quick study

Water-skipping stones and spheres

Tadd Truscott, Jesse Belden, and Randy Hurd

A highly deformable elastic sphere may bounce poorly on land, but it will skip spectacularly on water.

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Many of us have had fun sidearming a rock across a lake to see how many times we could get it to skip. There is something mysteriously satisfying—not to mention challenging—about coaxing the stone to hop repeatedly across the water surface. But can you imagine a 25-kg cannonball skipping more than 30 times across the water at 120 m/s? Though hard to believe, naval gunners as far back as the 18th century skipped cannonballs as a military tactic. Ricochet, in navy parlance, removed the launch angle as a variable and proved a reliable method for demasting enemy ships. Barnes Wallis recaptured the variable-reducing military advantage during World War II with his bouncing bomb. Designed to breach German dams, the weapon skipped over the water surface to avoid undersea torpedo nets.

Water skipping has returned to more docile roots of late, with toy balls such as the Waboba and WaterRipper that make it much easier to achieve multiple hops. Those spheres are made of an elastic material whose high compliance, or ability to readily deform, introduces some interesting changes to the skipping phenomenon. In this article we describe the physics underlying the water-skipping behavior of stones and spheres and highlight how elasticity and compliance facilitate skipping.

We have liftoff

When a cannonball, stone, or water-skipping toy with sufficient speed *U* hits a water surface at an angle, it forms a cavity that fills with ambient air, as shown in figure 1. In a successful skip, the object planes along the front of the cavity and is ultimately propelled off the surface by a pressure-driven hydrodynamic force.

For disk-shaped stones, the force **F** takes the form $\mathbf{F} = C_L \rho U^2 S \cdot \sin(\alpha + \beta)\,\hat{\mathbf{n}}$. Here C_L, the lift coefficient, is 0.5 for a disk, ρ is the density of water, and $\hat{\mathbf{n}}$ is the unit vector normal to the broad faces of the stone. As illustrated in figure 1, S is the wetted area and α and β are the instantaneous attack and course angles, respectively. When the stone spins faster than about 50 rotations per second around $\hat{\mathbf{n}}$, its angular motion gyroscopically maintains the attack angle. In that case, the maximum number of skips becomes sensitive to the attack and course angles. Figure 2a shows high-speed images of a skipping disk with an attack angle close to 20°, the value determined by past experiments to be optimal for skipping. Interestingly, a skipping stone retains much of its horizontal velocity until it is suddenly swallowed by the surface and plunges into the water.

Spheres are generally harder to skip than disks. In fact, previous research suggests an upper bound on the initial course angle of $18°/\sqrt{\gamma}$, where γ is the specific gravity of the sphere material. Thus for steel cannonballs, skipping can only occur for angles shallower than 7°. Highly deformable elastic skipping spheres, for which $\gamma \approx 1$, can skip at course angles of 50° or more, almost three times the predicted value of 18°.

What is the mechanism responsible for the dramatic increase in skipping performance? Figure 2b provides some insight: Within a few hundredths of a second, the highly compliant sphere deforms into a disk-like shape. Typically, the cross-sectional area of the deformed sphere is twice that of the undeformed sphere, which means that the amount of wetted area roughly doubles as well. Moreover, C_L is twice as big for a disk as it is for a sphere. Therefore, the hydrodynamic force acting on the sphere increases by a factor of roughly four as it deforms and rides along the water surface prior to liftoff. The secret behind the success of the water-skipping toy balls is twofold: During impact, compliance produces favorable geometry, and between skips, elasticity returns the sphere to an essentially undeformed state, so there's no need to preferentially orient it.

The flattening and rebounding of the compliant sphere proceed via the propagation of an elastic wave through the material. If the sphere can exit the water cavity before the wave has fully passed across it, the sphere will successfully

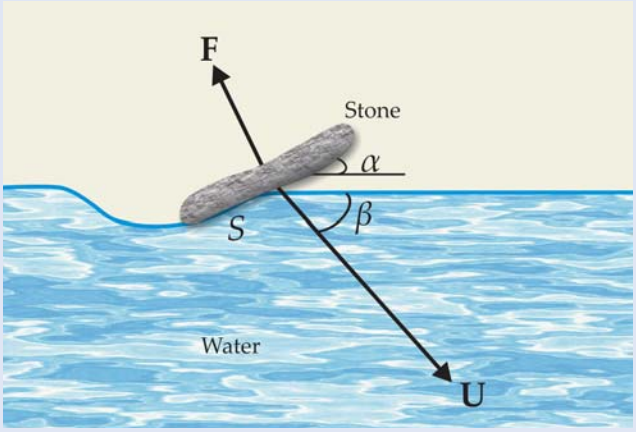

Figure 1. Before skipping off a water surface, a disk-shaped stone creates an air-filled cavity. A hydrodynamic pressure force **F** normal to the stone's broad surfaces then jettisons the stone. This illustration defines the geometric parameters that determine **F**. The attack angle *α* is defined by the orientation of the stone, the course angle *β* is determined by the stone's impact velocity **U**, and *S* denotes the area of the stone wetted by contact with water.

