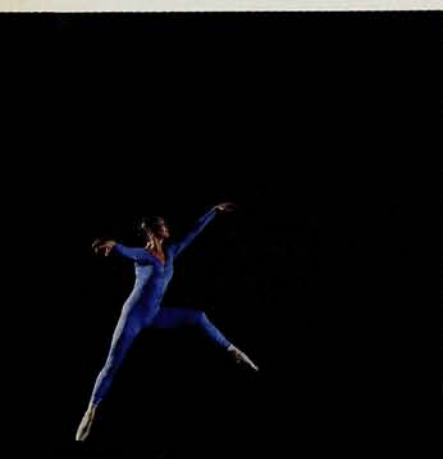




The physics of dance

Analyzing movements of dance in terms of Newtonian mechanics yields insights into aesthetic performance, and can be of value not only to students and teachers, but also to spectators of dance.

Kenneth Laws

Most dance enthusiasts—dancers, teachers and spectators—consider dance to be a purely aesthetic performing art, involving human body movement performed to music. They recognize that the challenge for the dancer is to communicate the visual images intended by the choreographer and the dancer. Many also realize that part of the enjoyment of dance depends on recognizing the difficulty of performing these movements well—making physically challenging steps appear smooth and graceful. Few, however, take the further step of analyzing the physics of these movements to understand the difficulties facing the performer. Why are certain movements particularly difficult? Some movements appear to violate fundamental physical principles. How does a dancer create such illusions? How do dancers use physical principles of motion to their advantage, rather than fight against them?

For example, no matter how much a dancer may wish to leap off the floor and then start turning (say for a *tour jeté*—that is, a turning leap), the law of conservation

of angular momentum absolutely prevents such a movement. Nevertheless, an understanding of the basic physical principles underlying that movement allows the dancer to create an effective *illusion* of jumping into the air and then turning.

There is a legitimate fear that one may sacrifice the aesthetic impact of dance by trying to analyze the art form scientifically. A newspaper dance critic reporting¹ on a scientific study of *pirouettes*—full turns of the body on the toe or ball of one foot—titled his article, "He Wants to Reduce Ballet to a Science." (The scientist did not share this obvious bias.)

The reduction of dance to a science ignores the aesthetic dimension and the essence of communication with an audience. As philosopher Suzanne Langer put it:²

In watching a dance, you do not see what is physically before you—people running around or twisting their bodies; what you see is a display of interacting forces. . . . But these forces . . . are not the physical forces of the dancer's muscles. . . . The forces we seem to perceive most directly and convincingly are created for our perception; and they exist only for it.

There is also a feeling that science doesn't really apply to aesthetic art forms. Bart Cook, a member of the New York City Ballet, told³ *Dancemagazine*, "It's that

vision of freedom you create when you're defying physical law. . . ." And Lisa de Ribère, a soloist with American Ballet Theatre who has submitted her talents to scientific scrutiny, says an understanding of physical principles is useful to a dancer in developing technique, but the last thing she would want to think about when on stage in front of an audience is controlling her moment of inertia or maximizing her angular momentum in a turn! Artistic sensitivities must occupy a dancer's full attention at such a time.

Because a focus exclusively on physical analysis may detract from performance or appreciation of dance as an art form, what is the value of such analysis? Dancers, dance teachers and people in the medical profession are now recognizing that a knowledge of anatomy allows dancers to use their bodies most effectively and safely. A knowledge of anatomical structure and constraints on human body movement can help maximize the individual's potential and prevent the kinds of injuries that interrupt many promising dance careers. And understanding how the muscles work in dance movement, what constraints are imposed by muscles and bones, and how much a dance student can expand the range of motion permitted by these constraints, is clearly a valuable tool for a dance teacher. Consider the *grand battement devant*—a large kick in the forward

Kenneth Laws is professor of physics at Dickinson College and studies ballet on a professional level with the Central Pennsylvania Youth Ballet, both in Carlisle, Pennsylvania. Laws adapted this article from his recent book, *The Physics of Dance*, with permission of the publisher; © 1984 by Schirmer Books, A Division of Macmillan, Inc.



Grand jete by Jennifer Davis of the Pittsburgh Ballet Theatre. By changing the position of her legs during flight, the dancer can make her head and torso briefly follow a horizontal trajectory, giving the illusion that she is floating. See the diagram on page 26. (Photographs in this article are by Michael Friedlander.)

direction without bending the knee. The structure of the hip may prevent the dancer from doing this maneuver while maintaining a complete turnout, that is, while keeping the feet pointed away from each other at 180° . The good teacher knows and teaches the ideal positions and body configurations, but recognizes the distinction between the ideal and the possible. Teaching involves a balance between eliciting the best possible technique from dancers and recognizing human limits.

