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Introduction

Most sports movements have an aerial phase. In sprinting the runner spends less than half of the time in contact with the ground (Hopper, 1973) while in the triple jump the aerial phases are much longer than the contact phases (Hay and Miller, 1985). Typically tennis players are off the ground when the ball is played (Elliott, 1989) and basketball players release the ball while airborne (Hay, 1993). The same is true for the release in the discus and shot events (Hay, 1993). In jumping activities it is the aerial phase that is evaluated to give a score for the performance. In the long jump and high jump events the horizontal and vertical displacements during the aerial phase are used as measures of performance while in trampolining and diving rotation and aesthetics are also included in the evaluation.

In an aerial phase of a sports movement the athlete is freely falling under gravity. In freefall the balance mechanisms of the inner ear do not operate normally since they too are in freefall (Graybiel, 1970). The otolith and semi-circular canals can no longer provide information on the orientation of the head relative to the vertical direction. They do, however, give information on linear and angular accelerations (Wendt, 1951) which can be used by athletes to help control aerial movements (Yeadon and Mikulcik, 1996).

Motion of the mass centre

In the aerial phases of most sporting movements, air resistance has little effect and the path of the mass centre follows a parabola that is determined by the position and velocity of the mass centre at takeoff. In the competition performance shown in Figure 1 the height of the mass centre at takeoff is 1.31 m while the horizontal and vertical velocities are 4.7 ms^{-1} and 4.5 ms^{-1}. During the aerial phase the horizontal velocity of the mass centre remains constant since there are no horizontal forces acting (if air resistance is neglected) while the vertical motion has a constant downwards acceleration of 9.81 ms^{-2} due to the weight of the body. The vertical takeoff velocity of 4.5 ms^{-1} determines that the mass centre rises to a peak height of 2.34 m in a time of 0.46 s. The horizontal takeoff velocity of 4.7 ms^{-1} determines that the mass centre covers a horizontal distance of 2.16 m during this time.

In the case of ski jumping, however, the takeoff parameters do not completely determine the path of the mass centre during flight since air resistance produces drag and lift forces which can be used by the skilled jumper to maximise the distance of the jump (Denoth et al., 1987; Hubbard et al., 1989).

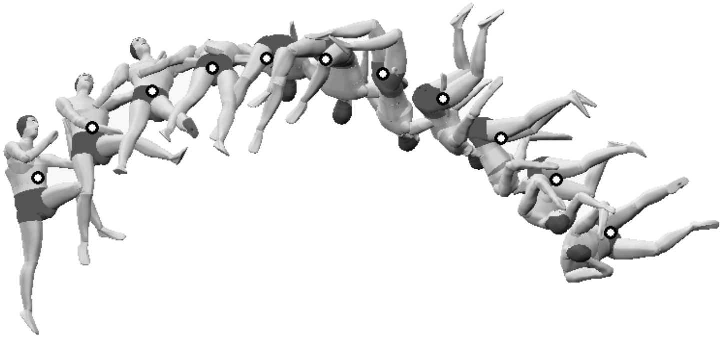

Figure 1. The flight phase of a high jump performance showing the parabolic path of the mass centre.

Rotation during flight

In running jumps, the takeoff phase typically produces rotation even where this is disadvantageous to the performance. In long jumping undesirable forward angular momentum is produced during the takeoff and a hitch-kick, involving arm and leg rotations, is often used to minimise the forward rotation in the aerial phase (Hay, 1975; Herzog, 1986). In high jumping, both twist and somersault rotations are produced during takeoff and these are used to advantage in clearing the bar (Dapena, 1980, 1995; Hopper, 1963). In gymnastics skills, the somersault is initiated during the takeoff phase, while twist may be initiated either during the takeoff or during the aerial phase (van Gheluwe, 1981). Although the movement of the mass centre is predetermined at takeoff (so long as air resistance can be neglected) the athlete has considerable control over rotational motion during the aerial phase.

At takeoff a gymnast has a certain quantity of angular momentum about the mass centre and this remains constant during the aerial phase since the only force acting is the weight of the gymnast and this force acts through the mass centre. For the simple case in which the body rotates about a single axis the angular momentum is the product of moment of inertia and angular velocity. A ballet dancer or a figure skater takes off for a twisting jump with arms wide and subsequently brings the arms close to the body. The effect of this is to reduce the moment of inertia about the twist axis and to increase the speed of rotation. In the double somersault shown in Figure 2 taken from a floor exercise at the 1996 Olympic Games, the gymnast is initially in an extended configuration and is somersaulting relatively slowly whereas subsequently the gymnast adopts a tucked position which has a smaller moment of inertia so that the somersault rate increases. By extending again at an appropriate time the gymnast can land the skill on the feet and maintain balance. For twisting somersaults in which rotations take place about more than one body axis, the situation is more complex but the same principle of angular momentum conservation governs the motion (Yeadon, 1993a).