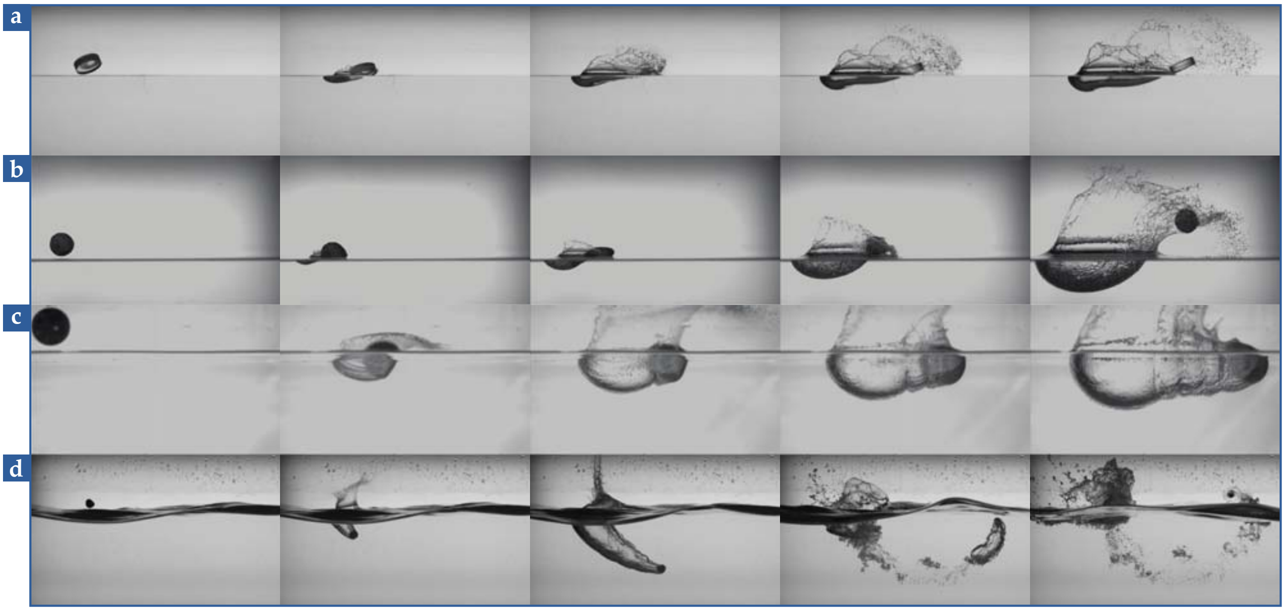

Figure 2. Compliant spheres skip, stiff ones don't. These stills, from videos available with the online version of this Quick Study, show four skipping trials. **(a)** The acrylic disk shown here was thrown into water per the usual sidearm method for skipping rocks. **(b)** An elastic sphere successfully skips after flattening into a disk-like shape. **(c)** A racquetball, which is much stiffer than water-skipping toys, does not skip. **(d)** An unconventional way to skip a rock is to launch it from a high angle and impart a lot of backspin.

skip and rebound. If the dwell time is too great, however, the elastic wave collides with the cavity, the sphere loses energy, and the number of skips goes down.

First-time users of water-skipping balls often find the toys' behavior counterintuitive, particularly since the balls bounce poorly on hard surfaces. On the other hand, racquetballs and other spheres that have a large restitution coefficient and bounce well on land do not skip well on water. Figure 2c shows why. The modulus of elasticity of a racquetball is about 5–10 times that of a typical elastic water-skipping toy ball—in other words, the racquetball is much stiffer than the compliant toy. It therefore deforms less under the same hydrodynamic impact loading and experiences a smaller lift force.

More than one way to skip a rock

This past summer, Maxwell Steiner tossed a rock across a lake at Riverfront Park in Pennsylvania and watched it hop a world-record 65 times. Interestingly, the previous best result—Russell Byars's 51 stone skips—was obtained at the same park. As noted above, optimal skipping is achieved with an attack angle α of about 20°, and the spin rate must be sufficient for gyroscopic stabilization to maintain the attack angle through repeated skipping events.

Launching the stone—be it disk shaped or spherical—with a smaller course angle β yields more skips. Indeed, to achieve more than 20 skips, naval gunners had to launch their cannonballs with a β less than about 2°. In principle, throwing the rock faster will help it achieve the maximal number of skips, though in practice the impact speed doesn't have to be particularly large. In any case, we humans are subject to a speed–accuracy tradeoff—the faster we try to do something such as move an arm, the less accurate we become. Stone skipping requires a high degree of accuracy to optimize α, β, and the spin rate. Elastic spheres, however, require only that you can control β; thus the speed–accuracy tradeoff is less of a hindrance to achieving amazing feats. We do not know what the world record for elastic-sphere skips is, but we have observed a colleague throw a Waboba into a lake and achieve 23 skips before the ball reached the opposite shore, some 50 meters away.

An alternative and unconventional skipping method involves imparting a great deal of backspin to a rounded stone so that it dives under the surface and then pops up and out of the water, as seen in figure 2d. The technique does not yield many skips, but it is impressive nonetheless. To pull it off, you need to throw the stone at the water surface at a much higher course angle than for the usual disk skipping. The backspin of the stone, coupled with its forward momentum, induces a lifting force called the Magnus force. That's the same force that soccer players exploit to bend the ball out of the goalie's reach and into the corner of the net.

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Additional resources

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