Physics and dance

However, analyzing the physics of dance can contribute still more fundamentally to the skill that a dancer uses in creating this art. Although dancers cannot see themselves totally in physical terms—as massive bodies moving through space under the influence of well-known forces and obeying physical laws—neither can they afford to ignore these aspects of movement. According to Allegra Fuller Snyder, former head of the UCLA dance department,

Dance is more than an art. It is one of the most powerful tools for fusing the split between the two functions of the brain—the fusing of the logical with the intuitive, the fusing of the analytical perceptions with the sensorial perceptions, the fusing of holistic understanding with step-by-step thinking. It is a discipline which within itself deals

with basic understanding of human experience and conceptualization.

How is the role of physics in dance best illustrated? Dance consists of both movement and line or position; it has both dynamic and static aspects. Most of the applications of physics have to do with the response of the body to the forces that lead to movement. To which aspect is the aesthetic quality attributable? The eye sees both movement and instantaneous position, but are they perceived simultaneously, or does the mind emphasize one or the other at a particular time? This question has always reminded me of Niels Bohr's principle of complementarity—that one can observe the wave-like properties (movement) of an entity clearly if one sacrifices observing at the same time the particle-like aspects (position). Perhaps motion and position are similarly complementary when they are seen by the eye and mind.

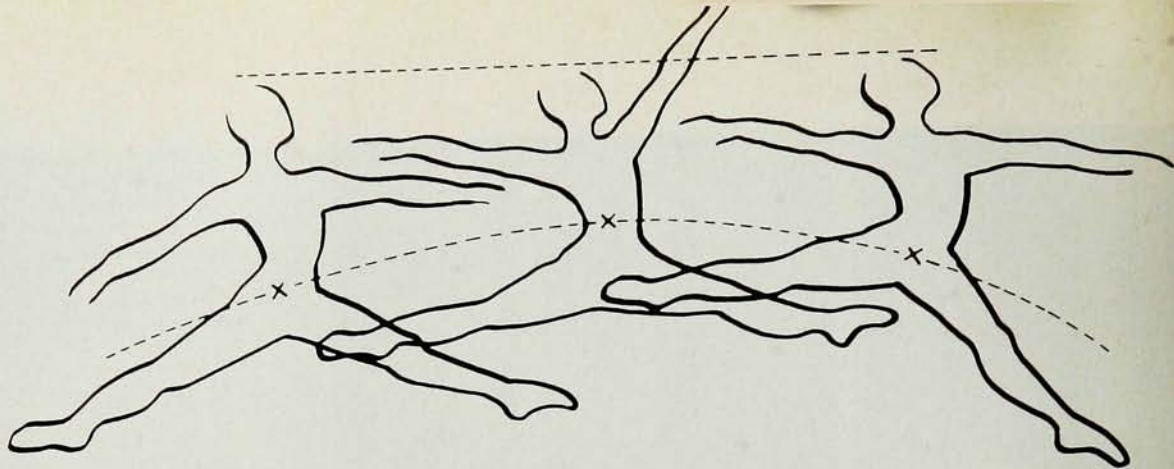
One of the challenges in dealing with the technical aspects of dance involves the use of appropriate vocabulary and terminology. How is a basis for communication established between such disparate fields as physics and dance? As physicists, we are aware that physics is built on precise definitions of pertinent terms. We intend these definitions to be as objective as possible so that they are universally usable, independent of the unique interpreta-

tions of individuals. Physicists may disagree on interpretations of observations, but we depend on an assumed agreement concerning the definitions of the terms.

People dealing with dance use language to form images in terms of dancers' individual senses of body and movement. A dance teacher may use words that have objective definitions, but unless students can translate those words into images, the information transfer is abstract and not useful.

Individual students, because of their different ages and backgrounds, have different levels and kinds of understanding. Dance teachers, who often deal with young people lacking a sophisticated vocabulary, create images by building on common understandings of how it "feels" to perform certain movements or maintain certain body positions. In teaching a student to perform a *pirouette*, the instructor may say, "Feel as if your body is squeezed into a drinking straw." This image communicates the physical idea, "Maintain a compact alignment around a vertical axis to perform a controlled turn." Or, more physical yet, "Minimize your moment of inertia about a vertical axis to minimize the torque and angular momentum needed for a given rate of turn." The message is the same; the student's background determines the frame of reference.

A dancer usually depends on three methods to learn or improve a particular move-



Floating illusion. The dancer's center of mass follows a parabolic trajectory, but changes its position in the body as the dancer's legs or arms move. This allows the dancer's head briefly to move horizontally. (Diagram by Sandra Kopell.)

ment: trial-and-error adjustments in the basic motions, the example of an experienced dancer executing the motion correctly, and the instructions of a teacher or peer. The instructions are often based on an intuitive feeling as to what makes the movement "right." Although the validity of these traditional methods of learning has been well proven historically, improved techniques for teaching dance are now becoming available. A more analytical understanding of how a particular body position or change in body configuration contributes to the desired form can enhance these techniques for teaching dance.

