Back-splash in rowing-shell propulsion

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Abstract

The term 'back-splash' is used in rowing to denote the splashing of water towards the bow of the boat which may occur when the oar is first placed in the water. If the oar is not rotating about the gate-pin in the horizontal plane when it is placed in the water, it will push water in the direction of boat motion, and the reaction of the water will be a braking force on the boat. If the oar is rotating, with the blade moving laterally away from the boat as it enters the water, the relative velocity of the water impinging on the back of the oar-blade (*i.e.* on the side of the blade facing the *bow* of the boat) is reduced with a consequent reduction of the braking effect of back-splash. It is generally considered desirable, other things being equal, to reduce the time taken and distance moved by the oar before it 'locks in' to the water. The amount of oar motion required to eliminate back-splash entirely is considerably reduced when the oar blade is extended as far as possible towards the bow of the boat (and the angle between the oar shaft and the side of the boat is as small as possible) before the oar enters the water. The benefits of this may be enough to outweigh any potential loss of propulsion efficiency of the oar in this extreme position; this may be one of the reasons that the long stroke is generally thought to be more effective than the shorter stroke.

Data taken at the Australia Institute of Sport measuring the rowing characteristics of an elite athlete rowing a single scull has been analyzed. The rotational inertia of the oar is significant so the simple lever arm rule is not accurate enough for our purposes to relate the blade force to the measured oar bending. The equations of motion required to deduce the handle force and the blade force are given. We estimate (for the boat speed of about 4.5m/s at the catch) that, if the only 1/5 part of the oar blades were immersed in the water while the oars were not rotating in the horizontal plane (*i.e.* not moving outwards and sternwards relative to the hull), a back-splash force of more than 9 kgs would act on each blade. If this force acted for as little as 0.03s it would reduce the average hull speed by more than 2%, which corresponds to a distance of more than 40m over a 2000m course. The oar-bending record shows no evidence of a back-splash force. All the data indicates that the oars are being rowed through the air for about 0.05s before entering the water, and through three or four degrees, which is a little more than the minimum required to avoid back-splash.

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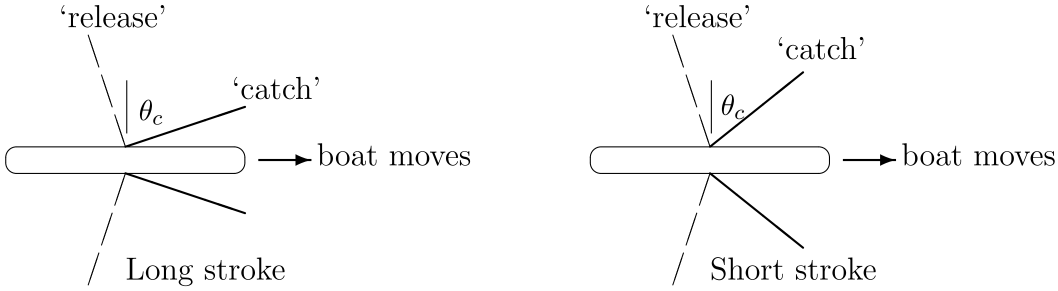

Figure 1: Schematic plan views of a single scull at the moment the ends of the oars (the blades) enter the water, making an angle θ_c (the 'catch angle') to the square position. The broken lines show the oars as they are withdrawn from the water (at the 'release' or finish of the stroke). For the long stroke, θ_c may be close to 70°.

1 Introduction

Rowing techniques and styles have changed over the years and between different countries. One such change has been in the 'length of the stroke' or the angle swept through by the oar while the blade is in the water. For example, the German Ratzeburg Men's Eight which won the gold medal at the 1960 Rome Olympic games used a short stroke with a high rate of striking (Edwards 1963, p. 73)[1]. It is probably fair to say that now a long stroke is the standard aspired to in competitive rowing in Australia, although probably not as long a stroke as that employed by the GDR crews which dominated the sport in the 1970s. One way of achieving a long stroke is to make the blade of the oar reach towards the bow of the boat as far as possible before it is placed in the water and the force is applied. Fig. 1 shows a schematic view of a single scull (a two-oared boat in which a rower controls an oar with each hand) and illustrates a long and short stroke. The angle of the oar forward (bow-wards) of the square position when it enters the water (at the 'catch'), is denoted as θ_c.

At first glance, the popularity of the long stroke may seem a little surprising since, when the shaft of the oar makes a small angle to the side of the boat, the water reaction on the immersed blade is primarily directed sideways into the boat (the 'pinching force' is large) and only a small component of the force on the blade is directed forwards to propel the boat. Put another way, when the oar is square to the boat (making an angle of 90° to the forward direction) all the water reaction on the blade is directed forwards, so that all the work being done by the rower is directed to propelling the boat forward, whereas in the early part of the stroke the rower is doing some work to push water sideways, which appears to be a wasted effort. Such wasted effort might be avoided by a shorter stroke.