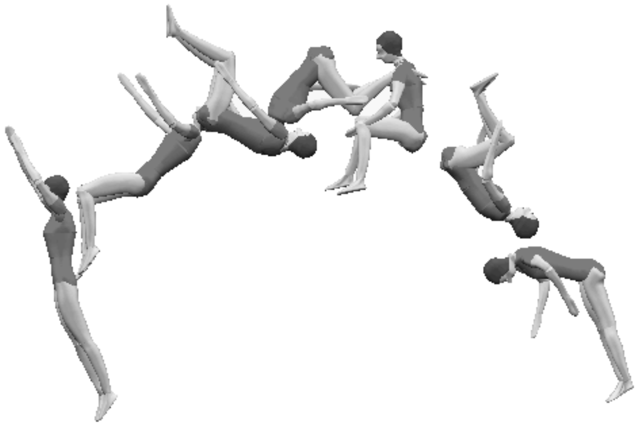

Figure 2. A double backward somersault from a floor exercise showing the increased speed of somersault rotation when the body is tucked.

Somersaulting

While a gymnast has considerable control over the rotation in the aerial phase the angular momentum for a specific skill is often quite tightly constrained by the requirements for the good performance. Figure 3 depicts a good performance of a double somersault dismount from the high bar in a straight or extended position. Since the gymnast must remain extended throughout the aerial phase he has only a limited ability to adjust his moment of inertia primarily by changing arm position. As a consequence the angular momentum generated prior to release must lie within fairly tight limits in order for a good performance to be possible. The angular momenta in four double somersault dismounts from the high bar in Olympic competition varied by as much as 16% although only one of the dismounts could be considered to demonstrate a good straight position during flight (Kerwin et al., 1990).

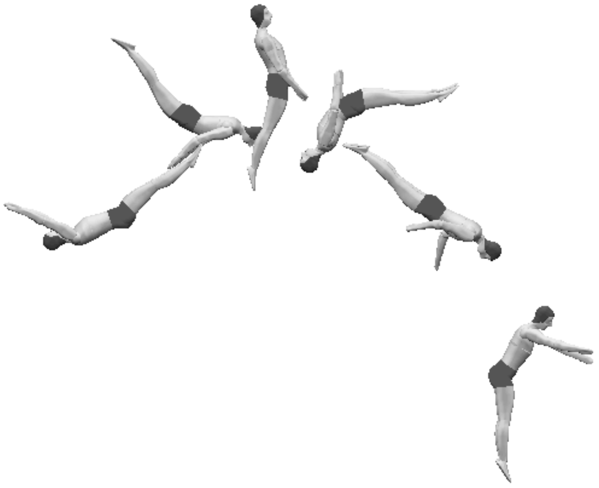

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Figure 3. A double somersault dismount from the high bar with a straight body.

For body positions other than straight there is more freedom for the gymnast to adjust the somersault rate. In the tucked triple somersault dismount from high bar shown in Figure 4 there is sufficient angular momentum to allow the movement to be completed successfully. If there were slightly less angular momentum than this, the gymnast could compensate by adopting a tighter tucked position. There could, however, be considerably more angular momentum without this being detrimental to a good performance. With more angular momentum the gymnast could delay the movement into the tucked position and could extend earlier prior to landing. In fact the angular momentum of the straight double somersault shown in Figure 3 is 18% greater than the angular momentum of the tucked triple somersault shown in Figure 4. This indicates that a gymnast who can do a straight double somersault dismount from high bar should be able to generate ample angular momentum for a tucked triple somersault dismount. Some gymnasts have employed a split tuck technique in which the knees are pulled wide to reduce the moment of inertia about the somersault axis but this technique is a break in form and only marginally increases the somersault rotation (Kerwin et al., 1990).

