Human-powered Watercraft

In striving for ever higher speeds the familiar racing shells propelled by eight oarsmen may have to give way to unconventional watercraft. Such a record-setting vehicle was designed and built by the authors

by Alec N. Brooks, Allan V. Abbott and David Gordon Wilson

Until recently the slender shells, or racing rowboats, made familiar by the Olympic Games, the races on the Thames River in England and other rowing regattas held throughout the world, were the fastest human-powered watercraft. The fastest of these, powered by a crew of eight oarsmen, achieve speeds of 12 knots over a standard 2,000-meter course. (One knot is equal to about half a meter per second.) Human-powered watercraft that are not bound by the arbitrary restrictions of officially sanctioned rowing events are likely to equal or surpass this level of performance. Designers of these unconventional craft are dispensing with oars and taking full advantage of modern high-efficiency propellers. They are even dispensing with hulls as they explore innovative ways to reduce the resistance against motion, called drag, that water exerts on a moving boat.

Indeed, two of us (Brooks and Abbott) have developed just such a record-setting human-powered watercraft. The craft, *Flying Fish II*, is ridden like a bicycle. It has a pair of hydrofoils, or underwater wings, and a high-efficiency propeller. It enables a single rider to complete a 2,000-meter course significantly faster than a single rower in a shell can, and it has attained a maximum speed of 13 knots over short distances.

Regardless of its design—whether it is a crude flotation device propelled by underwater kicking, a wood raft pushed along by poles, a dugout canoe powered by paddles or a dinghy moved forward by sweeping oars—every watercraft must contend with four basic forces: weight, lift, thrust and drag. Weight and lift are the simplest forces to understand. Weight is simply the gravitational force pulling down on the craft and its occupants; lift is the force that acts upward, counteracting the weight. As long as a boat does not experience any vertical acceleration, lift is equal to weight.

For most watercraft lift is generated by buoyancy: the displacement of water by the craft's hull. The lift is equal to the weight of the water displaced, and it operates even in the absence of motion. In addition many high-speed boats take advantage of dynamic lift, which is produced as the boat moves through water. A common example of dynamic lift is planing: when the bottom of the hull continuously deflects water downward so that lift is produced as a reaction force. A boat that relies on planing for most of its lift rides higher in the water—often right at the surface—and requires less buoyancy. Until recently designers of human-powered watercraft had not been able to successfully incorporate dynamic lift into their vehicles.

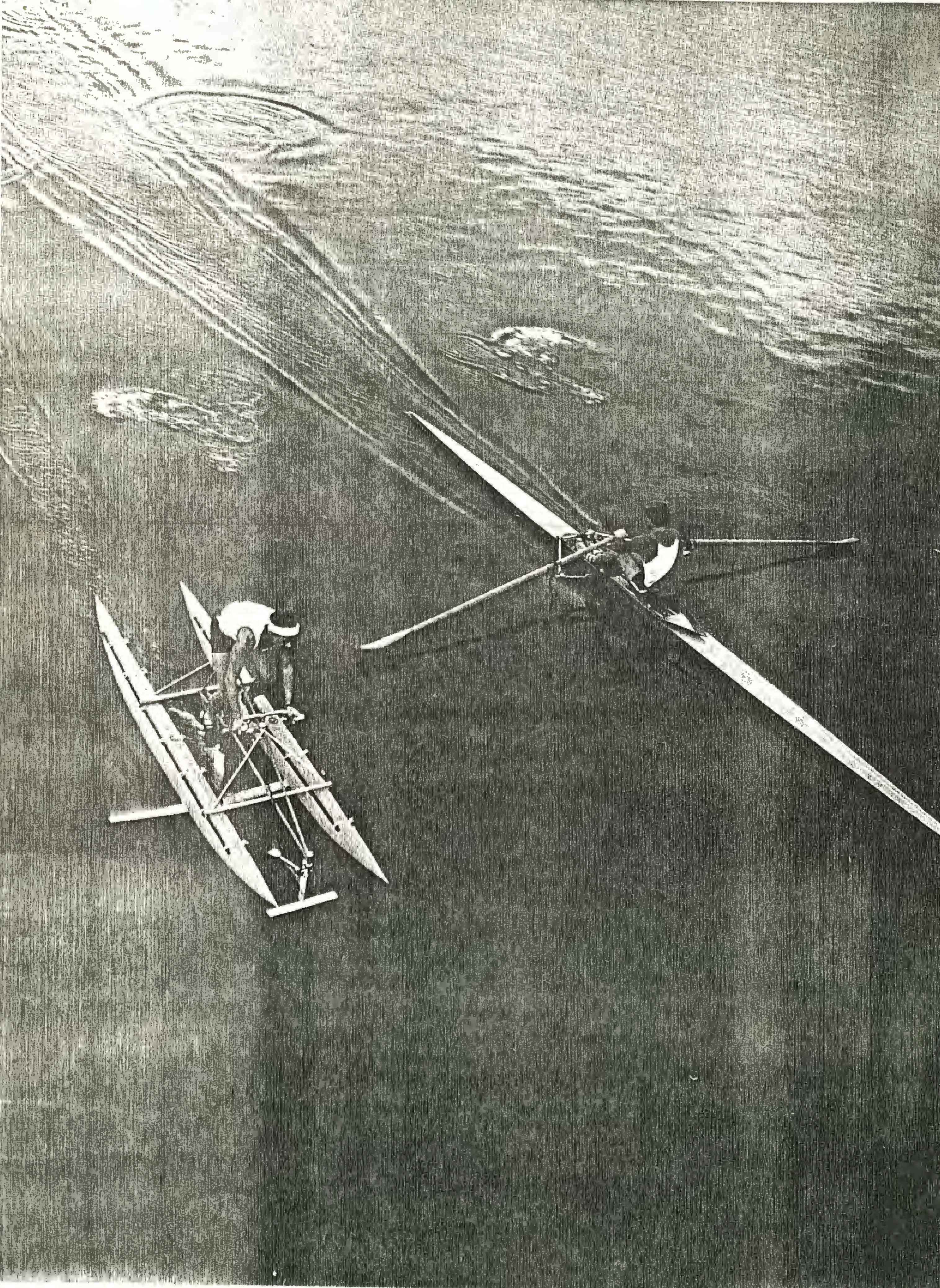
Thrust is the force (produced by the actions of the operator in the case of human-powered watercraft) that propels the craft. Drag is the force that by definition acts in the direction opposite to the direction of the craft's motion. If a boat is moving at a steady speed, the thrust is equal to the drag. In summary, at constant speed lift balances weight and thrust balances drag.

