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The physics of twisting somersaults

Fred Yeadon

Perhaps the most spectacular moment of the 1996 Olympic Games in Atlanta was the half twist performed in the air by Lilia Podkapayeva of Ukraine at the end of a double forward somersault from the floor. In order to score full marks out of ten, a competitive gymnastics routine must include a sufficient number of complex skills. Judges check how many of the required technical elements are completed, and deduct points for missing elements, imperfect body shapes and unsteady landings. So how is it possible for a gymnast to land correctly on every occasion?

To answer this question it is useful to compare the motion of an aerial gymnast with that of a falling cat. A cat falls out of a tree and unerringly lands on its feet. Meanwhile, an Olympic gymnast releases the rings or bars, performs one somersault without twisting and then magically produces a twist during the second somersault before making a perfect landing. The cat copes with an unexpected situation by making the necessary manoeuvres to land safely. The gymnast, on the other hand, makes pre-planned movements to produce the required number of somersaults and twists.

Since each performance is different, it is clear that in-flight adjustments have to be made based on a judgement of how the movement is progressing. Like the cat, a gymnast can judge his or her orientation in space from the balance mechanisms inside the inner ear, and from the information received by the eyes. It is useful therefore to be able to “see where you are going” in order to land correctly. To achieve this it is helpful to change the body’s orientation so that the landing area is kept in view. The cat achieves this by producing a half twist whenever it faces upwards rather than downwards. Similarly the gymnast can maintain visual contact with the ground during a double somersault by introducing a twist into the second somersault. Such a manoeuvre ensures that the landing area is in view continuously throughout the last half of the dismount. At first sight, however, it is not clear how such twisting movements can be produced while airborne.

The translational motion of the gymnast (or the cat) during flight is governed by Newton's Second Law of Motion. The gravitational force produces a constant acceleration of the centre of mass, since air resistance can be neglected for all aerial gymnastic movements and for cats falling from modest heights. If the initial position and velocity of the centre of mass are given then the subsequent flight of the mass centre is completely determined.

Since the weight acts through the centre of mass there is no net moment or torque about the centre of mass when airborne and so the angular momentum must remain constant throughout the flight. This determines the angular velocity of the body if the configuration changes during flight are known. Such changes in body configuration will change angular velocity both as a result of the angular momentum associated with the relative movement of body segments as well as changes in whole body moments of inertia. So while the linear velocity is completely determined, the angular velocity is not.

Conservation of angular momentum

In 1894, the Frenchman Etienne-Jules Marey, inventor of chronophotography, produced photographic sequences of a cat that had been held upside down and released. The falling cat performed a half twist in mid-air and landed on all fours. The cat had no angular momentum when it was dropped, and its angular momentum remained zero during the half twist. So, how was it possible for the cat to twist? Some explanations describe the cat twisting its upper body relative to the lower body.

While some cats may do this, presumably to get an early look at the ground, such spinal torsion does not contribute greatly to the production of twist.

In such experiments, the cat is initially held with its legs upwards and its spine bent forwards. On release, the cat bends to the side, arches its back, bends to the other side, and finally bends forward again. This “hula-hoop” movement has some angular momentum associated with it, and so the whole body rotates in the opposite direction in order to maintain zero angular momentum.

In the 1960s, while investigating various techniques that NASA astronauts could use to reorient themselves in space, the Stanford University engineer Thomas Kane explained the mechanics of the twisting cat in this way using a two-segment model to simulate the motion of a filmed cat. Kane demonstrated that the amount of twist produced depends on the amount of flexion used and the moments of inertia of the two body segments.

A complete cycle of such a hula-hoop movement only produces around 180^{o} of twist, which means that the technique is of somewhat limited use in gymnastics. So, how do gymnasts perform multiple twists while they are airborne?