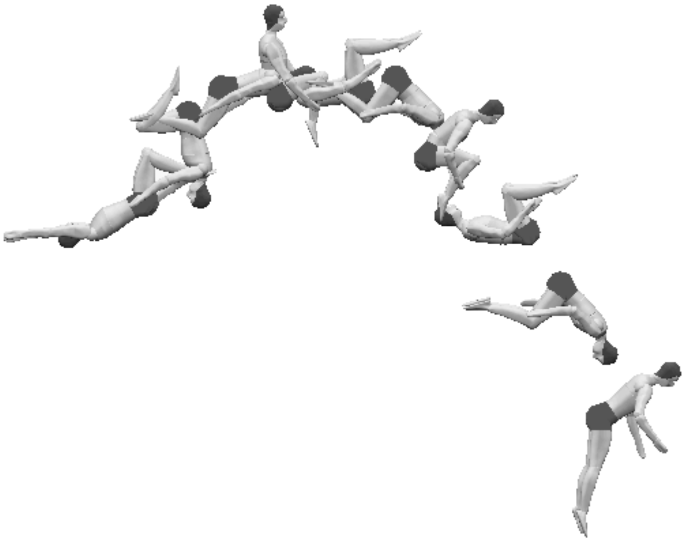

Figure 4. A triple somersault dismount from the high bar with the body tucked.

Twisting

To understand the mechanics of a multi-link system performing somersaults with twist, it is helpful to look at the rotational motion of a rigid body. There are only two general types of motion that a rigid body can exhibit (Yeadon, 1993a). The first of these is the *wobbling somersault* in which the body somersaults about a horizontal axis but also has an oscillating motion in which it twists one way and then the other (Figure 5). During this motion the body also tilts first one way and then the other so that the head is to one side of the feet and then later to the other (see the first and last images in Figure 5).

Figure 5. During a wobbling somersault the twist oscillates left then right.

The second type of motion is the *twisting somersault* in which the twist is always in the same direction (Figure 6). During this motion the body is always tilted in the same direction away from the somersault plane (the plane normal to the angular momentum vector). This tilt varies with the twist and is smallest for an even number of quarter twists (images 1, 6, 11 of Figure 6) and greatest for an odd number of quarter twists (images 3 and 9 of Figure 6). This variation in the tilt angle is known as *nutation* from the theory of spinning tops (Synge and Griffith, 1959) and is important for the understanding of how aerial twist is produced (Yeadon, 1993c).

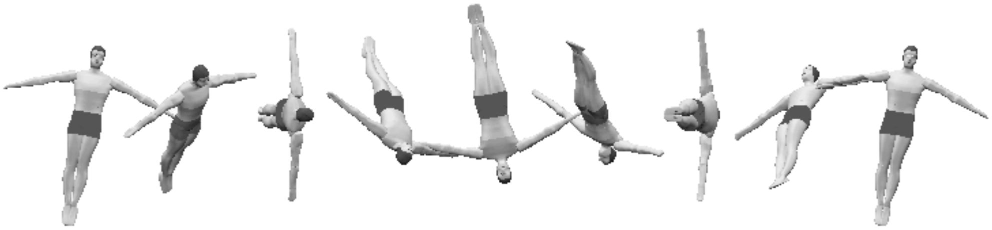

Figure 6. During a twisting somersault the twist continues in one direction.

Since there are two quite different types of rigid body motion it might be possible that a multi-link system such as the human body could change its motion from one type to the other merely by changing body configuration.

Contact twist

Angular momentum is built up while the body is in contact with the diving board or gymnastics apparatus so that it is somersaulting at takeoff. Twist may be initiated in a similar way by turning the arms and trunk in the direction of the twist while the feet are in contact with the takeoff surface. If the body is extended at takeoff this will produce a twisting somersault in which the body is tilted away from the vertical after half a somersault (Biesterfeldt, 1974; Eaves, 1969). Because this tilt disappears of its own accord after a complete somersault, it does not pose a problem in tumbling skills in which the gymnast takes off and lands on the feet. In twisting dives, however, there is a potential problem since entry is made into the water after one and a half somersaults. In the computer simulation shown in Figure 7 the body maintains left-right symmetry throughout (upper sequence in Figure 7) and overcomes this potential problem by adopting a piked position as the required number of twists nears completion. This causes the motion to change from a twisting somersault to a wobbling somersault. While the body is in the wobbling mode of motion the tilt angle is allowed to oscillate so that when the body extends it is almost vertical. This technique has its limitations since for large amounts of twist, the wobble in the piked position becomes excessive and the twist is much harder to control (Yeadon, 1993b).