In order to translate efficiently a given human power input into speed the most important objective is to minimize drag. One obvious way to lessen drag is to reduce the weight of the boat. Once a boat begins to move, its source of lift almost always exacts a drag penalty. By minimizing the weight of the boat the required lift is reduced, and hence the drag associated with the lift is lessened. Since the craft's operators are not likely to be overweight (assuming they are healthy, athletic individuals to begin with), the weight reduction must apply primarily to the vehicle itself.

Efforts to this end have led to racing shells that weigh only a small fraction of the operator's weight—a relation similar to that of a modern racing bicycle and its rider. In the past shells were generally made of cedar, spruce and mahogany, and they were made lighter by thinning their hulls. (Indeed, the term "shell" arose because a careless finger could easily puncture a wood hull.) In the 1950's experimental shells that had a skin of glass-fiber-reinforced plastic were tried, and by the end of the 1960's commercially available composite-based boats had challenged the dominant position of wood boats in rowing circles. Today the wood shell is becoming a rarity. Sophisticated composite materials consisting of a resin matrix interlaced with fibers of a polymer or graphite have brought down the weight of the lightest single-person shell to less than 10 kilograms.

Assuming that the weight of the racing shell has been reduced to its practical minimum, a designer's attention must turn to other ways of minimizing drag. Shells have what are called displacement hulls: virtually all their lift is produced by the buoyancy of the hull. Displacement hulls have the unique property that their drag approaches zero as their speed through the water approaches zero. Hence at very low speeds displacement-hull vehicles have extremely low drag and

AMONG THE FASTEST human-powered watercraft are conventional racing shells and the authors' unconventional vehicle, *Flying Fish II*. The shell, shown here being rowed by four-time Olympian John Van Blom, was built by Alfred Stämpfli AG of Switzerland. *Flying Fish II*, ridden by one of the authors (Abbott), is powered by a pedal-driven propeller and supported by two hydrofoils, or underwater wings, while racing. The floats are actually above the water surface and are meant to support the craft only at low speeds.



are among the most efficient of all vehicles. Racing shells, however, do not operate at low speeds.

As a shell's speed increases, its drag increases dramatically owing in part to the formation of waves that emanate from the bow and stern. The energy needed to produce these waves is manifested as wave drag. Wave drag increases rapidly with increasing speed but in an uneven fashion because the bow wave can interact constructively with the stern wave (so that the waves are in phase and reinforce one another) or destructively (so that the waves are out of phase and tend to cancel one another) as the craft picks up speed. At a speed called hull speed the bow is at the crest and the stern is at the trough of a single wave; in its passage through the water the hull has literally created a hill of water through which the boat must push. At this point a great expenditure of power is needed to increase the boat's speed. The human power plant cannot supply the required effort, and so hull speed acts as the effective speed limit of a human-powered displacement-hull vehicle.

Hull speed is proportional to the square root of the waterline length of a boat. Human-powered watercraft that have long displacement hulls are therefore less hindered by wave drag than boats that have short hulls with the same overall buoyancy. On the other hand, for a given buoyancy long, slender hulls have more wetted surface area than short, wide hulls. The greater the wetted surface area, the greater the drag caused by the friction of the water as it flows past the surface of the hull. This type of drag is known as skin-friction drag. Hence as a boat is made more slender, wave drag diminishes but skin-friction drag then becomes more of a problem.

A hull designed for speedy boats must therefore be shaped to minimize the sum of wave and skin-friction drag. Shells are designed to compete in six-to-seven-minute races at power levels of about half a horsepower per rower. (One horsepower is equal to approximately 750 watts.) The resulting optimal length-to-width ratios of these sleek craft exceed 30. A single-person shell, for example, has a length of between eight and nine meters and a width of no more than 30 centimeters. It turns out that the optimal shell shape results in a skewed distribution of drag at racing speeds: 80 percent of the drag operating on the shell is due to skin friction and 20 percent is due to wave production.

Given that skin friction is the dominant source of drag operating on a shell at racing speed, a substantial reduction in drag is possible if skin friction can be reduced. Skin friction arises from a thin layer of water, known as the boundary layer, that flows past the boat's hull. There are two fundamental types of boundary layer: laminar, in which the flow is smooth and steady, and turbulent, in which the flow is chaotic and unsteady. Laminar boundary layers produce much less skin-friction drag than turbulent boundary layers do. The boundary layer on a shell is laminar at the bow, but only a short distance back from the bow it typically undergoes a transition to turbulent flow. Drag is significantly reduced if the transition is delayed, thereby increasing the area of laminar flow on the hull.

