Storing of Momentum in Ballet Movements

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Suppose you are preparing for a day-long trip by car, and you want to be prepared for anticipated needs, such as thirst. You would probably take with you a bottle containing enough water to satisfy your thirst through the day. You would want a secure container to avoid spillage.

What, you ask, does that have to do with science principles applied to dance movement?

Well, replace "water" with "momentum" and you have a very viable analogy. There are instances in which you generate rotational momentum but, rather than using it at the moment it is generated, you want to store it for use at a later time. Consider, for example, a partnered "whip turn," in which the turning momentum is generated by forces from the partner on the ballerina's waist, with the ballerina starting in pirouette position rather than a preparatory position with both feet on the floor. When the partner exerts forces on the ballerina's waist, say the right hand pulling back and the left hand pushing forward, rotational momentum is generated, producing a rotation clockwise when viewed from above.

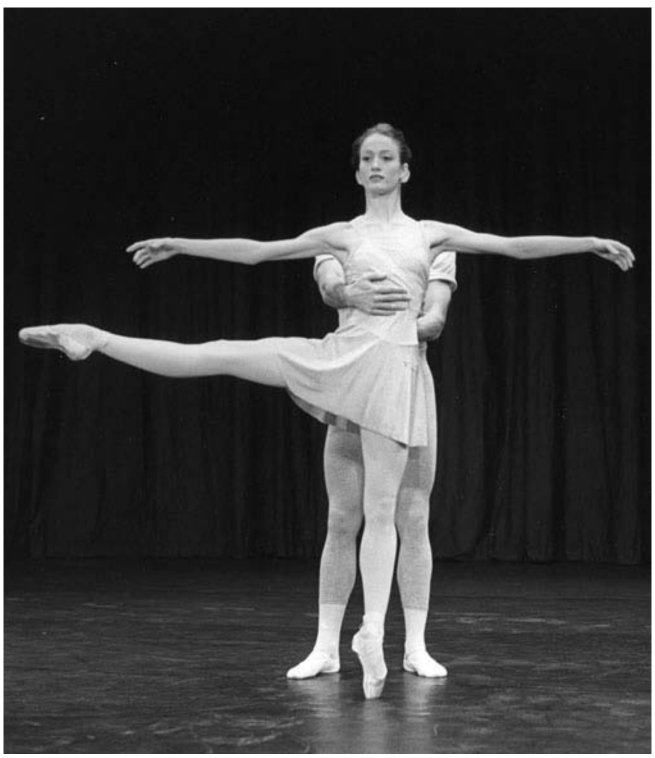
Now, if the ballerina remains as a rigid body in pirouette position, the forces from the partner will produce a rotation, but the magnitude of rotational momentum will not be very great, as the partner's hands cannot continue pulling and pushing after the ballerina has rotated away from her initial position. Thus, the total rotational momentum generated is limited.

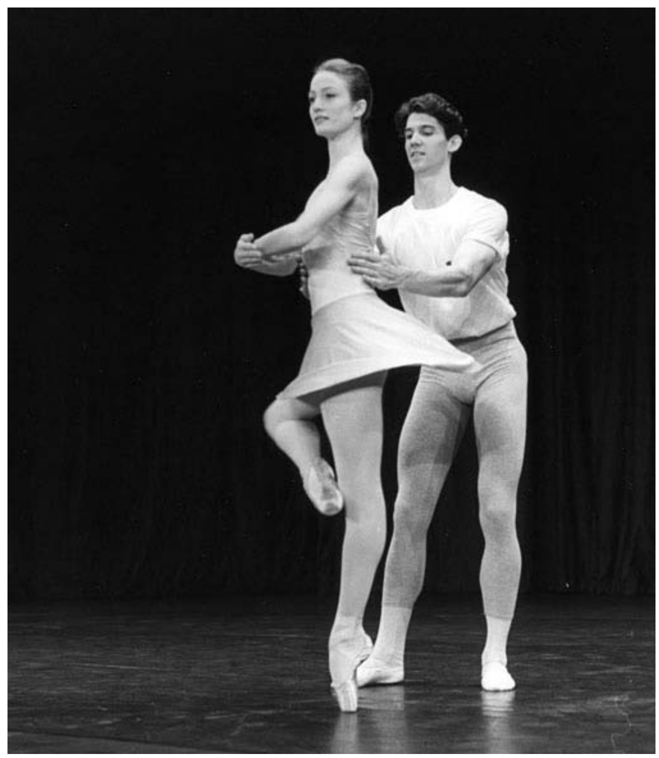
But suppose the ballerina starts with the gesture (right) leg horizontal and oriented about 45 degrees to the left of front, and then rotates the horizontal leg around to face right while the forces are being exerted on her waist. Then the rotational momentum generated by those partner forces is stored in that rotating leg rather than in the body as a whole. Note that the momentum, like the water stored in the bottle, is stored in the leg for use at a later time. In the dancer's case, the momentum was stored for use gradually, as the friction of the supporting foot on the floor would otherwise gradually destroy the momentum.