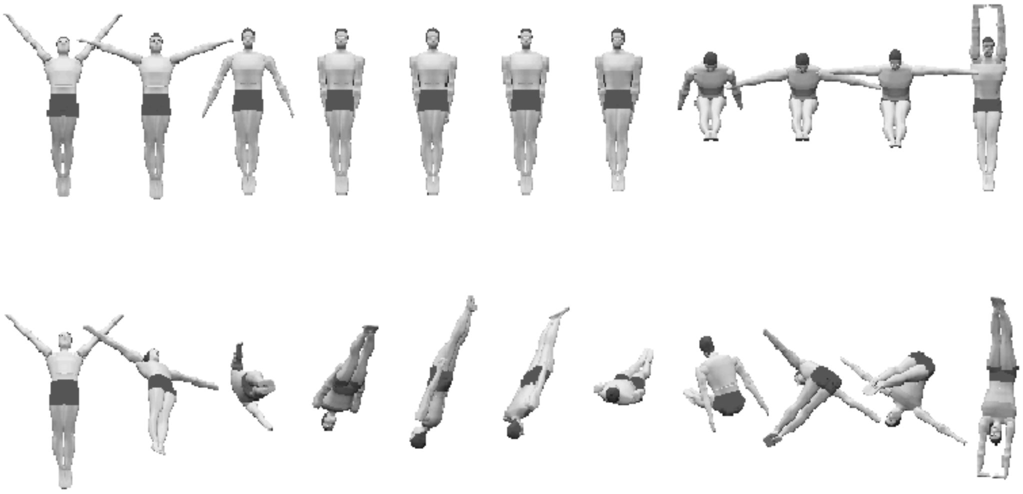

Figure 7. A computer simulation of a backward 1 ½ somersault dive with 1 ½ twists in which the twist is produced during the takeoff.

Aerial twist

The way in which a cat rights itself by producing a half twist in mid-air after being dropped in an inverted position has been studied for more than a century (Marey, 1894; McDonald, 1960). Some coaches have thought that this is the main mechanism that divers use to produce twist (Eaves, 1969; Rackham, 1960). The twist is produced by using a hula-hoop circling movement of the hips during the aerial phase. If the initial angular momentum is zero it must remain so during flight and so the angular momentum associated with the hip circling produces a twisting of the whole body in the opposite direction (Kane and Scher, 1969). A simulation of this movement is shown in Figure 8 in which the hips circle to the right producing a twist to the left. The body moves from a forward flexed position through a side arch over the right hip, into a back arch, through a side arch over the left hip and ends in a forward flexed position again, having completed a half twist. A skilled trampolinist can produce a full twist using two cycles of such a movement while airborne.

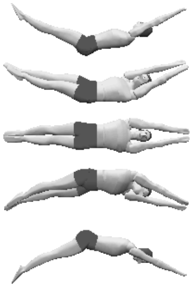

Figure 8. Computer simulation of an aerial half twist using the “hula” or “cat” technique.

It is evident that gymnasts, trampolinists and divers do not use this hula technique to produce multiple twists during the aerial phase of a somersault since the body typically remains straight during the twist. If somersault is present then any technique that tilts the body away from the somersault plane will result in twist in order to maintain constant angular momentum (Frolich, 1980). The most obvious way of producing tilt during freefall is to raise one arm laterally while lowering the other. In a plain jump there is no angular momentum and this arm movement will produce a tilting of the whole body in order to maintain zero angular momentum (upper sequence of Figure 9). If the same arm movements are made during a plain somersault, a similar amount of tilt (8°) results and the body automatically twists in order to maintain constant angular momentum (Yeadon, 1990).