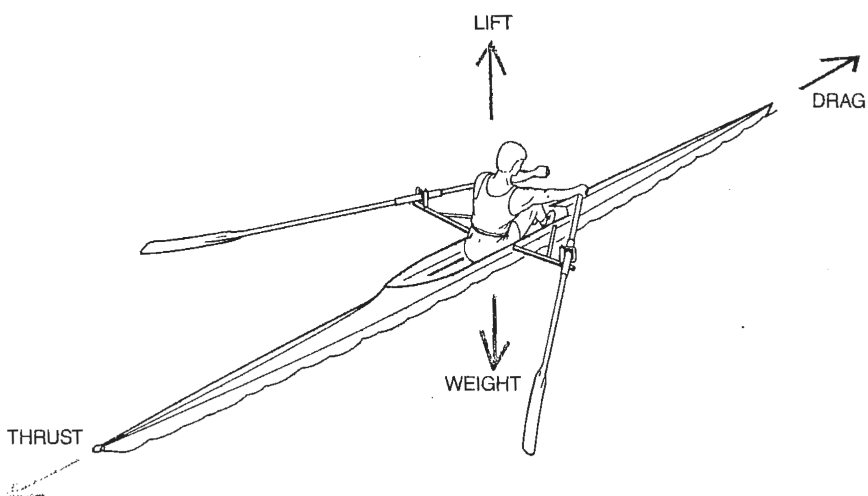
One method of extending the laminar boundary layer that is applied in some specialized underwater vehicles is the injection of long-chain polymers (sometimes referred to as slippery water) into the boundary layer near the front of the craft. Race-sanctioning organizations are not likely to allow this practice in competition, if for no other reason than that it pollutes the water. A similar approach that might be allowed, however, would entail carefully cultivating a layer of naturally slimy algae or some other innocuous microorganisms on the hull.

Boundary-layer suction is another technique that has been applied to stabilize a laminar boundary layer. In this approach fluid in the boundary layer is continuously "sucked" into the boat through pores or small slots in the hull surface. Shells could make use of boundary-layer suction if they were outfitted with a porous hull that would allow water to seep in slowly. A small pump would serve to bail the water out occasionally.

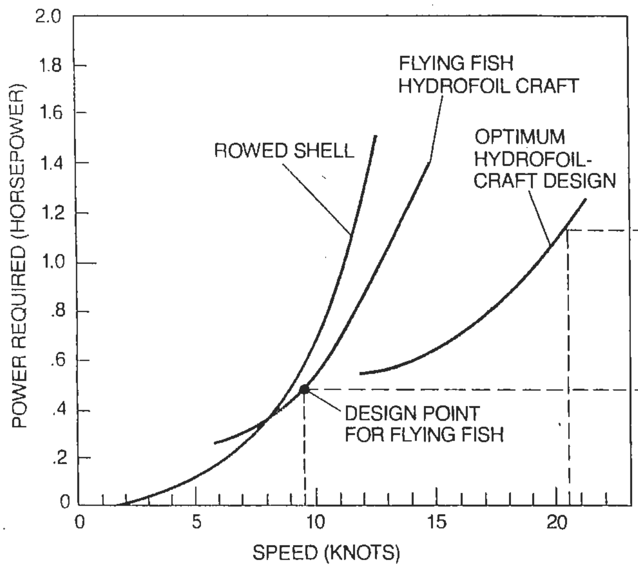
The texture of the wetted hull surface can also play a role in the reduction of skin-friction drag. Investigations under the auspices of the National Aeronautics and Space Administration have shown that a slick waxed surface does not always result in minimal skin-friction drag. Surfaces with very fine grooves running in the flow direction, called riblets, have shown 6 percent less drag than smooth surfaces.

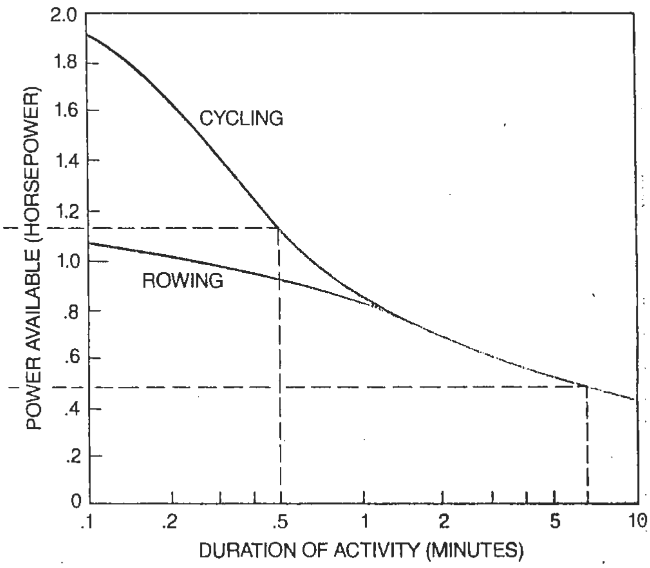
Riblets have been tested on rowed shells by a group from the Flight Research Institute headed by Douglas McLean of the Boeing Company. The group covered a single-person shell with an experimental plastic skin in which grooves had been formed. The spacing between the grooves was three-thousandths of an inch (about 80 micrometers)—finer than the groove spacing on phonograph records. Tests indicated that the shell's maximum speed was increased by 2 percent. Although this may seem like an insignificant amount, it is equivalent to a four-boat-length advantage over a standard 2,000-meter race.

