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Dancing with physics

Teaching physics by way of the forces on the human body experienced during dance can be an effective way to bring Newton's laws to life, describe **Richard Barber** and **David Popalisky**

Tristram Kenton

One of the biggest challenges when teaching physics is to bridge the perceived chasm between the abstract "scientific" world and the "real" world of experience. Newton's first law of motion, for example, states that an object remains in motion in a straight line unless acted on by an external force. However, our experience tells us that most objects keep moving only as long as something pushes them. The key to mastering physics lies in the ability to abstract the "law" from a reality that includes friction and other effects.

There are many ways in which this can be achieved. In a lecture we might drop a coin and a feather to show that both accelerate at the same rate. However, this demonstration will only be successful if we use an evacuated chamber, since the real world tells us that the feather falls much more slowly. Laboratory sessions are another option, whereby students carry out experiments designed to reinforce what they have learned in class. But this approach relies critically on how much preparation the student has done, since in practice it is often possible to do the experiments without understanding the science behind them.

A novel approach, which we have recently developed into a college course for non-science undergraduates, is to teach physics through the art of dance. The key theme of the course is to personalize the physics of motion by making each student the *object*, and to give them both the scientific tools to measure and understand as well as the personal experience of forces and motion. The physics involved is simply the mechanics of a moving body under the influence of gravity; the goal is to understand the physical principles that govern the dancer's motion.

The body senses motion and the forces acting on it via our "kinesthetic sense", whereby information from accelerometers such as the semicircular canals in our ears and "proprioceptors" located in our muscle tissue allow us to correct our movement when we stumble so that we do not fall over. To ensure that our bodies behave consistently, this internal "black box" effectively processes the same physical laws that we might also analyse as physicists. By blending physics with dance, non-science students can therefore gain an insight into the scientific approach while honouring both the creative and analytical aspects of both disciplines.

Noble origins

The scientific understanding of dance can be traced to the royal court of France in the early 17th century, when people began to study the human body during expressive movement. In 1672 Louis XIV established the Académie Royale de Danse, where regular training and the systematic study of ballet challenged the range of human motion. Individual dancers with specific

The art of physics
In 2005 the Rambert Dance Company developed a performance called *Constant Speed* based on Einstein's groundbreaking work on relativity, Brownian motion and the photoelectric effect. But dance can be an effective way to teach physics, too.

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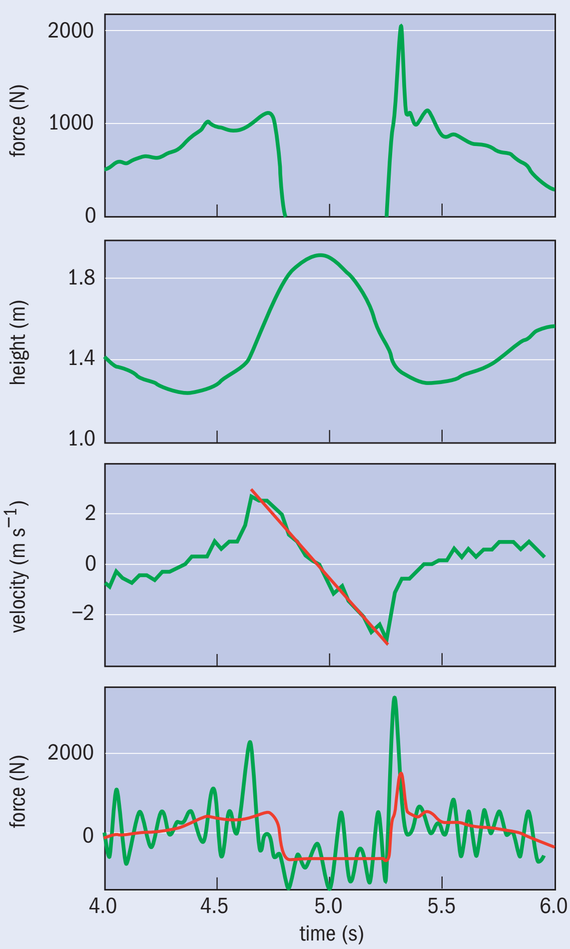
1 The laws of jumping



Vertical forces and kinematic data can be measured simultaneously during a simple vertical jump using force plates and a video recorder. While the student is in the air, the force plates register zero force, as expected (top), while the video data allow the vertical height to be calculated (second from top). From the slope of the displacement data, students can calculate the vertical velocity (third from top), and a linear fit during the free-fall portion of the jump then gives an estimate for the acceleration due to gravity of $-10.1\ \mathrm{m\ s^{-2}}$ (red). Finally, the net force (red) on the student can be calculated by subtracting their weight from the vertical-force measurement, which can then be compared with the result of multiplying the slope of the velocity graph by their mass (green). Although the "noise" in the slope calculations is large, the fact that the two curves are similar provides a direct visualization of Newton's second law.

natural skills, such as jumping or turning, continually raised the technical bar, thus forcing the teaching regimen to be revised.