Somersault, tilt and twist

The rotation of a gymnast can be described by three angles of rotation, known as the somersault, tilt and twist angles (figure 1). For simplicity, suppose that the gymnast is initially somersaulting around a horizontal axis so that the angular momentum vector points horizontally. Somersault rotation is described as forwards or backwards and takes place around an axis, a_1, which passes through the centre of mass and is fixed in space. Meanwhile, the gymnast can twist to the left or the right around the longitudinal axis of the body, a_3, which passes through the head and feet. The gymnast’s moment of inertia is a minimum about this axis, which moves with the body. Finally, tilt is the angle between the twist axis of the body and the vertical somersault plane that is perpendicular to the angular momentum vector.

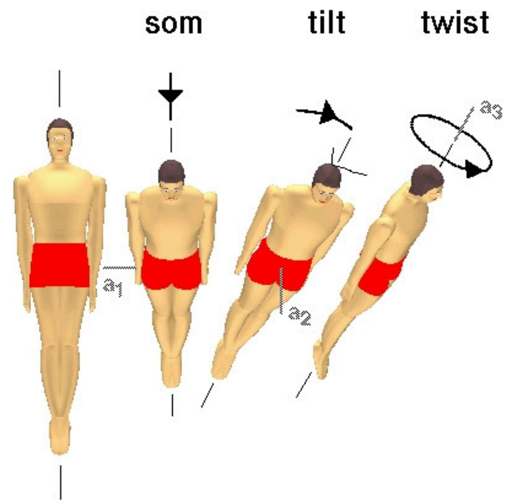

Figure 1. Defining angles

Angles of somersault, tilt and twist. The somersault axis a_1 is parallel to a fixed direction in space, while the gymnast twists around the longitudinal axis a_3, which is fixed in the body. The tilt is defined as the angle between the longitudinal axis and the vertical somersault plane.

In order to perform a somersault, a gymnast needs to generate angular momentum before he or she dismounts from a piece of apparatus. On the high bar, for example, a gymnast achieves this by swinging around the bar in successive giant circles which he accelerates by flexing his body near the lowest point and extending near the highest point. The gymnast then releases the bar when his body is almost horizontal -- at this point, his linear velocity is near vertical and his angular momentum is large. In contrast to the falling cat, which must move within the constraints of zero angular momentum, the gymnast has more possibilities to manoeuvre while maintaining constant angular momentum.

To understand the effect of introducing tilt into a somersault consider the following. The left side of figure 2 shows a gymnast somersaulting forwards as viewed from the front and from above. The overhead view shows the head moving forwards and the legs moving backwards. Since the head and the legs are in line, no clockwise or anticlockwise momentum is associated with this “plain” somersault.

The right side of figure 2 shows the same views after the gymnast has completed one somersault and has used suitable limb movements to tilt his body out of the vertical somersault plane. From the overhead view, we see that the movements of the head and feet are not in line so that the gymnast has some momentum in the clockwise direction. Since the total angular momentum must remain zero from this view, the gymnast must also be twisting to his left to counter the clockwise momentum. In other words, a gymnast can introduce twist into a somersault by producing tilt during the flight phase. Moreover the gymnast will continue to twist until he or she removes the tilt and returns to the vertical somersault plane.

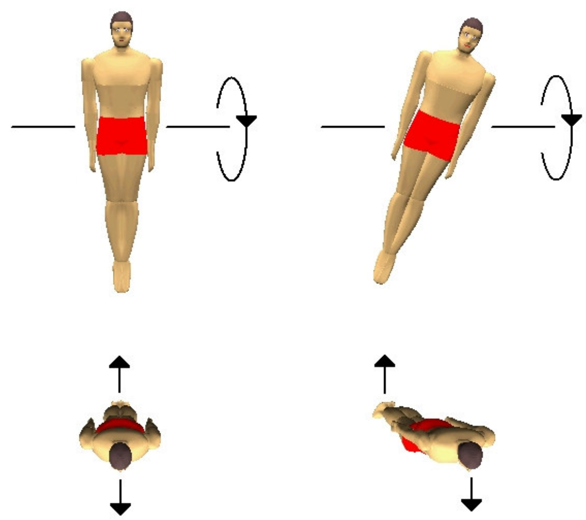

Figure 2. Angular momentum in action

The images show a forward somersault viewed from in front and above (*a*) when there is no tilt (left images) and (*b*) when there is tilt (right images). The combination of tilt and somersault gives rise to angular momentum, which can be clearly seen when viewed from above. As a consequence, the body twists in the opposite direction about the longitudinal axis that passes through feet and head.