On the basis of such encouraging results the experimental skin was applied to the hull of the U.S. Olympic



FOUR BASIC FORCES must be considered in designing boats such as the racing shell shown here: weight, lift, thrust and drag. Weight is the gravitational force acting on the boat and the operator. Lift is normally generated by buoyancy, the upward force equal to the weight of the water displaced by the boat's hull. Additional lift, called dynamic lift, can be produced by the flow of water under the hull. Thrust, in the case of human-powered water vehicles, is the force produced by the actions of the operator (here seen rowing) that propels the craft forward. Drag is the resistance to the boat's forward motion; it arises in most craft from the creation of a wake (wave drag) and the friction between the hull and the water flowing past it (skin-friction drag). When a boat has a constant speed, lift balances weight and thrust balances drag. The key objective in boat design is to minimize drag at the normal operating speed of the boat. At the speeds necessary for competitive rowing, drag is minimized by making a shell light, long and narrow.





POWER LEVEL necessary for a human-powered watercraft to reach a certain speed for a certain length of time depends on the craft's design. The graph at the left shows the power required for a rowing shell, which relies on the displacement of water by its hull for most of its lift, compared with two other craft designs (one being the authors'), which rely on the dynamic lift produced by hydrofoils. At low speeds displacement-hull craft are more efficient than hydrofoil craft. Actually hydrofoil craft have a minimum speed below which the hydrofoils cannot support the combined weight of the craft and the operator. At higher speeds, however, hydrofoil vessels are more efficient than displacement-hull craft. The graph at the right shows how the power a champion athlete can supply diminishes with the effort's duration. For brief durations the power output generated by the cycling motion is considerably higher than the output generated by the rowing motion. An optimal hydrofoil design could make it possible to reach speeds of more than 20 knots. Such a feat would require power levels that can be achieved only by cycling and only for a few seconds. A craft incorporating such a hydrofoil would be difficult to get started: its "takeoff" speed would be more than 11 knots.

team men's coxed-four rowing shell. (A coxed boat is steered by a coxswain, who does not row but calls out the rowing cadence.) The team made an excellent showing, winning the silver medal in the 1984 summer games.

In addition to low drag, another essential ingredient for a successful racing shell is good propulsive efficiency: as much as possible of the power from humans must be converted into useful thrust. In the case of rowing, two major advances in propulsive efficiency date from the mid-19th century. One was the development of the modern rigger in 1843. The rigger is a tripodlike device attached to the side of the boat. The oarlock, or pivot point for the oar, is located at the apex of the tripod. Since the oarlocks no longer needed to be attached directly to the gunwales, or edges of the sides of the boat, the hull could be narrower (reducing wave drag) and the oars could be longer (enabling rowers to take longer and more efficient strokes).

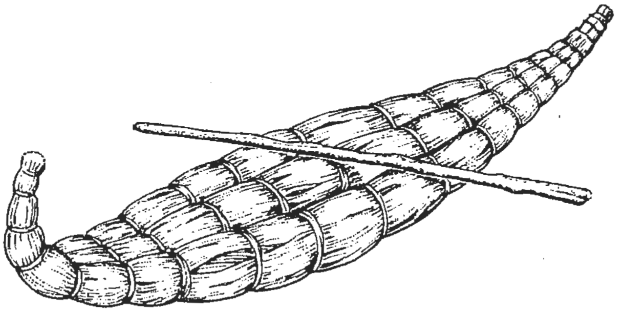
The second advance was made in 1856: the sliding seat. Until that time rowed boats were propelled through the use of the muscles of the arm, shoulders and back, whereas the larger muscles of the legs were used only to brace or support the body. The motion when rowing was one of heavy straining against a slowly moving resistance. The sliding-seat arrangement allows the energy of the leg muscles to be harnessed as the seat moves fore and aft with the bending and straightening of the legs during the rowing cycle. The first sliding seat was a rather crude device consisting of a sheepskin pad sliding on a greased panel. The sliding seat on bearings, still in use today, was invented in the U.S. in 1857.

A shell with a variation of the sliding seat was rowed by Peter Michael Kolbe to win the 1981 world championships in Munich. In contrast to conventional shells, which have sliding seats and fixed riggers and stretchers, or footboards, Kolbe's custom shell was equipped with a fixed seat and a sliding frame that supported the riggers and stretchers. Under this arrangement the rowing motion is the same as the motion for conventional shells, but since most of the rower's mass is on the fixed (rather than sliding) seat, the oscillations of the center of mass (which more or less coincides with the rower) are greatly diminished. This in turn diminishes the oscillations in velocity that a shell is subject to as it travels through the water. (These oscillations are manifested in a conventional shell by its distinctive jerky motion when it is rowed forcefully.)

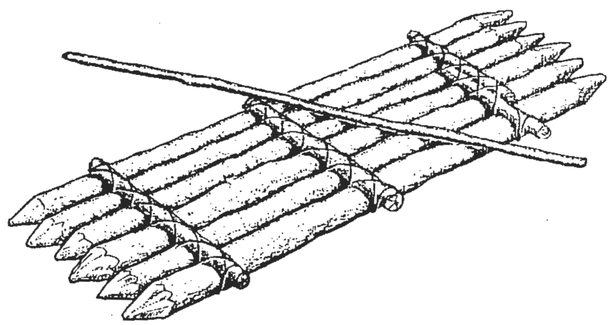
Because skin-friction drag is not a linear function of the velocity of the water in relation to the hull (it is in fact proportional to the square of the velocity), a fluctuating speed always produces more drag than would occur if the boat moved steadily at the average speed. The drag reduction obtained by the sliding-rigger arrangement is only slight, but it is enough to make a significant difference in the racing world. In the 1982 world championships five boats in the men's finals had fixed seats and sliding riggers. In 1983 all six finalists used sliding-rigger boats. After 1983, however, sliding-rigger boats were ruled ineligible for competition.