Because the leg carries significant mass, and much of that mass is carried far from the vertical axis of rotation when rotating, it can carry a significant magnitude of rotational momentum. When the rotating leg reaches an orientation directed toward the dancer's right, still in the horizontal plane, it transfers its accumulated rotational momentum to the body as a whole, producing a very effective rapid turn rate for a pirouette, possibly eight or ten revolutions in magnitude!

Another movement that employs the same physical principles is the fouetté turn sequence. That, like the partnered "whip turn" previously analyzed, uses the gesture leg as a rotating mass storing rotational momentum. In this case, however, the turning movement is continuous, with the body gradually losing momentum through friction between the supporting foot and the floor. Once each revolution, however, the supporting foot is twisted against the floor in a direction that allows the twisting force from the floor acting on the foot to contribute an amount of rotational momentum that just replenishes that lost to friction during the preceding turn. The turning movement is continuous, but varies with time, from a maximum following the twist from the floor on the supporting foot to a minimum when some of the momentum has been lost to friction. A proficient dancer can keep doing these turns to a total of perhaps 32 revolutions, as in a popular version of the "Black Swan" solo from "Swan Lake." And, once again, it is made possible by the storing of rotational momentum in one leg, in this case being transferred back and forth between that leg and the body as a whole.

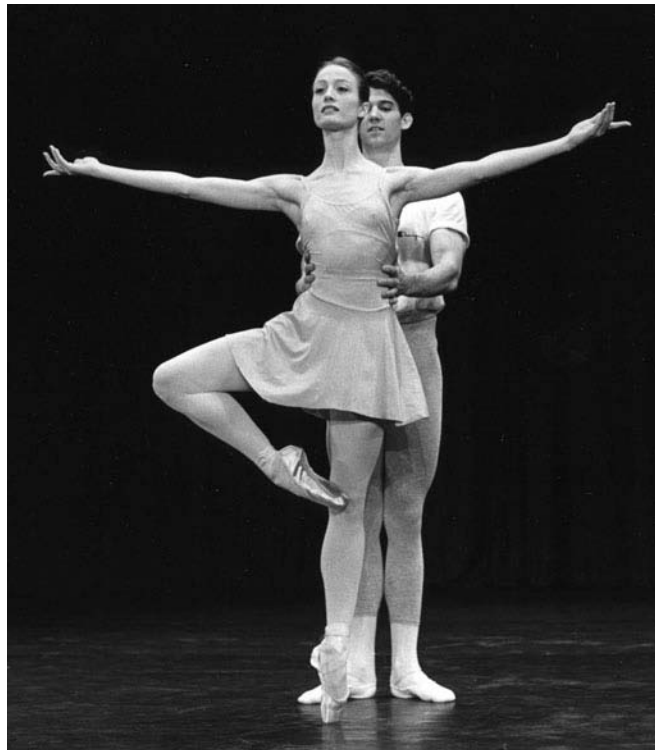
Be careful, however! There is another form of fouetté turn that employs an entirely different physical principle to accomplish an apparently quite similar result. If during the sequence of turns comprising the fouetté turns the gesture leg is not brought to the horizontal position facing to the left of straight forward so that it can rotate from left-front to right, storing momentum as it carries out that rotation, but instead merely extends to the right from the *pirouette* position to "second position," then the rate of turn will





slow down because the moment of inertia has increased because the leg is extended. That slowing of the turn rate allows the supporting foot enough time to come off pointe, exerting the twist against the floor that creates the additional momentum to replace that lost to friction, thereby keeping the rate of turn high.