We can extend the examples described above, involving placement for a *pirouette*. An instructor may tell a student to stretch vertically, pushing into the floor with the supporting foot while reaching for the ceiling with the head. The student finds that a strong and straight vertical body makes the *pirouettes* more successful, and that dancers with weak or flaccid backs have trouble with *pirouettes*. Physical analysis shows why these aspects of body placement contribute to successful *pirouettes*. If the body is properly "pulled up," the mass is compacted close to the axis of rotation, decreasing the moment of inertia and allowing for a substantial rate of turn. Such placement is thus not only desirable for aesthetic reasons, but also necessary to achieve a reasonable turn rate.

Although difficult physical feats are often accomplished by pure strength and agility, it is often true that the appearance of performing certain movements is illusory, and the dancer uses a deeper skill to create these illusions. The understanding that comes from a physical analysis of movement gives the dancer or teacher a basis for developing techniques that create or enhance the illusion of performing the impossible.

It is also true that an observer watching a dance performance can appreciate the movement more deeply by understanding both the limitations imposed by physical law and the role of illusion. Dance move-

ment often inspires awe in the observer, not only because of the beauty of the moving human form, but also because the dancer seems to defy the normal physical constraints that nature imposes on moving objects. An understanding of the appropriate physical principles allows the spectator to distinguish between possible and impossible movements, and to appreciate the subtle skill of a dancer who creates an illusion of performing the impossible.

The physical principles pertinent to an analysis of dance are, of course, Newton's laws of motion, which form the basis of any analysis of motions of massive, flexible objects. Conservation of linear and angular momentum, and the relationship between forces or torques and the resulting changes in the state of motion, form the basis of our analysis.

Dance movement can be broken down into categories characterized by the techniques required for analysis. Some movements involve primarily vertical or horizontal motions of the body as a whole, in which we can ignore rotations. We can study these motions using simple equations of linear motion in three dimensions. This analysis leads to a recognition and understanding of some interesting illusions and techniques, such as the appearance of floating horizontally in a *grand jeté*—a large jump in which the weight of the body is thrown from one foot to the other.

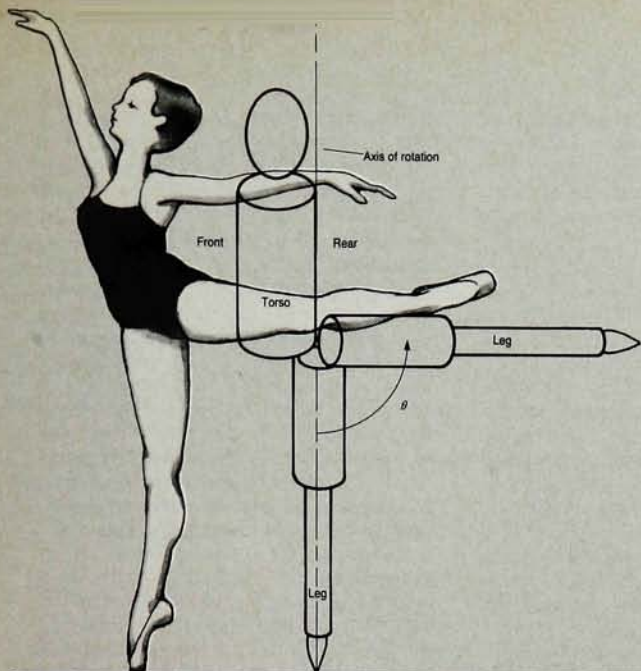
Rotational motions require different approaches, involving the way the body's mass is distributed, the different axes of rotation for different types of movement, and the sources of forces and torques that produce the rotational motion. The simplest rotational motions are *pirouettes*, but there are other movements that involve rotations. *Entrechats*, for example, involve rotational motion about horizontal axes through the hip. In this movement the dancer leaps straight into the air and crosses his or her feet a number of times, making a scissoring motion in the air. *Tours jetés*, in which the dancer jumps and turns, involve rotations about skewed axes.

Physical analyses can explain the effects of the size of dancers on the movements they can perform. Most choreographers and teachers recognize that small dancers have different ways of moving than taller ones, but what is the physical basis for the differences? How can teachers avoid expecting the impossible of tall dancers, and how can choreographers maximize the effectiveness of their use of different sizes of performers? Are there physical principles that make the slender, long-legged "Balanchine" dancers particularly appropriate for Balanchine choreography? Is there a way to choreograph specifically for the talented but "undersized" dancers who can outperform their taller counterparts in particular movements and tempos? Physical analyses can answer many of these questions.