For instance, an unnamed dancer – perhaps the late 18th-century August Vestris – mastered multiple pirouettes by continually tightening the circle of his arms (thereby reducing his rotational inertia) instead of maintaining the fully classical open circle of the arms in first position throughout the turn. Multiple pirouettes became more desirable than the previous clean maintenance of arm shape, and thereafter this "trick" became taught as official turning technique.

By the 20th century the study of human movement had begun to mature into a scientific discipline called kinesiology. A key figure was US dance educator Margaret H'Doubler, who in 1926 set up the world's first university dance course at the University of Wisconsin. She viewed a solid understanding of anatomy – and thus of the mechanical possibilities for human movement – as essential before students could actually explore expressive movement. H'Doubler understood that body mechanics needed to be first practised lying down, where the pull of gravity would not hinder efficient muscular action; her classroom experiments, in turn, informed the emerging science of kinesiology.

Physicists have tended to take a more fundamental approach to understanding dance than the anatomical and physiological starting point of kinesiology. In 1989, for instance, Ken Laws of Dickinson College in Pennsylvania explored why a dancer's motion does not follow a parabola during a large jump or leap. He reasoned that the dancer's head and torso do not execute a parabola because the centre of gravity of the body changes during the jump: the arms and legs – and thus the centre of gravity – are raised to their highest location at the midpoint of the leap, which makes the dancer appear to travel horizontally for a brief time. Despite obeying the fundamental laws of physics, this creates a wonderfully effective illusion for the audience.

Another example of a common illusion in dance occurs during an "assemblé". In this airborne movement, the trailing leg is brought forward into alignment with the leading leg (i.e. assembled) while the dancer is still in the air. But in doing so the trailing leg "robs" some forward momentum from the rest of the dancer, so the parabolic shape of the leap appears to be abruptly cut off as the dancer returns to the floor. Through a series of such investigations, culminating in his book *Physics and the Art of Dance*, Laws probed the beauty and illusion of the dance using the basic principles of mechanics.

As well as providing a framework for appreciating the motion of a dancer, physics can be used as a tool for improving dance. For example, a successful pirouette requires an external torque, which, due to friction, is just a reaction to the dancer's torque against the floor. One way for a dancer to increase the torque, and thus their rotational velocity, is to move their "pushing" leg further from the axis of rotation, but this shift also increases the body's moment of inertia and therefore slows the initial rotation. By optimizing these two competing variables, the number of rotations performed by a dancer can be increased.

Kinesthetic education

The idea for a "physics of dance" course at Santa Clara University was born in 2002, when one of the present authors (RB), a professor of physics, turned up at a weekly workshop called "dads don't dance" that was being run by the other author (DP), a professor of theatre and dance. We quickly realized the creative and analytical processes common to both physics and dance. A successful dance requires extensive preliminary organization as well as spontaneous decisions; likewise, a hypothesis worthy of analysis is often tested in a simple experiment first to see if the idea is robust enough to merit a more detailed experiment. Noting that the kinesthetic sense is the body's way of sensing motion, we realized that Newton's laws of motion could be explored using dance.

Over the summers of 2003 and 2004 we came up with a series of laboratory exercises based on dance movements that could be measured during class, therefore giving students a chance to analyse some real data. One was a simple vertical jump that videotape data easily showed to follow a parabolic height-versus-time relationship. Another experiment demonstrated how simple arm movements could be quantified in terms of the change in vertical forces, as measured by standing on a force plate. These plates act like very fast bathroom scales and can record the applied force 50 times per second.

The course at Santa Clara was finally rolled out in late 2004, and has been a huge success. Enrolment is roughly 20 students, the number being limited by the small dance studio to which we have access, but the demand for places is double this number. All students at the university are required to take one laboratory science class, and many such classes are designed specifically for those students not taking science degrees. Roughly one-third of the students have some formal dance experience, and about half the class are undertaking business degrees.

The course covers one topic per week and is taught in three sessions. The first is a lecture and discussion about the physics concepts, based partly on Laws' seminal book. The second is a laboratory session in the dance studio, where students are introduced to movements specific to the week's topic and use notebooks to record both their aesthetic experiences and quantitative data. The third session focuses on the techniques that the students need to analyse their results from the previous session.

Jumping high

One example of a week-long topic is a vertical jump, although before tackling the subject, students will have already been introduced to the kinematics of constant acceleration and the basics of vertical motion. For a simple vertical jump we need only consider two vertical forces: gravity pulling downwards and the floor pushing upwards, and this concept is derived during the first class of the week using Newton's second law. The following day, after a warm-up to make the jumps safer and more efficient, students use the laboratory session to perform and measure jumps with and without synchronized arm movements. In the third class of the week, students analyse their data using software provided with the force-plate equipment.