Although the addition of the rigger and the sliding seat significantly augmented the propulsive efficiency of rowing, rowing nonetheless has a fundamental limitation. Oars and paddles are basically drag devices: they generate thrust by slipping backward through the water. The slippage represents an efficiency loss; it can be reduced by increasing the size of the oar blade, but only to a limited degree because of practical constraints. Moreover, the aerodynamic drag caused by the blades when they are out of the water during the return stroke can be quite significant, particularly under windy conditions.

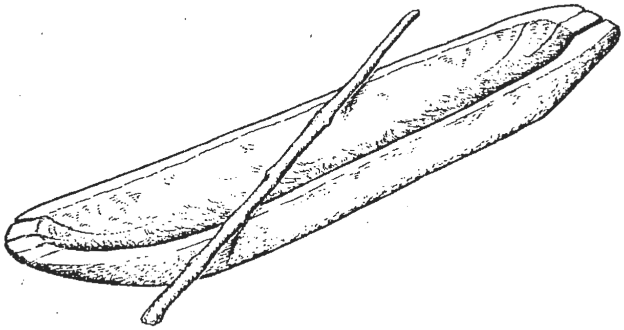
The efficiency of a propulsion system is defined as the ratio of useful power output, which is the product of the average thrust and the velocity, to the human power input. The detailed physics of rowing is not entirely understood but analysis by many investigators has put the propulsive efficiency of rowing at between 65 and 75 percent. Hence about two-thirds of the *a* REED RAFT



