Jean-Philippe Boucher and **Romain Labbé** are PhD students in fluid mechanics at the laboratory of hydrodynamics (LadHyX) at the École Polytechnique in Paris. **Christophe Clanet** is a CNRS research director at LadHyX.



Row bots

Jean-Philippe Boucher, Romain Labbé, and Christophe Clanet

By dipping their oars into the water asynchronously, a rowing crew can reduce the friction on their racing shell. Experiments with robots determine whether that trick increases the boat's speed.

Rowing is a challenging sport, and not just for athletes. It mixes physiology, mechanics, and fluid dynamics, so from a physicist's perspective, the sport is much more complex than the elegant movement of a rowing shell might suggest.

Many scientists have tried to work out the details of rowing propulsion, often with a view to improving the performance of rowing crews. For example, in a 1971 *Science* paper (volume 173, page 349), Thomas McMahon showed that the speed of a racing boat scales as the number of rowers to the power 1/9. In our research, we have taken a closer look at the boat speed within one rowing cycle. In a single stroke, a propulsive phase is followed by a gliding phase. As the figure shows, for racing boats, the variation in speed during the stroke is typically around 20% of the mean speed of 5 m/s or so. Such a variation is a consequence of the synchronized rowing of the crew, a technique that seems to be essential for success in top-level rowing competitions. Consider, however, that for a boat moving through water, larger fluctuations about the boat's average speed imply increased friction on the hull. As a consequence, the mean power dissipated due to fluid friction for speed variations typical of a racing boat is about 5% higher than it would be if the boat could somehow be propelled steadily at the same mean speed.

Desynchronizing the rowers can reduce speed variations. Nature employs an out-of-sync propulsion strategy in, for example, shrimp-like krill that swim with the so-called metachronal movement of five pairs of legs that are activated in a desynchronized way. Indeed, a 2010 study by Silas Alben and colleagues published in the *Journal of the Royal Society Interface* (volume 7, page 1545) showed that the krill's metachronal kinematics leads to the highest average body velocity for a given amount of work. Some fishing spiders also display unsynchronized swimming at the surface of water. Given that in rowing competitions, 2 km races are often won by less than a boat length, it's worth considering the possible advantage of unsynchronized rowing.

Row, rOw, roW your boat

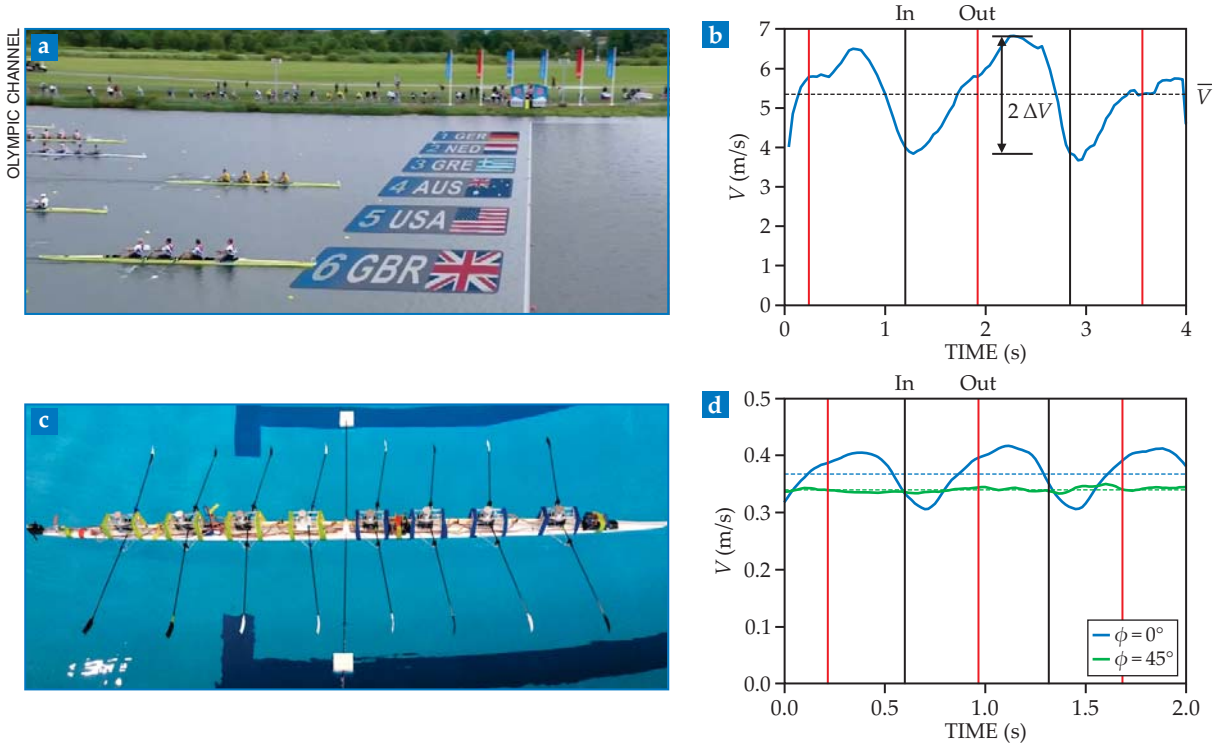
Phase-shifted rowing had been tried as early as 1929, by the London Rowing Club; you can see a video of the effort at www.youtube.com/watch?v=zQ6fxsmo3V8. But the London club's exercise and others conducted in the UK during the early 1930s led to indecisive results. As one reporter for the *Sydney Morning Herald* mused on 11 October 1933, the experiments raised the question of "whether the trifling gain is worth the loss of all the rhythm, apart from neutralising the genius of strokeship." At the 1981 and 1982 World Rowing Championships, the Soviet women's coxed four crew placed the coxswain (the person who steers the boat) between the two pairs so that they could row perfectly out of phase. However, on race days the crew chose to row in synchrony. Despite the full-scale trials and other studies, out-of-phase techniques never have convincingly been shown to be more or less efficient than conventional synchronized rowing.