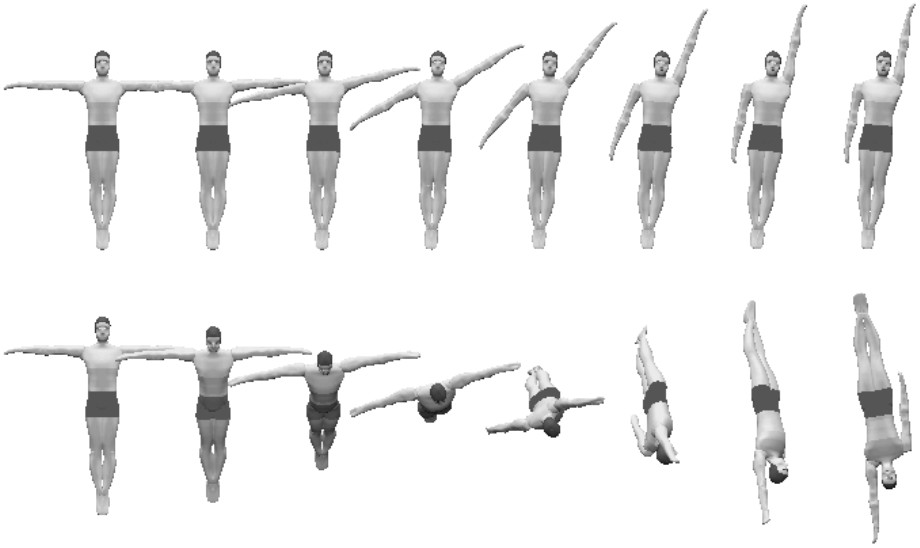

Figure 9. Aerial twist in a somersault resulting from tilt produced by asymmetrical arm movement.

Any movement in which left-right symmetry is not maintained is likely to produce some twist. In the simulation shown in Figure 10 the body makes a partial hula movement while extending from a piked to a straight position. In a plain jump this hula movement with wide arms produces tilt while the body is in a side arch configuration due to a reorientation of the principal axes of inertia (Yeadon and Atha, 1985). Once the body extends, however, the final tilt is only 3° (upper sequence of Figure 10). If the same movements are made during a somersault the situation is somewhat different. Once the body is in a side arch position with wide arms there is considerable tilt (10°) of the principal axis corresponding to minimum moment of inertia and so the body starts to twist in order to maintain zero angular momentum. As the twist increases up to a quarter twist, the tilt angle also increases due to the nutation effect. When the body extends to a straight position the tilt angle is not reduced in the same way as for a plain jump with a hula movement since this extension is made at around the quarter twist position and any reorientation therefore changes the somersault rather than the tilt. As a consequence this technique produces considerable tilt (11°) in a somersault and is a viable method of producing aerial twist.

It is fortuitous that the hula movement that produces a twist to the left in a jump also produces tilt which will result in a twist to the left in a forward somersault. During the takeoff for a forward somersault from the floor or trampoline or diving board the body flexes at the hips so that initially it is in a piked position which is suitable for this technique. For a backward somersault the body is initially arched and use of a partial hula movement while extending again produces tilt which results in twist in the same direction as the hula twist. If the body is rotating backwards in a piked position, however, the tilt produced by a hula movement results in twist in the opposite direction to the hula twist. This conflict greatly reduces the effectiveness of the technique (Yeadon, 1993c) and it is preferable to use asymmetrical arms movement to produce aerial twist from a piked configuration when rotating backwards.

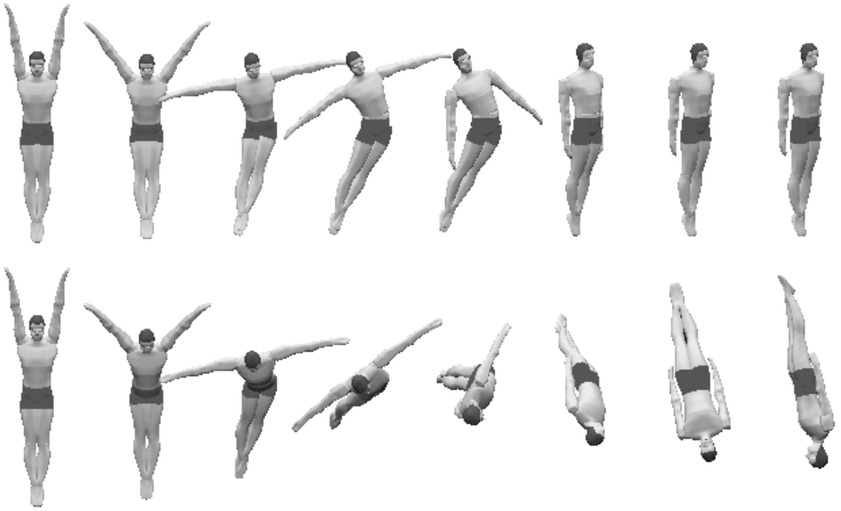

Figure 10. Aerial twist in a somersault resulting from tilt produced by asymmetrical hip movement.