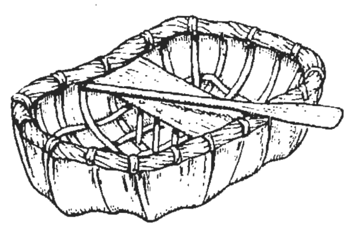
b LOG RAFT



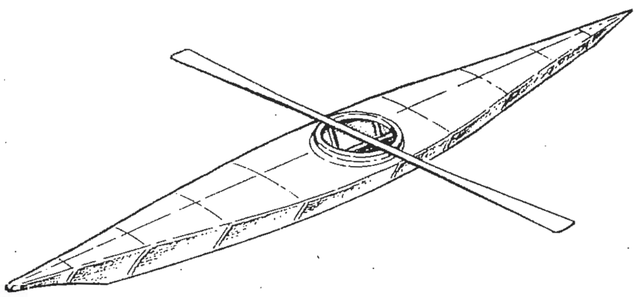
c DUGOUT CANOE



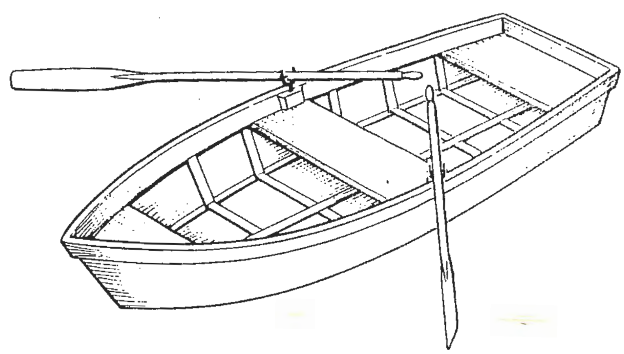
d CORACLE



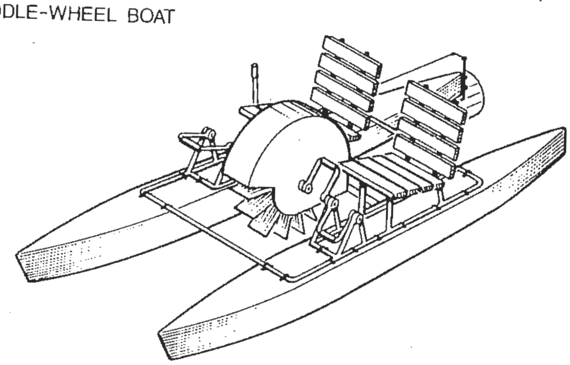
e KAYAK



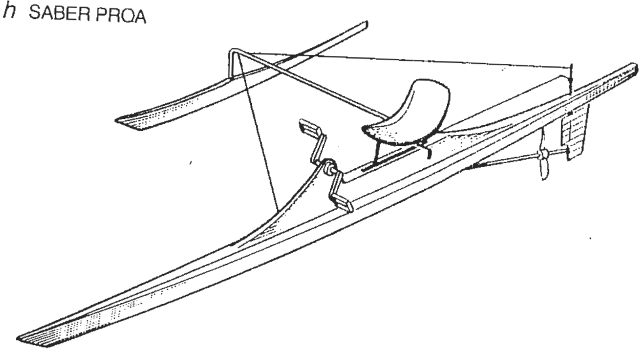
f DINGHY



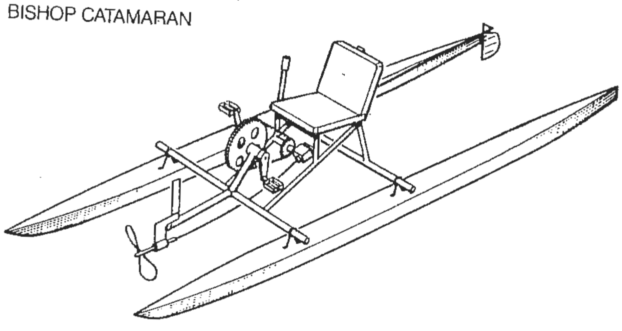
g PADDLE-WHEEL BOAT



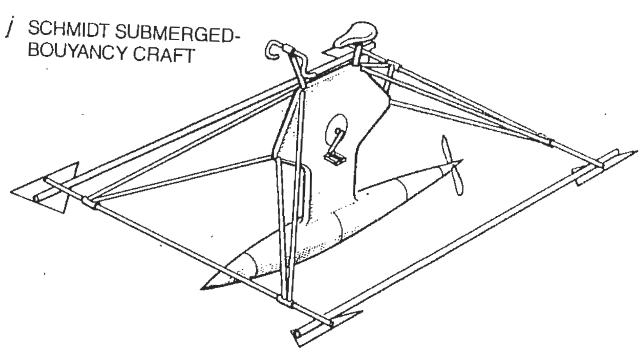
h SABER PROA



i BISHOP CATAMARAN



j SCHMIDT SUBMERGED-BOUYANCY CRAFT



rower's power output is delivered to the boat as useful work; the rest goes into creating disturbances in the water and air.

Motorized boats abandoned propulsive drag devices, such as paddle wheels, long ago in favor of propellers. Interestingly, before the development of small gasoline-fueled outboard motors at the turn of the century, human-powered propeller-driven boats were in fact being developed for practical transportation purposes. Such propeller-driven boats proved to be much faster and less tiring than canoes or rowboats. In the 1890's a three-rider propeller-driven catamaran (a twin-hulled boat) was shown to be 13 percent faster than a three-oarsmen shell over a 163-kilometer course on the Thames River.

Some disadvantages of propellers are that they can be fouled with weeds and can strike bottom in shallow water, but otherwise propellers are particularly suited for human-power applications [see "The Screw Propeller," by E. Eugene Larrabee; SCIENTIFIC AMERICAN, July, 1980]. Slender-bladed, high-efficiency propeller designs can be applied, since the power level is quite low. In addition, propeller-tip speeds are low enough so that cavitation is not a problem. (Cavitation, the formation of bubbles of water vapor, arises when the absolute pressure on some part of the rotating propeller is reduced below the water's vapor pressure; it reduces efficiency and can cause excessive wear on the blade surfaces.) Several new human-powered watercraft have been outfitted with propellers whose efficiencies exceed 90 percent.

The rotating motion of propellers also makes it relatively easy to drive them by an arrangement of pedals, sprockets and chains much like that of bicycles. Such an arrangement takes advantage of the rapid and strong movements of the legs. The circular pedaling action in bicycling remains the most efficient practical method of transferring continuous power from a human being to a machine. (It is not coincidence that record-setting human-powered air and land vehicles depend on a bicyclelike drive train.)

A champion cyclist can produce nearly two horsepower for a few seconds of maximum effort. For periods of continuous exertion lasting for six minutes, however, the power output is generally no more than half a horsepower. Various factors affect power production, including pedaling rate, seat height, pedal-crank length and the physical condition and determination of the cyclist. The traditional rowing motion, in which the rower sits still and brings into play only the muscles of his back, shoulders and arms, yields considerably less power than the cycling motion. The addition of the sliding seat, however, increases the power level of rowing to rival that of cycling—at least for periods of more than a few minutes. (The short-period advantage of cycling is lost after about a minute because of the limitations imposed by the human circulatory and respiratory systems.)

The inherent advantage of pedal-driven-propeller boats over rowed boats therefore lies chiefly in the fact that oars are a less efficient mechanism for channeling human energy to the propulsion of the boat. Furthermore, a rowed boat's uneven speed exacts more of a drag penalty than the smooth, continuous speed that can be achieved with a propeller.

Designers of fast human-powered watercraft have also attempted to minimize drag in novel ways. One way to virtually eliminate wave drag and at the same time reduce skin-friction drag is to submerge the hull; the operator would have to be supported above the water by narrow struts extending upward from the hull. The minimal-drag hull in this case is teardrop-shaped, with a length between three and four times its width.

Such a configuration is like that of a unicycle, and balancing would likewise be difficult, if not impossible, for the rider. Theodore Schmidt alleviated this problem somewhat by attaching four small outrigger hydrofoils to an experimental submerged-hull craft of his own design. A tricyclelike arrangement of three smaller submerged-buoyancy hulls would be stabler but not as efficient. Since the ratio of surface area to displacement gets smaller as displacement increases, one big hull has less surface area than three smaller hulls with the same total buoyancy.

The balancing problem of a single underwater hull could be solved by putting the operator in the hull—in effect creating a submarine. But a streamlined hull big enough to enclose a rider displaces much more water and has more surface area than a hull that provides just enough buoyancy to support a person's weight. Although it is not optimal for human-powered transport near the surface of the water, a human-powered submarine could be a great improvement over a skin diver with flippers. In the early 1950's a two-person human-powered submarine called the Mini-Sub, designed by Calvin Gongwer, was produced in limited quantities by the Aerojet-General Corporation. Pushed forward by twin 760-millimeter counterrotating propellers, the Mini-Sub reportedly could achieve speeds of seven knots—about three times the speed at which a diver can swim underwater.