Grand jeté 'floating' illusion

Dancers can create an interesting illusion by changing their body configuration during flight. One sometimes sees an impressive *grand jeté* in which a dancer seems to defy gravity by floating horizontally near the peak of a jump rather than following a parabolic trajectory. We know that once the body loses contact with the floor the center of gravity follows a trajectory that is totally determined by the conditions of motion at the beginning of the trajectory. Although the dancer may change the shape and configuration of the body in flight—a maneuver that can produce certain illusions—the dancer can do nothing to change the trajectory of the center of gravity. The trajectory will reflect a constant horizontal velocity and the vertical motion associated with a jump—a rising motion with decreasing speed, a moment with no vertical motion, followed by an accelerating downward motion.

It is true that a jump made during horizontal motion can be higher than a simple vertical jump because the dancer can transfer some of the horizontal momentum to vertical momentum. An ex-



Anatomical data for a dancer

Body segment	Men		Women	
	Weight (percent)	Length (percent)	Weight (percent)	Length (percent)
Trunk	48.3	30.0	50.8	30.0
Head	7.1		9.4	
Thigh	10.5	23.2	8.3	24.7
Shank	4.5	24.7	5.5	25.6
Foot	1.5		1.2	
Upper arm	3.3	17.2	2.7	19.3
Forearm	1.9	15.7	1.6	16.6
Hand	0.6		0.5	

Weights and lengths are given as percentages of total body weights and heights, respectively. The data are averages for six female college-aged gymnasts and 35 college-aged men. (From Stanley Plagenhoef, reference 4.)

Arabesque turn analysis

To analyze the *arabesque* turn and the problem of the oscillating leg, we assume that the body consists of three main parts, as shown in the diagram above. We will ignore the contribution of the arms to the moment of inertia, because they are so light; and we will ignore the contribution of the supporting leg, because its mass is concentrated so close to the axis of rotation, which we assume lies in a vertical line along the edge of the cylindrical torso and head. Assume the dancer is a female of height 5 ft 3 in (1.60 m), weight 97 lb (44 kg), with a torso of effective radius 12 cm. Other body-segment lengths come from the table above.

The total moment of inertia of a cylinder rotating about an axis along an edge is

$$I_0 = \frac{3}{2}Mr^2 = 0.66 \text{ kg m}^2$$

The moment of inertia of the gesture leg making an angle θ with the vertical is

$$I_1 = I_0 \sin^2 \theta$$

The moment of inertia I_0 of a horizontal leg is 1.44 kg m².

We can treat the effect of the centrifugal force on the leg as a torque around a horizontal axis through the hip, tending to increase the angle θ . This torque is proportional to the square of the angular velocity ω , and is given numerically (after an integration over the length of the leg and with the assumed masses and lengths) as

$$T_1 = (1.44 \text{ kg m}^2)\omega^2 \sin \theta \cos \theta$$

The torque tending to decrease the angle θ (to lower the leg) is due to gravity acting on the center of gravity of the leg, and is given by

$$T_2 = (25.5 \text{ kg m}^2/\text{s}^2) \sin \theta$$

Thus the total torque on the leg tending to increase its angle with the vertical is, in SI units,

$$T = 1.44 \omega^2 \sin \theta \cos \theta - 25.5 \sin \theta$$

We assume the angular momentum of the rotating body is constant; that is, we neglect accelerating or retarding torques

between the supporting foot and the floor. What is this angular momentum? Let us choose a rotation rate of 0.8 revolutions per second, with the leg at the equilibrium angle for that rotation rate, such that the dancer is exerting no torque in the hip to support the leg. (This is artificial: Most dancers will exert a torque to help support the leg. We will take that torque into account later as a perturbing factor in the simpler analysis.)

One can find the equilibrium angle by setting the total torque in the above equation to zero and finding the angle θ that corresponds to the assumed value of the angular velocity ω . The result is

$$\theta_0 = 45^\circ$$

With that angle, the total moment of inertia can be found from the first equation, and the angular momentum is

$$L = 6.95 \text{ kg m}^2/\text{s}$$

If this angular momentum is a constant, even when the angle θ and the rotation rate change, we can eliminate ω from the equation for total torque. The angular velocity is given by

$$\begin{aligned} \omega &= L/I = 6.95/(I_0 + I_0 \sin^2 \theta) \\ &= 4.84/(0.46 + \sin^2 \theta) \end{aligned}$$

Now we can construct an expression for the torque, tending to change the leg angle θ in terms of just one variable, θ . Because the torque is the product of the moment of inertia of the leg around the horizontal hip axis and the angular acceleration α of the leg around that axis, we have a final expression,

$$\begin{aligned} 1.44 \alpha &= 1.44 \left(\frac{4.84}{0.46 + \sin^2 \theta} \right)^2 \\ &\times \sin \theta \cos \theta - 25.5 \sin \theta \end{aligned}$$

This is a nontrivial differential equation, which can be solved by assuming that the angle θ is close to θ_0 . The numerical solution for $\theta(t)$ shows a frequency of oscillation of about 1.1 cycles per second. This frequency is close enough to the turn rate of 0.8 revolutions per second that, with

the significant uncertainties in the analysis, the two may be equal, giving rise to a "resonance" in which the leg undergoes one up-down-up oscillation while the body makes one complete turn. There is probably a mental reinforcement for an oscillation that involves a slowing of the body's rotation each time the dancer is facing the original direction. This reinforcement would be particularly strong if the head is spotting to that direction once each revolution also.