Producing tilt using asymmetrical arm movement

Once the apparatus has been released, the gymnast makes appropriate limb movements that cause the body to tilt and therefore to twist as well. The most obvious way a gymnast can produce tilt is by moving the arms asymmetrically. The upper sequence in figure 3 shows what happens when a gymnast with no angular momentum raises his left arm sideways while lowering his right arm. This anticlockwise arm movement has an associated angular momentum, and so the whole body rotates in the opposite direction (i.e. tilts clockwise) to keep the gymnast's total angular momentum equal to zero.

The lower sequence in figure 3 shows what happens when the gymnast makes exactly the same arm movement during a somersault. Again the arm movement produces tilt but now the gymnast will also acquire a twist velocity in order to maintain constant angular momentum. Asymmetrical arm movement can also be used to remove the tilt and stop the twist.

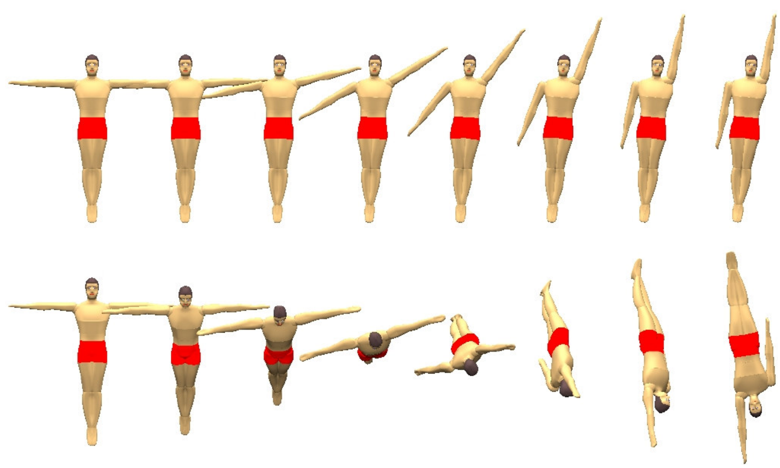

Figure 3. Tilt and twist from asymmetric arm movements

The upper sequence shows that when the gymnast has no angular momentum, an asymmetrical arm movement causes the whole body to tilt in the opposite direction. In the lower sequence, the same arm movements are made while the gymnast somersaults. Once again this movement produces tilt, which in turn causes the gymnast to twist.

In springboard diving, divers often use asymmetrical arm movements to produce the twist after they have taken off from the board, and they continue to hold one arm over the head during the twist. Competitors doing a forward-somersault dive incorporate 1, 2, 3, or 4 twists so that the water is kept in view just prior to entry. Backward-somersaulting dives use ½, 1½, 2½, or 3½ twists for the same reason.

In forward-somersaulting dives, the arm movement may simply be reversed near the end of the dive to remove the tilt and ensure that the diver enters the water vertically. In backward-somersaulting dives, however, the arm positions (one arm up, one arm down) must be reversed during the twist. During this movement the diver keeps the arms close to the body to avoid affecting the tilt angle and twist rate. This arm reversal positions the correct arm overhead ready for removing the tilt by lowering the upper arm and raising the lower arm when the twist nears completion.

In trampolining the arms are held close to the body in symmetrical positions during the twist even when an asymmetrical arm movement is used to initiate the twist. To remove the tilt the trampolinist first moves one arm away from the body, followed by the other.