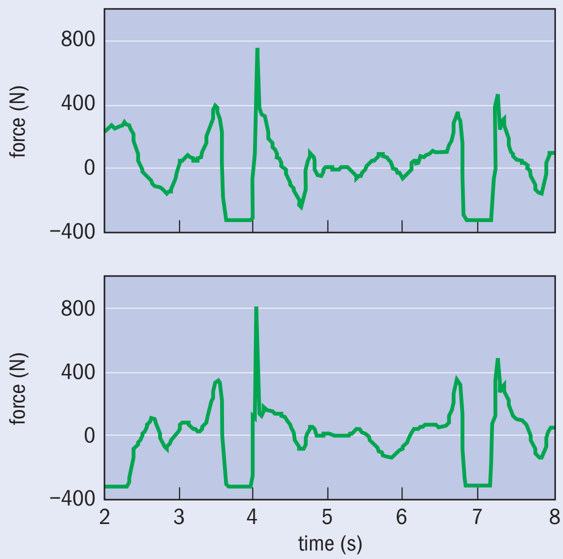
To make a safer and more stable target on which students can jump, the vertical-force data are usually recorded using one force plate under each foot so that the students just have to add two data columns together. However, they also convert positional data into velocities and accelerations with the goal of calculating the acceleration due to gravity (see figure 1). As the roughly linear slope in the centre (i.e. free-fall region) of the velocity graph shows, the experiment produces a reasonable value of $-10.1\ \mathrm{m\,s^{-2}}$.

Other topics that we cover in the course include balance, horizontal acceleration, rotation and partnering (which involves lifting and weight-sharing). Balance is a good first subject because students can shift their weight while standing on the force plates and then simply add the values from both plates together to calculate their weight. Rotation is studied using videotape shot from directly above the dancers while they execute pirouettes and other turns. The analyses of the rotation data are often rich in detail, for example revealing the effects of changing leg and arm positions on the rotation rate. The results provide an effective way of discussing moments of inertia and the conservation of angular momentum.

Each week the course attempts to build on the experiments and analysis of the previous week, concluding with a group project at the end of the course. The latter is a simple choreography, components of which are recorded, analysed and repeated to reflect both the creative and the experimental process. For example, students might do vertical jumps with and without arm motion and then compare the heights and forces that they measure. After performing their dance, each group gives a brief talk. The idea is to give the students enough experience with simple choreographic craft, devising experiments, recording data, analysing results and drawing conclusions that they can give a scientifically sound presentation.

In some cases, the final projects have given students research experience that is usually rare in an under-

2 Impulsive measurement



By measuring the force exerted on force plates placed under each foot, one student found that she used more impulse from her left foot (top) during take-off and more from her right foot (bottom) for landing during a vertical jump. The impulse is just the area under the force–time graph, and the data suggest that the student "tilts" while jumping. This analysis was the original idea of students Rose Hacking and Kristina Chiapella.

The kinesthetic experience enhances student understanding and gives the participants an accurate glimpse of the scientific process


Charles Barry

Asymmetric jump Measurements of the vertical force on the body can help improve performance.

graduate course. For example, while analysing some vertical-jump data during the course, two students noticed that the impulse – which is easy to calculate using the force-plate data – generated by the left foot and by the right foot was different (figure 2). Instead of simply adding the two data sets immediately, the students chose to focus on the difference for their final project. The asymmetries in the impulses for the take-offs and landings of each of their jumps suggest that one of the students was tilting during the jump, while the other is either right-footed or their right leg is longer than their left.

Such findings may be of interest to professional dancers when fine-tuning their technique. Indeed, we are currently planning a workshop to determine the jump asymmetries for dance students at Santa Clara University, with the aim of helping dancers improve the efficiency and safety of their jumps.

Engaging physics

Exploring the laws of motion through dance involves students directly and personally in the study of physics. We witness a high level of student engagement, not only during the lab work but also during the many hours that they spend on computers grappling with the analysis of their data. The kinesthetic experience enhances student understanding and gives the participants an accurate glimpse of the scientific process.

Only two other courses, to our knowledge, make a similar connection between physics and dance: one developed by physicist Pan Papacosta at Columbia College in Chicago; and another by Andrea Lommen, also a physicist, at Franklin and Marshall College in Pennsylvania. Indeed, physics teacher Megan Desroches at Albany High School in California intends to include some of the exercises from our course in her class. Our intent is to eventually publish the course material and laboratory outline of "physics of dance" to make it available to other educators at a variety of levels. With the number of students who study physics in decline in many countries, a course that engages students with physics so effectively seems too good to ignore. ■


Smart Holograms