Thus, fouetté turns can be performed either by storing momentum in the gesture leg while the supporting foot does its job of twisting against the floor to generate the added momentum needed to keep the turn going, *or* the gesture leg is merely extended to the side, thereby increasing the moment of inertia of the body, resulting in a slower rate of turn which allows the supporting foot to twist against the floor, generating the additional momentum to keep the body from slowing with time. The final result in both cases is to allow the dancer to maintain the rate of turn to



stay with the music and keep the energy in the movement.

Now let's go back to a normal pirouette, in which the preparation position has one foot well behind the other, so that when the two planted feet push in opposite directions they produce a rotational torque that causes the turning movement to start. What role does the upper body play in this process?

Note that, for a turn to the right, instinct leads us to rotate the right arm toward the front and around to the right side as the turn is initiated. Does that movement of the arm, sometimes called a "windup," contribute positively to the effectiveness of the turn, or does it merely compromise the aesthetic quality of the pirouette? Apparently the arm does indeed make a useful contribution, in that it stores some rotational momentum such that when it stops rotating relative to the body it contributes its momentum to the body as a whole. The magnitude of contributed momentum, however, will be significantly smaller than that stored in the leg, as the arm's length and mass are smaller than those of the leg.

Suppose you are now asked to jump vertically from rest to as great a height as you can achieve. What technique do you use? First of all, you would not try to jump from straight knees, or without flexing the ankles. You would probably crouch as you prepare for the jump, and, significantly, you might prepare to thrust your arms from a low position to a level high above your head.

What might be accomplished by thrusting the arms overhead while accelerating your mass vertically upward? As you exert as great a downward force of your feet against the floor as possible, the floor is exerting an equal upward vertical force against your feet. If that is the only vertical force acting on your body besides gravity, it will determine the magnitude of vertical acceleration of the center of mass upward. But the location of the center of mass in the body will be rising as you bring your arms from a low position to above your head. In fact, those arms are accelerating upward, gaining vertical momentum as they accelerate. When the arms reach their maximum height relative to the rest of the body, their velocity relative to the body will quickly return to zero, and the arms will remain in a constant location above the head. But in the process of slowing down their relative speed, they will transfer their vertical momentum to the rest of the body. Momentum that has been stored in the arms while they were accelerating upward relative to the rest of the body is returned to the body as a whole when that relative acceleration ends. Thus, once again, momentum stored somewhere in a part of the body is brought out and used later to supplement what was in the body before that transfer.

In all of these cases of momentum storage, if the "container" is "leaky," there is a loss of effectiveness in the process, and the movement itself might be compromised. The timing of the movement is important, as seen in the whip turns analyzed here. If the leg rotates from left/front of the body around to the right side before the partner's forces have done their job, the contribution of that leg rotation to the total rotational momentum will be out of phase, and the total momentum will be less than it would be had the movements occurred with a more synchronized timing.[1] The importance of synchronization can also be seen in the "wind-up" with the leading arm as a normal en dehors pirouette is initiated.

In the movements analyzed here it has been shown that, if the timing is carefully controlled, momentum can be generated that adds to the momentum resulting from the basic movement itself, resulting in a more effective performance.

[1.] This insight is credited to Kelly Fahnestock, a ballet teacher from Pennsylvania.

Glossary

Acceleration. Rate of change of velocity.

Axis of rotation. The line around which a body rotates.

Force. The magnitude and direction of "push" or "pull." The total of the forces acting on a body determines its rate of change of momentum.

Mass. The inertial resistance to a change in linear motion. A large mass will accelerate less in response to a particular force than a small mass.

Momentum. A quantity of motion, quantitatively equal to the product of the mass and the velocity of a system.

Rotational momentum. A quantity of rotational motion; the product of the rotational inertia and the rotational velocity.

Torque. "Turning force." The magnitude of torque determines the rate of change of rotational momentum. The magnitude of torque for two forces acting in opposite directions and separated by a distance D is just F times D.

Velocity. Rate of change of position, with magnitude and direction both specified.

This paper is based on material found in *Physics and the Art of Dance by Kenneth Laws* and Momentum transfer in dance movement – vertical jumps: a research update by Kenneth Laws and Caren Petrie. The specific references can be found in the suggested reading list.

Suggested Reading List

Laws K. *Physics and the Art of Dance* (2nd ed). New York: Oxford University Press, 2008.

Laws K, Petrie C. Momentum transfer in dance movement – vertical jumps: a research update. Med Probl Perf Art. 1999 Sept;14(3):138-40.