Other designs seek to reduce the second major drag component, skin-friction drag, by employing dynamic lift to raise part of the boat out of the water and thereby reduce the boat's wetted surface area. Although dynamic lift does incur a drag penalty of its own, in many instances the reduction in skin-friction drag more than compensates for the drag generated as a by-product of the dynamic lift.

Human-powered water vehicles that take advantage of the dynamic lift achieved by planing are still in the imagination of designers, but another way to generate dynamic lift has been applied successfully: hydrofoils. Hydrofoils are underwater wings that produce lift in the same way as airplane wings produce lift. The required size of a hydrofoil wing is quite modest compared with airplane wings. For example, at a speed of nine knots something under a tenth of a square meter of foil area is needed to produce enough lift to support a single rider above the water. A hydrofoil designed to produce the same lift at twice the speed would require only a fourth as much area.

Although the small wetted area of hydrofoil wings results in minimal skin-friction drag, hydrofoils do incur a different type of drag. As the hydrofoil travels through the water it leaves behind a vortex wake, just as airplane wings do. The energy expended in generating the vortex wake is manifested as a drag called induced drag. Also, the spray kicked up by the vertical struts supporting the hydrofoil as they cut through the surface of the water results in additional drag.

Another major problem with hu-

HUMAN-POWERED WATERCRAFT display assorted shapes, construction materials and propulsion devices. Relatively primitive craft are poled (*a–c*) or paddled (*d, e*) and are made of such diverse natural materials as reeds, wood and animal skins. More modern craft are made of wood or metal and are rowed (*f*), an action that calls for the use of the arms, shoulders and back, or are paddled with foot pedals, bringing into play the strong leg muscles (*g*). Pedal-driven-propeller boats (*h–j*) have greater propulsive efficiency than either rowboats or paddle-wheel boats. Novel designs and materials have also cut back on the drag such craft encounter. The submerged hull of Theodore Schmidt's experimental craft (*j*), for instance, effectively eliminates the problem of wave drag.

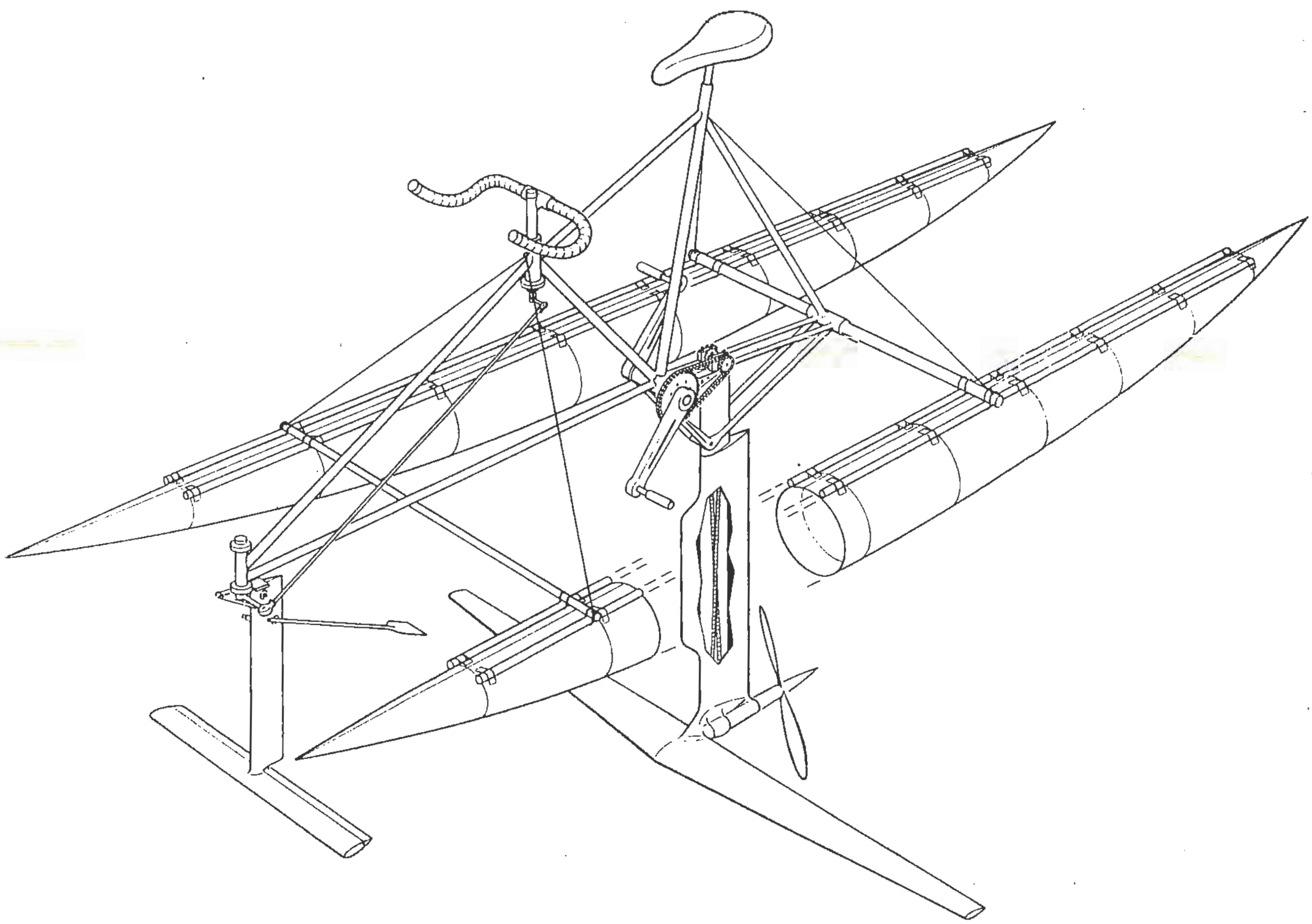
man-powered hydrofoil craft is that they need to reach relatively high water speeds before they can "take off," or lift themselves above the water. Since hydrofoils produce zero lift at zero speed, another support system, such as a displacement hull, is required for the initial and final phases of a "flight." A wing selected for all-out speed may have to be moving through the water at 10 knots before it can generate enough lift to support the craft and rider. This speed may well be impossible to achieve while the craft is still supported on the water by its displacement hull. A larger hydrofoil wing could reduce the takeoff speed, but the drag caused by the increased surface area would not allow the craft to go as fast.