In the 1970s Cliff Frolich of the University of Texas and Nicolai Suchilin at the Pedagogical Institute in Moscow gave theoretical explanations as to why asymmetrical arm movements produce twist during a somersault. Later, in the 1980s, Nancy Pike of Pennsylvania State University in the USA produced a computer simulation of a full twisting forward dive, while Bart van Gheluwe at the Free University of Brussels simulated a full twist in a backward somersault using asymmetrical arm movements.

Producing tilt using asymmetrical hip movement

Gymnasts, divers and trampolinists can also produce tilt from a “piked position” -- where the body is bent forward at the hips -- by straightening the body asymmetrically during a forward somersault. This is done by flexing the hips sideways while straightening from the forward-flexed position. The upper sequence in figure 4 shows the result of this hip movement when the gymnast has no angular momentum. The flexion to the side can be seen clearly in the fourth and fifth graphics of the upper sequence. At this point, the twist axis -- the principal axis about which the moment of inertia is a minimum -- is approximately parallel to the legs and is tilted away from the vertical. Once the body is straightened, however, the tilt all but disappears again since very little twist has been produced and the body is still facing forwards. The hip movement is similar to the first quarter of the “hula-hoop cycle” used by falling cats when they twist. As a consequence, the amount of twist that results is small -- as shown in the last graphic of the upper sequence.

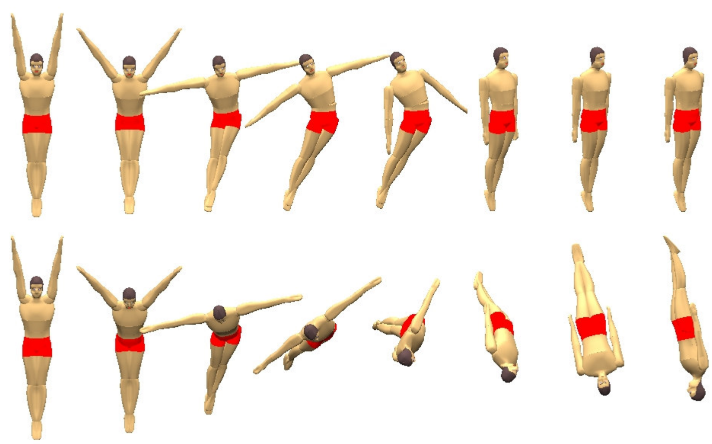

Figure 4. Tilt and twist from asymmetrical hip movements

The upper sequence shows a simulation of gymnast moving through a side flexed position as he straightens from a piked position when the angular momentum is zero. The lower sequence shows that when the same asymmetrical hip movements are made as the gymnast somersaults, tilt is produced which results in twist.

The lower sequence in figure 4 shows what happens when a gymnast makes exactly the same hip movement during a forward somersault. Again the fourth and fifth graphics correspond to a tilting of the twist axis away from the vertical plane and this results in twist because somersault is present. However, in this case the tilt angle does not disappear when the body is straightened. This is primarily because the body has twisted through about a quarter turn when the body extends from the flexed position. As a consequence any reorientation of the twist axis changes the somersault angle rather than the tilt angle.

Another reason why the tilt is greater when somersaulting is that a freely-rotating rigid body that is twisting and somersaulting will “nutate”. In other words, the tilt angle will oscillate. The nutation arises because the principal moment of inertia about the axis through the front of the body (a_2 in figure 1) is larger than the principal moment of inertia about the lateral axis through the hips (a_1 in figure 1). This difference in the moments of inertia is more pronounced when the arms are wide and the body is flexed sideways, as in the fourth graphic of figure 4.

As a consequence of this asymmetry in the moments of inertia, the tilt angle oscillates together with the somersault and twist rates in order to maintain constant angular momentum. The nutating tilt angle reaches a maximum after a quarter twist, so it is advantageous for the gymnast to straighten at this time. Once the gymnast has straightened his or her body and pulled the arms in close, the two large principal moments of inertia will be nearly equal and the nutation in the subsequent motion will be small. In other words the tilt angle will remain large and the twist will be fast.