The tilt produced by an asymmetrical arm movement will be greater when the arms move through a large angle. In order to achieve this in a computer simulation, the left arm is first lowered to the side of the body together with some adduction and abduction so that it passes in front of the body (upper sequence of Figure 11). This minimises the negative tilt produced by the initial arm movement and places the arms in an asymmetrical position from which each arm may be rotated through half a revolution. This produces twice the tilt (16°) of the arm movement shown in Figure 9 since the arms move through twice the angle. When the same arm movements are made during a somersault a similar amount of tilt results and a rapid twist ensues (lower sequence of Figure 11). As the twist nears three revolutions the body flexes at the hips and the arms are spread wide. This removes the tilt so that a 1 ½ somersault dive with three twists can be completed. It is important that the left arm initially sweeps across the body as it is lowered to the side as otherwise the body becomes tilted in the opposite direction and twists to the right while the arm is being lowered. In this case the double arm movement occurs around the quarter twist position and produces little change in the tilt angle since the reorientation of the body manifests itself mainly as a change in somersault rotation.

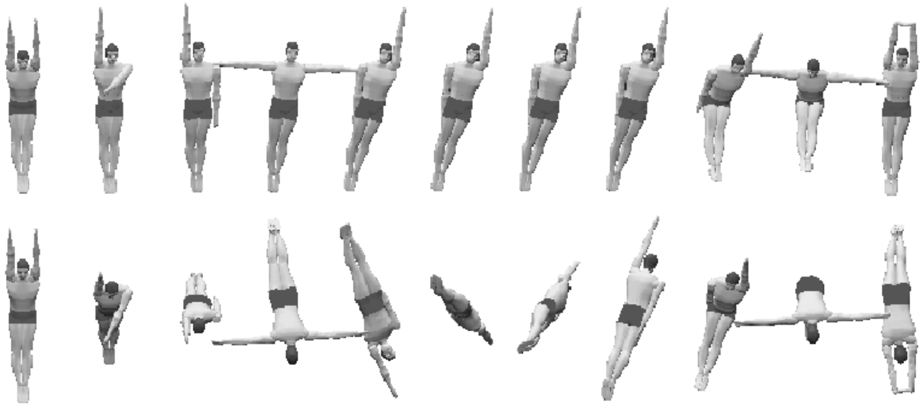

Figure 11. Simulation of a forward 1 ½ somersault dive with three twists using asymmetrical movements of the arms.

The asymmetrical hip technique shown in Figure 10 may be used to produce 1 ½ twists in a single or double somersault. In Yeadon (1997a) a progression based on computer simulations is described for learning a double somersault with 1 ½ twists in the second somersault (Figure 12). In the first somersault the body is flexed into a piked position and then moves through a side arch position with wide arms while extending. The arms are then adducted to accelerate the twist and as the 1 ½ twists are completed first the right arm and then the left arm is abducted to help remove the tilt. The body also moves through a side arch position while flexing in order to use the asymmetrical hip technique to help remove the tilt. The asymmetrical hip technique is capable of producing tilt when the somersault is forwards and of removing tilt when the somersault is backwards. It is not effective in removing the tilt in a dive such as in Figure 11 where the final somersault direction is forwards.

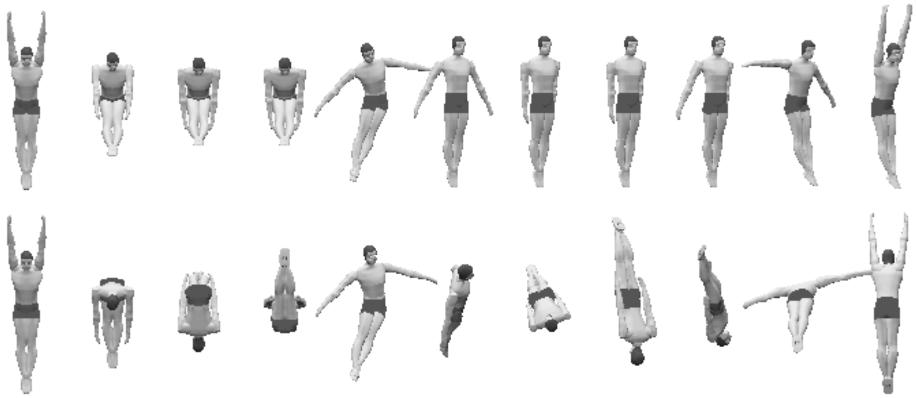

Figure 12. A double somersault with 1 ½ twists in the second somersault produced using asymmetrical hip movement.

