarily be so, as shown in table 12.2.

When the film values of the body configuration angles and the initial orientation angles and angular momentum were used as input to the simulation model, the agreement between film and simulation was good during the first somersault (see figure 12.5a, b). During the second somersault the effects due to instability became pronounced and almost one-half twist resulted in the simulated movement. This indicates that without correction the instability would have led to noticeable twist after two somersaults. The discrepancy between simulation and film is to be expected since the estimated error in the arm abduction angles obtained from film was 1.3° and this is sufficient to produce substantial twist in the second somersault (see table 12.1).

The search for modified arm abduction angles that produced a nontwisting double somersault was successful. In a simulation that allowed the arm abduction angles to deviate from the film values by up to a maximum of 1.4° the twist was controlled and the agreement with the film sequence became good throughout the simulation (see figure 12.5a, c). This demonstrated that the twist in figure 12.5b was a result of the instability rather than any inadequacy of the model. Hence the trampolinist must have made corrective movements during flight although what these movements were and what control strategy was used is unknown.

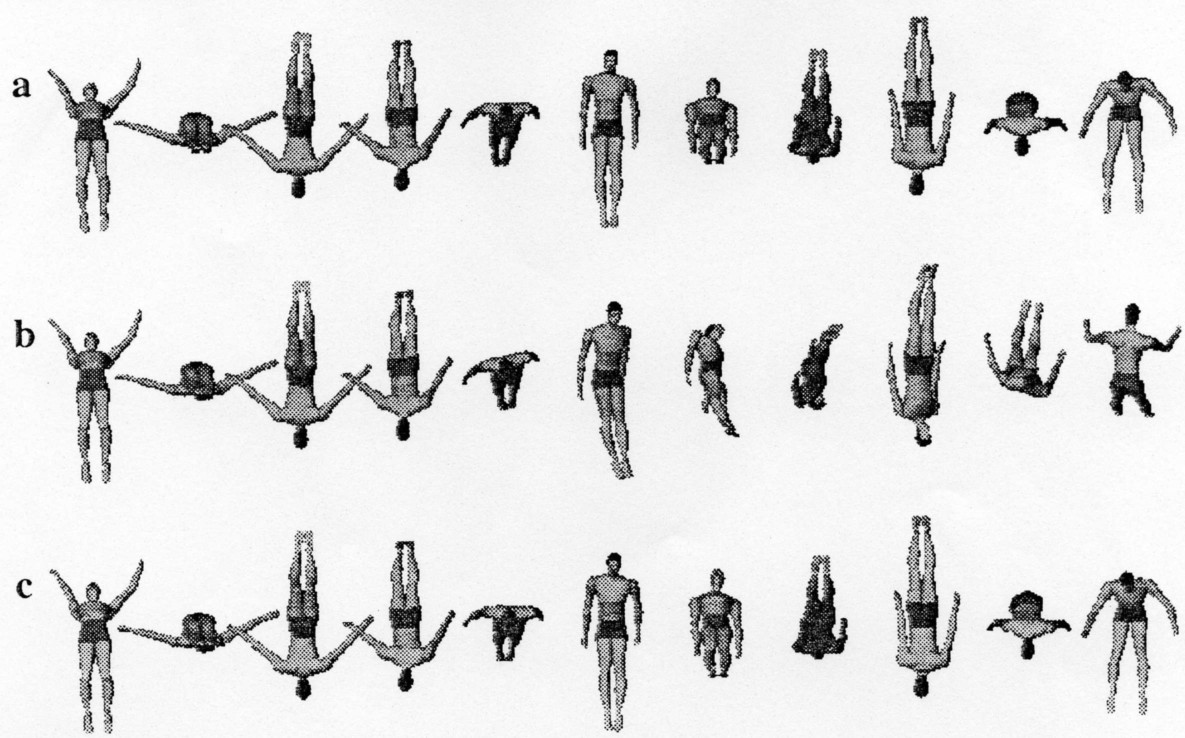

Figure 12.5 Performance of a straight double somersault obtained using *(a)* film analysis, *(b)* simulation, and *(c)* simulation with modified arm abduction angles.

Passive Control

Playter and Raibert (1994) showed that a three-segment model, comprising a body and two arms with torsional springs at the shoulders, automatically makes corrective movements when somersaulting. Providing that the arms are abducted more than about 30° from the midline of the body and that the springs have suitable stiffness, the system is neutrally stable and will perform double and triple somersaults without appreciable twist. The implication of this study of passive stability is that the bodies of gymnasts may automatically and instantaneously make compensatory movements. The majority of straight double somersaults are performed with the arms adducted close to the body. In this configuration passive corrections are insufficient to prevent the buildup of twist, whereas the simulation using PD control based on film data (see figure 12.5c) shows that active corrections can maintain control. This suggests that passive corrections may not be of mechanical importance in the control of twist. On the other hand, the tendency of the limbs to move in the appropriate direction may provide additional feedback information for input to the control system used.

Visual Feedback

An experiment was conducted in order to determine whether visual feedback was necessary for the control strategy used by a trampolinist. The subject performed six straight double somersaults, each from a plain jump. He was then instructed to close his eyes immediately after takeoff and to open them when instructed later in the flight phase.