Now let us reconsider the cavalier assumption about the lack of torque from the hip. Suppose the hip exerts a constant lifting torque such that the equilibrium angle of the leg increases to 75° from the vertical. The torque necessary to accomplish that more nearly horizontal *arabesque* position can be calculated, and has a numerical value of

$$T_H = 15.6 \text{ N m}$$

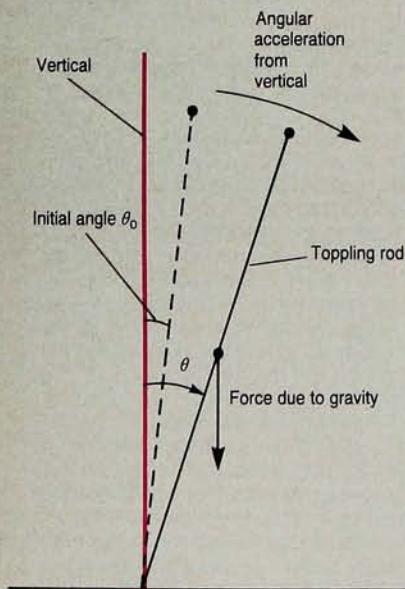
The total constant angular momentum is greater in this case, because the leg is extended farther from the axis of rotation. The relationship between the angular acceleration of the leg around the hip joint and the angle θ must take into account the additional hip torque. A solution of the revised equation gives an oscillation frequency of 0.9 cycles per second, a bit slower than for oscillations around the lower angle of 45°. In fact, this oscillation frequency is even closer to the frequency of rotation, implying an even closer coupling between the rotation and the oscillating leg.

Again the result is important in that the natural tendency to slow the turn, or pause, after each revolution is enhanced by the "drooping leg syndrome" in which first the leg is high and the rotation slow; then the leg descends, speeding the turn; and then the leg rises again after about one revolution to slow the turn when the body again is facing the original direction. The fact that the movement is performed without the culprit leg in sight of the dancer makes it difficult to correct this fault, which has such a negative effect on the aesthetic line of the *arabesque* position during the turn.

Losing and regaining balance

To analyze balance, imagine the body to be a stick that is somewhat heavier at the upper end than the lower. This stick can balance vertically on the floor. If it is displaced from the vertical by a small angle θ_0 , it will start toppling, and the angle θ will increase at an accelerating rate as indicated in the figure below.

The force of gravity acts on the center of



gravity, and thus exerts a torque around the point of support whenever the stick is displaced from the vertical. The equation relating the angular acceleration away from the vertical and the torque due to gravity is

$$mgR_c \sin \theta = I\alpha = mR_g^2 \alpha$$

In this expression, m is the mass of the body, g is the acceleration due to gravity, R_c is the distance from the point of support to the center of gravity, I is the moment of inertia of the body toppling around an axis through the point of support, R_g is the radius of gyration [defined as $\sqrt{I/m}$], and α is the toppling angular acceleration. If the angle is small, we may replace $\sin \theta$ by θ with very little error. The result is a simple differential equation whose solution, taking into account the initial condition, is a hyperbolic cosine function:

$$\theta = \theta_0 \cosh(\sqrt{gR_c/R_g^2} t)$$

For a uniform stick of length 5 ft 10 in (1.78 m), the center of mass would be at the midpoint, so $R_c = 0.89$ m; R_g would be 1.03 m. Assuming the body is more massive at the upper end, let us increase each of these quantities arbitrarily by 15%. Thus $R_c = 1.02$ m and $R_g = 1.18$ m. The coefficient of the time t in the above equation is then

$$\sqrt{gR_c/R_g^2} = 2.7/\text{sec}$$

Note that this coefficient is greater for a small person, so that the acceleration away from vertical is, as one would expect, more rapid than for a larger person.

The table below shows the angle of displacement from the vertical as it varies with time for a few initial angles of displacement for a 5 ft 10 in dancer and for a dancer 15% shorter (just under 5 ft).

Regaining balance. Can a dancer do something to correct an unbalanced condition? One might think not, for the only source of horizontal force is at the supporting point itself. However, one sees dancers squirm and wiggle in attempts to regain balance. One can, in fact, move one's body so as to exert a horizontal force against the floor and regain balance under the influence of the reaction force from the floor.