Analysis of twisting techniques

The movements shown in figures 3 and 4 were produced using a computer simulation model developed by this author. The model comprises 11 body segments that are linked by 10 joints: one at each elbow, shoulder, hip and knee and at three points on the spine. The mass, location of the centre of mass, and principal moments of inertia of each body segment are parameters of the model.

Input for a simulation consists of the angular momentum and initial orientation of the body, together with the time histories of the movement at each joint. The simulation model is implemented in the form of a computer program that solves the equations of constant angular momentum for the rates of change of the three orientation angles shown in figure 1. The program then integrates these rates of change to give the somersault, tilt and twist angles as functions of time.

The model may also be used to assess how such aerial twisting techniques contribute to a real gymnast's performance of twisting somersaults. For example, figure 5 shows how the simulation model was used to determine the effect of asymmetrical arm movement on the twist in a double somersault dismount from the rings. The gymnast's movement is first recorded using two video cameras, and the three-dimensional coordinates of the joints are reconstructed so that the orientation and configuration angles can be calculated as functions of time.

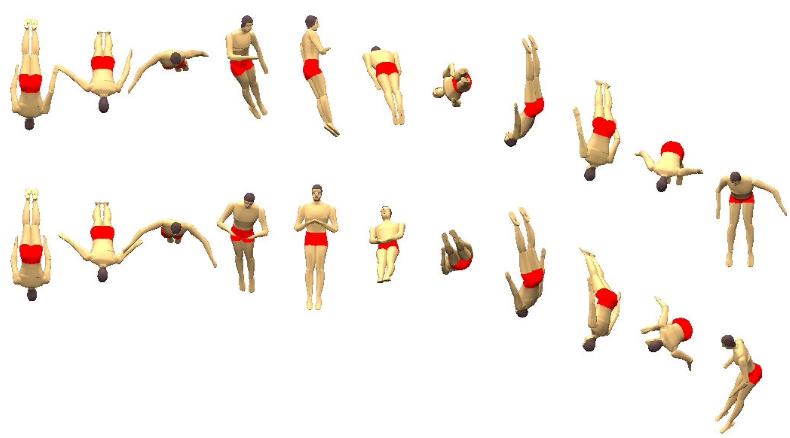

Figure 5. Analysis of a twisting double somersault

The upper sequence depicts a computer simulation of a full twisting double somersault dismount from the rings. The lower sequence shows a simulation in which the movement of the left arm mirrors the right arm, resulting in the disappearance of the twist.

The movement is then simulated to ensure that the somersault, tilt and twist angles are in close agreement with those in the video (upper sequence in figure 5).

The movement is then modified so that the movement of the left arm is changed to mirror the actual movement of the right arm (see the lower sequence in figure 5).

In other words, the upper sequence in figure 5 uses the actual asymmetrical arm positions adopted by the gymnast, while the lower sequence uses symmetrical arm positions throughout. In this modified simulation, the gymnast only twists through a quarter revolution to the right rather than through a whole revolution to the left. This result shows that asymmetrical arm movements are responsible for producing the twist. The same kind of procedure can be used to determine how asymmetrical hip movements contribute to twisting performances.

Since 1980 the author has investigated twisting techniques used in competitive gymnastics, trampolining, diving and freestyle aerial skiing. In general, elite competitors use asymmetrical arm and hip movements to initiate the twist when they are airborne, rather than starting the twist during takeoff. The advantage of aerial twisting is that the takeoff and the landing are simpler. Moreover, the competitor can use the same takeoff technique regardless of whether he or she is performing twisting or non-twisting somersaults. There is also less chance that the competitor will still be twisting on landing when aerial twisting techniques are used.

Applications to coaching

The primary value of this kind of research is that it provides a fundamental understanding of the mechanics of twisting techniques, rather than a personalised analysis for an individual competitor. Such an understanding makes it possible to provide advice to all competitors and coaches, and allows them to develop skills in a structured way.