In the first two attempts at straight double somersaults under these conditions the trampolinist completed one and a half somersaults without twist before being instructed to open his eyes. During the last half somersault a quarter twist occurred on both occasions. The trampolinist reported that he was aware of the instability but was uncertain about trying to correct it with his eyes closed. He was instructed to make adjustments with his eyes closed. In the next four attempts the trampolinist successfully completed a straight double somersault with eyes closed for the first one and a half somersaults. This experiment using visual deprivation of a trampolinist showed that it was not necessary to have visual feedback in order to maintain control in a straight double somersault.

Twisting Somersaults

Since the straight double somersault needs continual correction to prevent twist occurring, it should be relatively easy to produce a straight double somersault with twist. A hypothetical example is shown in the simulation depicted in figure 12.6 in which twist is introduced into a nontwisting somersault by means of asymmetrical arm movements during flight. In the first somersault small arm asymmetries produce a buildup of twist that is accelerated after one somersault by adducting the arms. The tilt out of the vertical somersault plane is apparent after one somersault. In order to obtain a correct landing position the twist must be stopped after one revolution and the tilt angle must be removed. This was

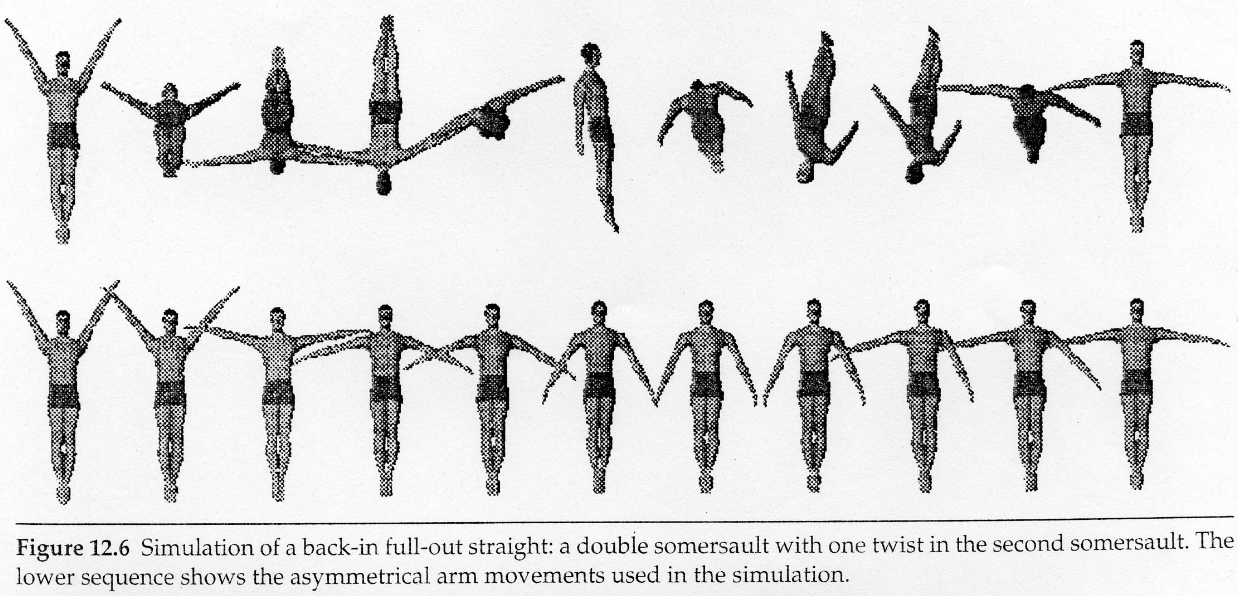

Figure 12.6 Simulation of a back-in full-out straight: a double somersault with one twist in the second somersault. The lower sequence shows the asymmetrical arm movements used in the simulation.

achieved using asymmetrical arm movements toward the end of the second somersault. The right arm is abducted at around the three-quarters twist position in order to slow the twist rotation without increasing the tilt angle. When the twist is almost complete the left arm is abducted in order to remove the tilt. This latter stage of the movement is very similar to the control of the nontwisting straight double somersault, and so it is to be expected that the skills necessary for controlling nontwisting somersaults are also used for controlling twisting somersaults. This may explain why it is rare for instability problems to occur in the learning of straight double somersaults. By this stage the gymnast will have learned how to control unwanted twist both in single straight somersaults without twist and in twisting somersaults.

The other method for preventing twist considered for nontwisting somersaults was to arch or flex sufficiently at the hips in order that the somersault becomes stable. This technique can also be used to change a twisting somersault into a nontwisting somersault. Figure 12.7 depicts a simulation of a hypothetical straight double somersault in which twist is present at takeoff. As the twist reaches one revolution, the body flexes at the hips so that the lateral axis corresponds to the maximum principal moment of inertia. Somersaults about this axis are stable, and so the motion changes from a twisting somersault into a wobbling somersault (Yeadon 1993a, 1993b). Near the end of the second somersault the body extends and the arms are abducted symmetrically. If the timing of these movements is correct it is possible to complete the correct amounts of somersault and twist rotation without any tilt away from the vertical (see figure 12.7).