Although dancers may intuitively realize that it is possible to regain balance while supported on one foot, they may fail to recognize that it is not the manipulations of the body directly that restore balance, but

the horizontal force exerted on the floor that accomplishes the shift in position of the center of gravity. That is, movements of the body that maximize the horizontal force of the supporting foot against the floor will be most effective in restoring (or destroying) balance.

What types of body manipulations are effective in restoring balance? If you have ever walked along a rail of a railroad track, you have observed a very important instinct at work. If you start falling to your right, your upper body will suddenly bend toward the right, as indicated in the figure at the left. Some have claimed that this reaction is counterproductive, and have admonished dancers to overcome the instinct and merely move back toward balance (to the left in this example). However, recall that what one needs is a means of exerting a horizontal force on the rail directed toward the right, so that the rail will exert a force to the left that will translate into a force to the left on the center of gravity, moving it back toward balance.

The upper body suddenly moving to the right causes the feet to exert a force to the right on the rail or floor. This is particularly clear in the extreme case of a "jack-knifing" motion to the right. If that movement were performed on ice, the feet would slip to the right. The rail exerts a friction force to the left preventing that slipping, thereby pushing the body back to the left. So our instincts are indeed correct.

A dancer, of course, must make these movements very small and subtle to avoid destroying the illusion of motionless balance, and to avoid sudden jerking of the body that could be injurious. To be able to correct by very subtle movements, the body must be acutely sensitive to very small departures from balance. Clearly a rigid upper body will prevent the sensing of small changes in position and make it difficult to apply small correcting manipulations. On the other hand, an unrigid supporting leg, hip and lower body will prevent those subtle manipulations from being effective in balancing on a strong support. Hence, part of the accepted technique for maintaining balance involves keeping the lower body rigid while keeping the upper body relaxed and sensitive to small departures from balance, without losing the quality of line. This technique is not only aesthetically and conventionally "correct," but also it makes sense in terms of the physical principles of balance.

Toppling from rest

Height	Time (seconds)	Initial displacement angle			
		0.5°	1°	2°	4°
5 ft 10 in	1/2	1.0°	2.1°	4.1°	8.2°
	1	3.7°	7.5°	15°	30°
	1 1/2	14°	29°	57°	> 60°
	2	55°	> 60°	> 60°	> 60°
5 ft	1/2	1.0°	2.3°	4.5°	9.0°
	1	4.6°	9.1°	18°	36°
	1 1/2	20°	39°	> 60°	> 60°
	2	> 60°	> 60°	> 60°	> 60°

Entries show the increased angle of displacement from the vertical for tall and short persons toppling from various initial angles of displacement.

treme case of this transfer is a pole vaulter who uses the flexible fiberglass pole to maximize the transfer of horizontal momentum to vertical.

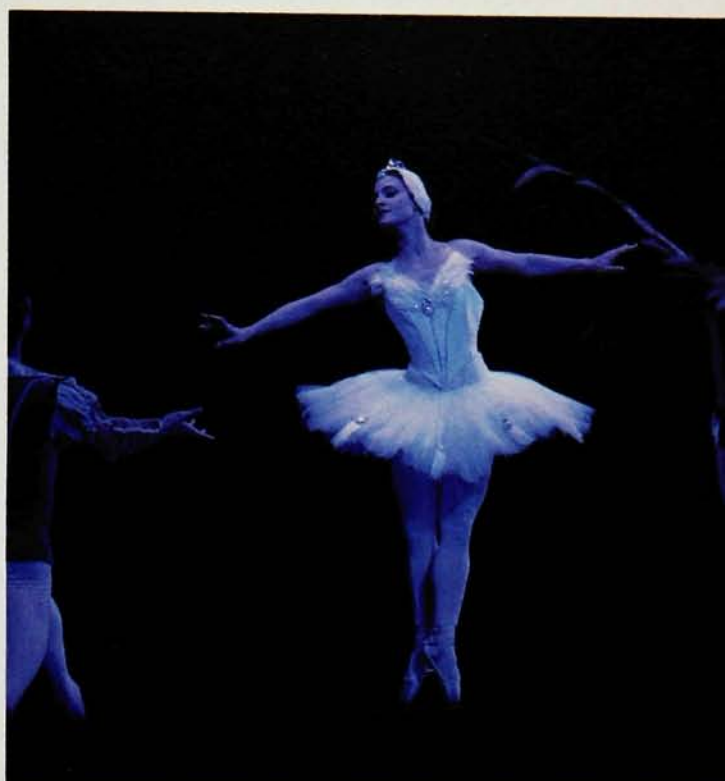
The illusion seen in the *grand jeté* is partly due to the simple fact that the vertical motion of the body is rapid at the beginning and end of the jump, but slow near the peak as the vertical speed slows to zero and reverses for descent. In fact, half of the total time the body is in the air is spent at more than three-quarters of the height of the peak. For example, if the center of gravity rises two feet during the *grand jeté*, the total time in the air is about 0.7 second, half of which, or 0.35 second, is spent within six inches of the peak. The dancer can manipulate the body in such a way that the appearance of floating is even stronger.