Stacking hydrofoils so that smaller foils are placed below larger ones, as is done on motorized hydrofoil vessels, might circumvent the problem. A craft with such a tapered "ladder" arrangement of hydrofoils could take off at low speed on the large upper foils. Once sufficient speed has been attained so that the lift produced by the lower foil is enough to support the craft, the craft could rise up farther, raising the larger foil out of the water and thereby reducing drag. Because of the inherent difficulties associated with hydrofoils, human-powered hydrofoil craft do not have the same speed potential as human-powered airplanes, which have achieved speeds of more than 25 knots.

Until recently all human-powered water-speed records were held by displacement boats propelled by oars. With the intent of exceeding these speeds, two of us (Brooks and Abbott) in 1984 designed and built *Flying Fish I*, the first hydrofoil capable of sustained flight on human power alone. The sticky problem of initially getting the craft up to takeoff speed, which had plagued earlier designers, was bypassed initially by eliminating the need for a displacement hull. Flying speed was attained by catapulting the craft into the water from a floating ramp, much as jets are launched from aircraft carriers. Using this "flying start" launching method, cyclist Steve Hegg, an Olympic gold medalist, pedaled *Flying Fish I* a distance of 2,000-meters in six minutes 38 seconds, eclipsing the world record for a single rower by 11 seconds. The times, of course, are not directly comparable, because the rowing record was set from a standing start.

Flying Fish I has a high-efficiency, pedal-driven propeller and two slender wings supported by narrow vertical struts. The main wing, which carries 90 percent of the craft's weight, has a large wingspan (1.8 meters) to minimize induced drag and a small chord, or width, to reduce skin-friction drag. The smaller front wing has a configuration much like an inverted T and is lightly loaded; its main purpose is to provide stability and control. To this end it is fitted with a small, spatula-shaped device that automatically controls the depth of the wing. The device skates over the water surface, continuously adjusting a thin flap (analogous to the elevator on an airplane tail) to which it is linked.

The front wing strut doubles as a rudder and is connected to bicycle



FLYING FISH II is a human-powered hydrofoil craft designed and built by two of the authors (Brooks and Abbott). The craft, powered by a pedal-driven, high-efficiency propeller, takes off at six knots and has a top speed of about 14 knots. It is ridden just like a bicycle. The first version of the craft did not have side pontoons and required a catapult-launch ramp to bring it up to takeoff speed. The pontoons on the current version support the craft so that it can now reach takeoff speed from a standstill. The depth at which the hydrofoils "fly" is controlled automatically by a spatula-shaped surface follower linked to a thin flap on the front hydrofoil. The craft has completed a 2,000-meter course approximately 10 seconds faster than the record for a single-rower racing shell.

handlebars for steering. The craft is ridden much as one would ride a racing bicycle. The structure that is normally above the water is, in fact, a modified bicycle frame.

Flying Fish II was developed as a refinement of the first version of our craft. We attached lightweight pontoon floats to it in the hope that an unassisted takeoff could be made from a standstill. This proved to be possible, and with practice acceleration from a standing start to the fully foil-borne mode took only three seconds. The craft also became much more practical because it could now "land" on, as well as take off from, its floats. (The catapult-launched *Flying Fish I* gave the rider a dunking whenever he stopped pedaling.)

Aboard the *Flying Fish II* one of us (Abbott) recorded a time of six minutes 39.44 seconds over a 2,000-meter course from a standing start—about 10 seconds faster than the single-person rowing-shell record. From a flying start the hydrofoil watercraft also was able to sprint 250 meters in 38.46 seconds, reaching a maximum speed of approximately 13 knots.

The time is ripe for a technological revolution in human-powered recreational watercraft. Laser International has just introduced the Mallard, a partially enclosed, seaworthy boat designed by Garry Hoyt. Several new pedaled catamarans and proas (boats that have one main hull and a smaller stabilizing outrigger) offer rough-water seaworthiness and impressive speed. Jon Knapp of Saber Craft has designed and built a propeller-driven proa that is faster than a shell in rough water but, unlike a shell, requires no special skills to operate. The Dorycycle, a propeller-driven single-hulled craft designed by Philip Thiel, provides good load-carrying capacity at speeds twice that of the rowed dory from which it was derived.

Whether or not hydrofoil craft become popular for recreation, there seems to be little doubt that they will figure prominently in the next round of breaking records. The International Human Powered Vehicle Association encourages competition in human-powered vehicles—on land, on sea and in the air—without any arbitrary limits placed on their design. Such competition will push the speed of human-powered hydrofoil craft ever higher. It is not farfetched to envision such craft reaching speeds as high as 20 knots—one and a half times as fast as the speeds attained by *Flying Fish II* and significantly faster than the speeds attained by racing shells powered by eight athletic oarsmen.