To perform a systematic study of the influence of rower synchronization on boat speed, we built a boat at 1/10 scale with eight robotic rowers. A real racing boat with eight rowers, known as a coxed eight, has a length of about 20 m and weighs about 100 kg. Our 2-m-long model, shown in panel c of the figure, has a fiberglass hull with the same shape as on a real coxed eight. The mass ratio of robot rower to model boat is the same as for human rowers and racing boats, and we designed the mechanics of the robotic rowing to be as human as possible. With the help of a device called an Arduino board, we were able to control the stroke speed and synchronization of our robot rowers.

Which strategy is best?

We measured the speed of our rowing boat at the swimming pool of the École Polytechnique and explored how it changed as we varied the phase difference ϕ between consecutive rowers. Panel d of the figure shows the results for two of our trials, which you can view in the supplemental videos available online. In the synchronous configuration, $\phi = 0°$, the velocity profile of our boat is similar to the one obtained from videos of real rowing races (as in figure panel b). The speed increases during the power stroke, from a black vertical line to a red one in the figure plots, due to the propulsion given by the oar blades. During the recovery stroke, from red line to black line, the speed decreases, partly due to the hydrodynamic friction on the hull. The similarity of the velocity profiles proves that our model boat does a good job of imitating real rowing boats.

At a pace of one stroke per second, our boat moves at a mean speed close to 0.36 m/s, almost 0.2 boat length per rowing cycle. By means of comparison, real race boats travel roughly 0.45 boat length per rowing cycle in competitions. As with real boats, our model displayed large variations around its average speed—approximately 12% of the mean.



ROWING IN AND OUT OF SYNC. Great Britain holds a slim lead over Australia **(a)** halfway toward its victory in the men's four rowing final at the London 2012 Olympics. **(b)** The velocity V of the British boat was determined from a video of the race. The black vertical lines in the plot indicate the times at which the blades enter the water, and the red vertical lines indicate the times at which the blades are lifted out. The mean speed of the boat $\overline{V}$, about 5.3 m/s, fluctuates by about 20%, as indicated by ΔV. **(c)** Robots row a 2-m-long boat at the École Polytechnique swimming pool. **(d)** The robots were able to row synchronously ($\phi = 0°$) or asynchronously; in the out-of-sync trial plotted, each robot is 45° out of phase with its neighbor. As we expected, relative fluctuations were reduced for asynchronous rowing, but we were surprised to learn that the mean speed (indicated by dashed lines) was also reduced.

For phase-shifted rowers, we show $\phi = 45°$ in the figure panel and supplemental video. The bots row one after the other to propel the boat, and when the last rower on the boat finishes its power stroke, the first one starts anew. In this case the instantaneous velocity profile displays much less speed variation than in the synchronized case: about 2% of the approximately 0.34 m/s mean speed. The diminished fluctuations were expected, but we were surprised and initially puzzled that the mean speed of our boat was also reduced—by about 5%. We repeated our experiments for many phase differences spanning the range 0°–360°. Although the quantitative values varied, we found that compared with synchronized rowing, desynchronized rowing always decreases both the relative fluctuations and the mean speed.

Another propulsive mechanism

Our main result thus contradicts our initial intuition that reducing velocity fluctuations would increase the mean velocity. So, luckily for rowing athletes who have trained to row synchronously, we can confirm the commonly accepted wisdom that rowing together maximizes speed.

In our initial thinking, we failed to take into account that the rowers are not stationary. Indeed, if you return to the velocity profiles in figure panels b and d, you'll see that the speed in the synchronized configuration keeps increasing at the beginning of the recovery stroke—that is, after the oars have been lifted from the water, as indicated by the red lines. If the velocity keeps increasing when the oars are out of the water, there must be an additional propulsive force that does not depend on oars. In fact, the force results from the motion of the rowers on the boat. When the rowers return together to the stern of the boat during the recovery stroke, they pull the hull beneath them and accelerate the boat. Since the crew of a coxed eight weighs several times what the boat does, the rowers generate a significant force. When they are desynchronized, that inertial boost is reduced.

For krill, whose tiny churning legs are always underwater, there is no such inertial boost effect. They do better with desynchronized propulsion.

Additional resources

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