Although the dancer's center of gravity follows a curved trajectory determined by the conditions of the initial jump from the floor, the dancer can move the position of the center of gravity relative to the body. Suppose, as in the figure above, the center of gravity when the dancer first leaps is in the abdominal area, when the legs and arms are rather low. If when the center of gravity has risen part way through its parabolic trajectory the arms and legs are raised, the center of gravity will move up in the body, perhaps to the stomach or above. If the timing is right, the dancer's torso and head will actually move horizontally while the center of gravity moves near the peak of its curved trajectory. Because the eye of the observer is likely to follow the performer's head and torso, the dancer creates the illusion of floating horizontally for a few brief moments! A necessary component of body motion to accomplish this illusion, then, is the raising of the legs, ideally to a "split," at the peak of the leap. The dancer must time the split to coincide with the peak of the curved path of the body's center of gravity to produce the smoothest appearance of horizontal motion. Such a split is often part of an impressive *grand jeté* (see the photographs on pages 24–25), but it is now seen not only as an added flair unrelated to the jump itself, but as a component of the motion contributing directly to this illusion of "floating."

Arabesque turn

An *arabesque* turn in classical ballet is a beautiful movement when performed well. In this movement, the dancer turns while standing on one leg, with the other leg fully extended to the rear. There is a common error that one can observe in students learning the movement, and there is an interesting physical reason behind the prevalence of this error.

The *arabesque* turn is usually an "*en dedans*" turn, rotating toward the supporting leg. It requires the dancer to exert torque with both feet on the floor, and then to lift the push-off leg into a horizontal position to the rear, where it is not visible



Balance. Dancers make subtle movements to maintain balance; these are analyzed on page 28. This photo is from last fall's performance of *Swan Lake* by the Pittsburgh Ballet Theatre.

to the dancer. After the leg reaches the horizontal position, there is a strong tendency for it to drop lower, as in a *grand battement derrière*, or kicking movement to the rear. When the leg is fully extended horizontally, it represents a large contribution to the total moment of inertia of the body, which makes the angular velocity small for the magnitude of angular momentum that resulted from the initial torque. When the leg drops, it moves closer to the axis of rotation, decreasing the moment of inertia. This reduced moment of inertia increases the angular velocity, making the turn seem easier, faster and more satisfying. Because the drooping leg is behind the body, the dancer does not see it easily, except in a mirror.

An interesting phenomenon now occurs. Because the angular velocity has increased, there is an increased centrifugal force away from the axis of rotation tending to throw the leg out toward the horizontal again! (It is reasonable to deal with "centrifugal force" here because the dancer is dealing with perceived forces in the rotating frame of reference.) So a dancer may experience an oscillation of the leg up to the horizontal, down, then up again, possibly repeated for a multiple *arabesque* turn. In fact, one can observe such an oscillation in students who do not concentrate on keeping the leg fixed in the *arabesque* position through proprioceptive senses—the internal senses that the mind uses to determine body positions without visual cues. One may ask if this oscillating-leg syndrome is indeed bad; perhaps the

choreographer intends such a movement! But the traditional *arabesque* turn in ballet, which is a common and impressive movement, is done ideally with the gesture leg fixed in a horizontal position.

At what frequency might the gesture leg oscillate up and down? The problem is not a simple one, because the centrifugal effect tending to throw the leg out depends on the angular velocity of the turning body; that angular velocity, however, depends on the angle the gesture leg makes with the vertical.

An analysis of the problem is presented on page 27. The analysis involves a number of assumptions, beginning with the leg modeled as a cylinder of one thickness for the thigh and a smaller thickness for the lower leg. The entire leg is free to oscillate in a vertical plane from the hip, with the pivot lying on a vertical line above the point of support (the foot of the vertical supporting leg). As shown in the box, the moment of inertia of the gesture leg is a function of the angle the leg makes with the vertical. This moment of inertia determines the instantaneous angular velocity, which in turn determines the centrifugal force, and this, in combination with the effect of gravity on the gesture leg, helps determine the angle the gesture leg makes with the vertical. To make the resulting equations solvable, I assume that the total angular momentum is such that the leg's equilibrium angle is 45° , and that the oscillations around that angle are small. For a leg of typical length, the result is an equation that relates the oscillation fre-

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quency of the leg to the rotation frequency.