Stopping the twist

In the simulation shown in Figure 11 tilt was removed using a reversal of the initial asymmetrical arm movement that was used to produce the tilt. This technique may be used in dives with an even number of half twists. For an odd number of half twists a reversal of the initial arm movement would increase the tilt and speed up the twist. In such a case it is necessary to reverse the arm positions during the twist without affecting the tilt so that they are in a suitable position for removing the tilt prior to entry. In backward and reverse twisting dives there are typically 1 ½, 2 ½ or 3 ½ twists and this technique is often used. The lower sequence of Figure 13 is taken from a performance of a backward 1 ½ somersault dive with 1 ½ twists. The upper sequence shows the body configurations used in the dive. After takeoff the left arm is lowered and the right arm is held high producing tilt that results in a twist to the left. During the twist the arm positions are reversed while keeping the arms close to the body so as not to slow the twist. As the 1 ½ twists near completion the diver first pikes and then lowers his left arm while raising his right arm so as to remove the tilt. By first flexing at the hips the moment of inertia about the frontal axis is reduced so that more tilt can be removed by the asymmetrical arm movement.

Figure 13. Stopping the twist by removing the tilt in a backward 1 ½ with 1 ½ twists using asymmetrical arms.

Contributions

The simulation model of Yeadon et al. (1990a) has been used to determine the contributions of the various twisting techniques to the production of tilt and hence twist in actual performances by using modifications of the body configurations used by the athlete. To determine the contribution of asymmetrical arm movement, for example, a modified simulation can be carried out in which the right arm mirrors the original left arm movement so that the arms move symmetrically. The difference in the tilt angles produced in this simulation and the original simulation based on the actual arm movement gives a measure of the contribution to the tilt angle from asymmetrical arm movement (Yeadon, 1993d). Other contributions can be determined in a similar manner.

Figure 14 depicts a performance of a double somersault from trampoline with a full twist in the second somersault. In such a movement where almost a complete somersault occurs prior to the initiation of twist it is to be expected that little contact twist is used and that aerial techniques are responsible for the production of twist. Prior to twisting the body is piked and since it is rotating backwards asymmetrical hip movement is unable to produce much tilt since the directions of hula twist and tilt twist are in conflict. As a consequence it might be expected that the twist is produced by asymmetrical arm movement in the aerial phase and a simulation analysis yields just this result (Yeadon, 1993d). Such simulation analyses have shown that the greatest contributions are made by asymmetrical arm and hip techniques in the aerial phase in springboard diving (Yeadon, 1993e), in single somersault dismounts with one twist from high bar (Yeadon et al., 1990b) and in double somersault dismounts with one twist from the rings (Yeadon, 1994). There is some evidence, however, that major contributions are made by contact techniques in multiple somersaults with twist when there is substantial twist in the first somersault in, for example, high bar dismounts (Yeadon, 1997b) and freestyle aerial skiing (Yeadon, 1989).

Figure 14. Performance of a piked double backward somersault from trampoline with one twist in the second somersault.

Control

If a rigid body is somersaulting about its intermediate principal moment of inertia the motion is unstable in the sense that twist will build up exponentially until the body completes a half twist (Hinrichs, 1978; Marion, 1965). In practice this will pose a potential problem for somersaults about a lateral axis when the body is held straight. Figure 15 depicts a hypothetical simulation of a double somersault in which slight arm asymmetries lead to a quarter twist towards the end of the movement. Nigg (1974) suggested that the arms could be extended laterally during a straight somersault in order to minimise the effect of this instability. Yeadon and Mikulcik (1996) showed that this strategy will not decrease the build-up of twist. An alternative strategy of asymmetrical arm adduction and abduction based upon the twist angular velocity and acceleration is capable of preventing the build-up of twist providing that the time delay in the feedback loop is less than a quarter of a somersault. There is evidence that the inner ear organs normally used for balance provide the required feedback data on twist velocity and acceleration rather than the visual system (Yeadon and Mikulcik, 1996). 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 (Rezette and Amblard, 1985).

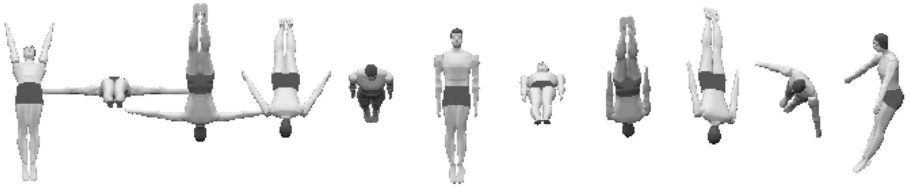

Figure 15. Simulation of an unstable double backward somersault leading to a quarter twist.