Summary and Potential Applications

In this study the abilities of various hypothetical strategies for controlling twist in twisting and nontwisting somersaults have been evaluated using computer simulations. Such theoretical analyses cannot indicate which techniques are actually used by gymnasts but can indicate whether a proposed technique is viable. The results given in this chapter should provide a useful starting point for investigations on the techniques actually employed by competitive athletes.

The strategy of symmetrically abducting the arms during flight, as advocated by Nigg (1974), does not reduce the buildup of twist in straight single and double somersaults (see table 12.1). Arching the body during flight progressively reduces the buildup of twist for small perturbations even when there is insufficient arch to ensure that the motion is in the stable wobbling somersault mode (see table 12.2). In a single somersault it may not be necessary to make corrections (see figure 12.5b). This contradicts the speculation of Hinrichs (1978) that single somersaults about the unstable intermediate axis require in-flight correction. For larger perturbations, arching that is sufficient to ensure the motion is in the stable wobbling somersault mode is not sufficient to ensure that there is no appreciable buildup of twist (see table 12.2). In this case additional arching is required to limit the magnitude of the twist oscilla-

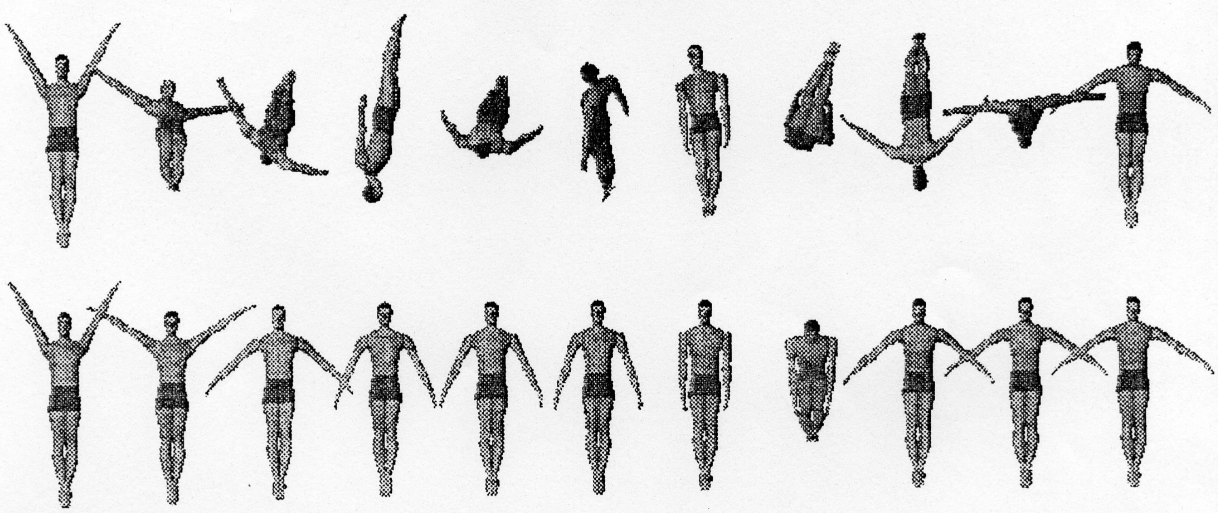

Figure 12.7 Simulation of a full-in back-out pike: a double somersault with one twist in the first somersault. The lower sequence shows the symmetrical arm movements used in the simulation.

tions. Although it is possible to control instability in a double layout somersault using arching, the competitive athlete is likely to lose points due to form breaks (see figure 12.2) since it is an expectation of judges that the body will appear to be straight.

It has been shown that the buildup of twist can be controlled using appropriate arm movements providing that the feedback time delay is not greater than a quarter of a somersault. For double layout somersaults in a gymnastics floor exercise this delay is equivalent to about 150 ms, which cannot be much more than a gymnast's reaction time. In this theoretical study the angular velocity $\dot{\varepsilon}$ of the arm movement was used as the control variable and was a linear function of the twist angle ψ and twist angular velocity $\dot{\psi}$ for PD control. In a practical situation control will be effected using neural stimulation of the appropriate muscle groups, and this input will be related to the joint torques. This suggests that the control variable used by gymnasts will be similar to the angular acceleration $\ddot{\varepsilon}$, which would be a function of $\dot{\psi}$, ψ, and $\ddot{\psi}$ for PID control. Thus the result that PD rather than PID control should be used is equivalent to saying that gymnasts must base their control on the twist angular velocity and acceleration values but not on the twist angle itself. Since the otolith organs of the inner ear can detect angular velocities due to centrifugal effects and the semicircular canals respond to rotational accelerations (Wendt 1951), it is possible that vestibular control is used rather than visual control. This idea is supported by the experiment involving an athlete closing the eyes during a straight double somersault. The main function of the eyes may be to obtain angular information on body orientation in space in order to make in-flight adjustments for correct landing orientation rather than to control instability during flight (Rezette and Amblard 1985).

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