For a body size and weight typical of dancers, and an angular velocity typical of an *arabesque* turn, the calculation gives an interesting result. The leg's oscillation frequency is equal to the rotation frequency when the dancer takes about two seconds to complete a full turn. This resonance between the two frequencies may make it particularly difficult to overcome the oscillating-leg problem, because the natural frequency of that oscillation makes the leg "bounce" just once each revolution. The good *arabesque* position would occur when the body is facing one direction, then occur again when the body returns to that orientation. In between, the leg is lower and the dancer rotates more rapidly.

Future contributions

Physics has been around for centuries, and dance for as long as human beings have tried to interpret their experience through movement. Because physics deals with the properties and causes of movement, why have the two areas not contributed to each other more fruitfully? For what reasons might we see a change in this situation on the horizon?

The application of biomechanics to sports is a lively and accepted field. Why has dance not progressed in a parallel way? One answer lies in the fact that quality of performance in sports is quantifiable, while in dance the judgment of quality depends on aesthetic interpretation. What we are now finding, however, is that a lack of understanding of applicable physical principles imposes constraints and limitations on dancers in much the same way that it limits athletes. A dancer who can use such understanding to attain extra height from a jump, a sharper turn in a *tour jeté*, or a smoother landing from a *tour en l'air* has more tools to work with, and more flexibility with which to achieve aesthetic goals.

As the scientific study of dance expands, it can take different directions. Increasing numbers of researchers are studying particular movements in detail, using modern technical tools such as high-speed cinematography and computer analysis. This is certainly a useful direction, and such studies will form a foundation on which teachers, dancers and other researchers can build a better understanding of dance, both for the sake of pure understanding and for the improvement of dance technique. These studies, however, must be complemented by physical analysis, which gives an overview of movement in dance. Such an overview should include qualitative analyses of many different movements, with the emphasis on understanding which basic physical principles apply, how the body takes advantage of these physical laws and what connections exist between different movements in dance and in other types of human body movement. We must not lose the "forest" of a broad physical context as we investigate the

"trees" of individual movements.

The time is ripe for expanding our involvement with dance analysis. Dancers, particularly ballet dancers, have traditionally begun their training at too young an age to grasp abstract physical principles and apply them to human body movement. By the time they have developed their analytical capacities, dancers have come to think of their work as an activity learned and motivated more by instinct, feeling and the copying of models than by questioning and analysis. However, children are now growing up in a world that more readily accepts analytical approaches to a variety of human endeavors, from economics to politics, from literature to music. People are rapidly discovering the immense potential of computers and other technical tools for contributing to our knowledge in a wide variety of fields. Children are increasingly exposed to analytical ways of thinking. Some will reject these approaches as being, at best, a necessary evil for "others" to cope with, and some will accept and use these approaches comfortably. In this increasing dichotomy, will many dancers see the benefit of an analytical approach to creative and aesthetic arts?

Dance teachers will increasingly find that an analytical understanding can complement existing techniques rather than replace them. Some students will respond well to this approach, and some will not. But teachers will have additional tools at their disposal with which to help students learn dance.

The danger that dance will become too analytical, and that the emphasis will shift toward athletic accomplishment rather than aesthetic quality, has been with us as long as there have been observers of dance who are not sensitive to its artistic dimensions. But the traditions of dance have always been strong enough to withstand this danger. There are also those who are uncomfortable with the new approaches

and are threatened by them. Perhaps these people will become convinced as they see examples where the scientific approach is useful and not damaging. It is the responsibility of the scientists involved in this work to bring their ideas constantly to earth, and to maintain the connection of these ideas to the world of real flesh-and-blood dancers.

Where can people go who are interested in learning more about physical analyses of dance movement? Much of the literature in this area now is oriented toward a pure understanding, rather than toward applications to improvement of technique. As more people become involved, particularly those who have experience in the teaching of dance, these analyses will be brought into the traditions of dance instruction. An increasing number of workshops, conferences and publications will be dealing with these analyses. The *Kinesiology for Dance* newsletter, for example, is an informal publication with an expanding coverage and circulation. (Readers may contact the author for information about this publication.)

We can look forward with great anticipation to the progress in the art of dance that can result from a marrying of the technical and the aesthetic, the rational and the emotional—the mind and the body.

References

1. D. Webster, *Philadelphia Inquirer*, 4 April 1978.
2. S. K. Langer in *Problems of Art*, Scribners, New York (1957), p. 5.
3. *Dancemagazine*, September 1978.
4. S. Plagenhoef, *Patterns of Human Motion*, Prentice-Hall, Englewood Cliffs, N.J. (1971), Chap. 3; S. Plagenhoef, after W. T. Dempster, WADC Tech. Report 55, 159 (1955); S. Plagenhoef, after K. Kjeldsen, *Body Segment Weights of College Women*, Master's thesis, University of Massachusetts (1969). □



Arabesque en pointe. In this set pose, the dancer stands on one leg, with the other leg fully extended to the rear. (Pittsburgh Ballet Theatre photograph.)