In actual performances of straight double somersaults such asymmetrical arm movements are not readily apparent to an observer or to the performer making the corrective adjustments. This is probably because the corrective movements made are small and the build-up of twist is small. Occasionally, however, the build-up of twist may be corrected somewhat late and a larger arm asymmetry will be required. An example of such a case is shown in Figure 16 which depicts an actual performance of a double straight somersault on trampoline in which considerable arm asymmetry is evident after 1 ½ somersaults.

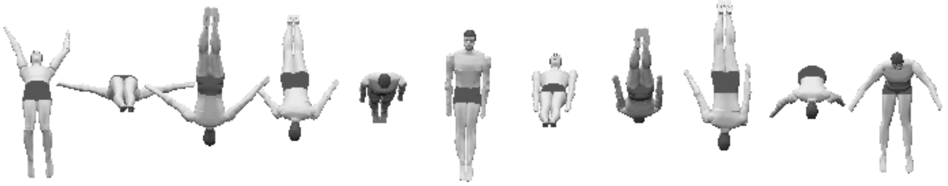

Figure 16. A performance of a double straight somersault in which corrective arm asymmetry is apparent late in the movement.

The build-up of twist can be used to good effect to produce an aerial twist using only a small asymmetry in the arm positions. Figure 17 depicts a theoretical simulation of a double somersault with one twist in the last 1 ¼ somersaults. During the first three quarters of a somersault the arms are spread wide but with a small (5^o) asymmetry. This leads to a slow build-up of tilt and twist during the first somersault. The twist is accelerated by adducting both arms towards the end of the first somersault. As one revolution of twist nears completion, first the right arm is adducted and then the left arm in order to remove the tilt and stop the twist. Since this asymmetrical arm movement for stopping the twist comprises exactly the same technique as for preventing the build-up of twist in a straight somersault it is likely that learning this type of control in a twisting somersault is carried over into the control of non-twisting somersaults or vice versa.

Figure 17. Simulation of a double backward somersault with one twist in the second somersault arising from slight arm asymmetry in the first somersault.

Summary

Most sports movements contain an aerial phase during which the body loses contact with the ground or apparatus. While the path of the mass centre during flight is determined by its location and velocity at takeoff, the amount and type of rotation of the body is largely under the control of the athlete. Somersault rotation is a consequence of the angular momentum generated during takeoff. Twist rotations may be initiated during takeoff or during the aerial phase by means of asymmetrical arm or hip movements. Asymmetrical arm movements may be used to stop the twist in a twisting somersault or to prevent the build-up of twist in a non-twisting somersault. The control of the twist in this way is possible using feedback via the inner ear balance mechanisms provided that the somersault rate is not too high.

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Figure 1. The flight phase of a high jump performance showing the parabolic path of the mass centre.

Figure 2. A double backward somersault from a floor exercise showing the increased speed of somersault rotation when the body is tucked.

Figure 3. A double somersault dismount from the high bar with a straight body.

Figure 4. A triple somersault dismount from the high bar with the body tucked.

Figure 5. During a wobbling somersault the twist oscillates left then right.

Figure 6. During a twisting somersault the twist continues in one direction.

Figure 7. A computer simulation of a backward 1 ½ somersault dive with 1 ½ twists in which the twist is produced during the takeoff.

Figure 8. Computer simulation of an aerial half twist using the "hula" or "cat" technique.

Figure 9. Aerial twist in a somersault resulting from tilt produced by asymmetrical arm movement.

Figure 10. Aerial twist in a somersault resulting from tilt produced by asymmetrical hip movement.

Figure 11. Simulation of a forward 1 ½ somersault dive with three twists using asymmetrical movements of the arms.

Figure 12. A double somersault with 1 ½ twists in the second somersault produced using asymmetrical hip movement.

Figure 13. Stopping the twist by removing the tilt in a backward 1 ½ with 1 ½ twists using asymmetrical arms.

Figure 14. Performance of a double backward somersault from trampoline with one twist in the second somersault.

Figure 15. Simulation of an unstable double backward somersault leading to a quarter twist.

Figure 16. A performance of a double straight somersault in which corrective arm asymmetry is apparent late in the movement.

Figure 17. Simulation of a double backward somersault with one twist in the second somersault arising from slight arm asymmetry in the first somersault.