For example, simulations may be used to develop learning progressions for twisting skills. A gymnast who is learning how to perform a forward somersault with 1½ twists using asymmetrical hip movement should first perform a half-twisting somersault while keeping the arms outstretched wide (see the upper sequence in figure 6). The gymnast produces the tilt by flexing over the right hip (shown in the second graphic) and later removes it by flexing the over the left hip. Once this wide-arm half twist has been mastered it is relatively simple for the gymnast to bring the arms close to the body once the twist has started, reducing the moment of inertia about the twist axis and producing 1½ twists. The asymmetrical hip movement that produces the twist is shown in the second and third graphics of the lower sequence, while the hip movement that removes the tilt and stops the twist is evident in the seventh and eighth graphics.

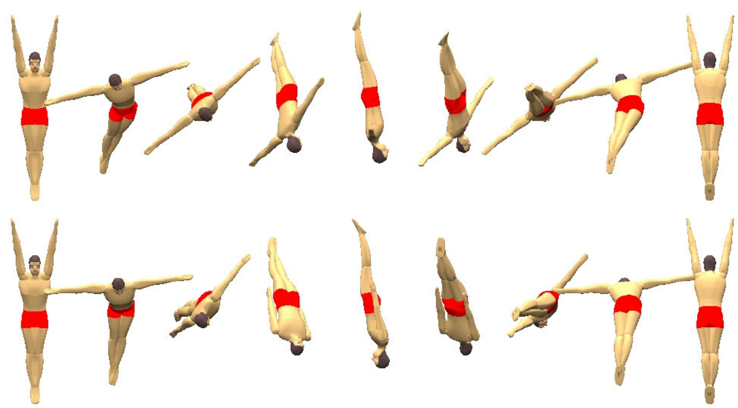

Figure 6. New skills for old

The upper sequence shows a simulation of a forward somersault with a half twist that is produced using asymmetrical hip movement during flight. The lower sequence shows a simulation of a forward somersault with 1½ twists using the same technique with the arms held close to the body.

After winning the bronze medal at the 1990 World Trampolining Championships, Sue Challis, the 1984 World Champion, wanted to relearn her twisting skills using straight arms since this is more highly rated in competitive trampolining. Under the guidance of the author, she used the method just described to learn how to perform single and double somersaults with twist while keeping her arms straight. This enabled her to remain competitive until she retired in 1998, winning the European Championships in 1993. Film recordings of this learning process have been incorporated into a video of simulation and coaching progressions produced as part of a collaborative effort between Loughborough University and British Gymnastics to inform gymnastics coaching.

A look to the future

Advances in sporting performances arise from an improved understanding of technique and training. Such understanding comes from sports science research as well as from advances within the sport. Thirty years ago, for example, the most complex trampoline routines were mainly composed of double somersaults with twists, and perhaps included one half-twisting triple somersault. Since then routines have steadily increased in difficulty with the record for the most triple somersaults in a ten skill routine standing at five -- held jointly by Igor Galimbatovski of the Soviet Union (1986 World Championships) and by Daniel Neil of Great Britain (1999 World Championships).

And we can look forward to more spectacular performances later this month in Sydney where trampolining will make its Olympic debut. Who knows what twisting movements will be performed thirty years from now? Perhaps we will even see free-fall competitions in orbiting space stations!

Further reading

B Van Gheluwe 1981 A biomechanical simulation model for airborne twist in backward somersaults *Journal of Human Movement Studies* 7 1--22

T R Kane and M P Scher 1969 A dynamic explanation of the falling cat phenomenon. *International Journal of Solids and Structures* 3 39--42

M R Yeadon 1993 The biomechanics of twisting somersaults Parts I-IV *Journal of Sports Sciences* 11 187--225

M R Yeadon 1994 Twisting techniques used in dismounts from rings *Journal of Applied Biomechanics* 10 178-188

For clips of the simulations see www.lboro.ac.uk/departments/ps/biomech/aerial.html

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