There may be a number of advantages of the longer stroke that outweigh this apparent inefficiency. Some of these advantages may be associated with the slightly lower stroke rate which generally accompanies the longer stroke[2]. For example, there

[1]In sweep rowing, such as in the Ratzeburg Eight, each rower controls one oar only and the arc is generally shorter than for the sculling data which we consider. Nevertheless 70° of arc for the Ratzeburg crew (Edwards 1963) is considerably less than the 87° measured for sweep rowing at the Australian Institute of Sport (Kleshnev 2005, Fig. 18.13).

[2]The slower stroke rate is also (arguably at least) associated with the increased use of a larger blade area in the early 1990s.

may be physiological reasons which make the lower stroke rate preferable for an endurance sport, or the boat speed variation over the rowing cycle may be reduced compared to a higher stroke rate (McBride 1998). Since the water drag force on the hull can be expected to vary approximately as the square of the hull speed, the average drag is reduced when the hull speed variation is reduced[3].

Here we examine a particular consequence of the large catch angle θ_c that is not directly related to stroke rate: the larger the catch angle the easier it is to insert the oar into the water without causing 'back-splash', which is the term used to describe water thrown towards the bow by the bow-wards face of the oar-blade as it enters the water[4]. That 'back-splash', considered in isolation, is detrimental to boat speed should be obvious. If the oar throws water towards the bow, the water reaction on the oar has a component towards the stern, and the oar is acting momentarily as a brake. Sir Steve Redgrave puts it thus:

> As the blade descends towards the water it should be travelling [...] towards the stern of the boat [...], this prevents backsplashing (*see* Chapter 6: Faults). To effect a clean blade entry into the water [...] the blade should enter the water at the *same* speed as the boat is travelling. If the blade doesn't enter the water smoothly it will act as a brake thus slowing the forward motion of the boat. (Redgrave, 1995, pp 60-61. See also p 82.)

To say that the blade should be travelling towards the stern at the same speed as the boat is travelling (forward) expresses the general idea, but is strictly only true if the first contact with the water is made with the oar approximately square to the boat. The velocity (*i.e.* speed *and* direction) of the blade relative to the water which is required to make the blade enter the water 'smoothly' is shown later in Fig. 4. As we will see, the blade must be rotating (moving) with respect to the hull, which is the idea we think Redgrave is here expressing.

As a first approximation, we can ignore any forces from the air acting on the system (consisting of hull, rower and oars) as negligible compared to the water forces. Any motion of the rower or the oars, without the oars touching the water, cannot create an extra propulsive force on the system. Therefore rowing the oar through the air appears to be a wasted effort[5] or, if it is more than the minimum necessary to avoid back-splash, a wasted opportunity to develop propulsive force on the system. Some authors, as we will see in §5, imply that this rowing-in action has a greater detrimental effect than the back-splash it avoids. The argument usually refers only to the loss of hull speed just before the catch, so it is not clear whether these authors believe rowing-in is detrimental to overall system speed which, in our view, is what

[3] Let the drag force on the hull be given by $F_D = kV^2$ where V is the hull speed through the water, and k is a constant. Since the hull speed varies over the cycle, we may write $V = \overline{V} + v$, where $\overline{V}$ is the average speed (a constant) and v is the time-varying deviation (plus or minus) of the instantaneous hull speed from the average. The time-averaged drag force is then $\overline{F_D} = k\overline{V}^2 + k\overline{v^2}$, where $\overline{v^2}$ is the average value of v^2 and is always positive. For a given mean hull speed $\overline{V}$ the smaller the variation of hull speed, the smaller the value of $\overline{v^2}$ and the smaller the average drag.

[4] The rower faces the stern. The 'back-splash' water is thrown backwards relative to the rower.

[5] We say 'appears' to be a wasted effort because it may not be entirely wasted. The rower and blade have acquired some momentum relative to the water before the blade hits the water, and an impulsive force is exerted on the water on contact. In other words, at least some of the effort of rowing-in will eventually be converted to propulsive force.

matters[6]. The only external force on the system during rowing-in is the water drag on the hull, so it would seem that rowing-in can only be detrimental to the system by increasing that water drag. The average drag might be increased by 'bouncing the boat', or through fore-and-aft rocking of the hull, or by increasing the hull speed variation over the entire cycle. A benefit of a large catch angle is that, as is shown below, it reduces the amount of movement of the blade through the air which is required to avoid back-splash. Furthermore, even if the rower does create some back-splash, the large catch angle will reduce the braking effect of the back-splash compared to a small catch angle.

2 How quickly do rowers insert the oar?

It is sometimes suggested that to effect a quick catch, rowers do (or should) merely let the oar fall into the water under gravity[7]. Bourne (1925, p 51) used a slow motion film to estimate that at a stroke rate of 21.8 strokes/minute it took 0.088s to immerse the blade. He speculated that at a greater rate the time might be half this. His rough calculation of the speed at which an oar would fall into the water under its own weight, showed that freefall would be far too slow in his estimation.

Dr. V. I. Kleshnev, a sport scientist formerly at the Australian Institute of Sport, has supplied data (personal communication) measured in a single scull, rowed by an elite male athlete, 196 cm (6′ 5″) tall weighing 88 kgs (194 lbs), rowing at a rate of 36.3 strokes/min. The average hull speed is $\overline{V} = 5$ m/s, which corresponds to a time of 1 min 40 seconds for 500 m. Similar data has been used by Kleshnev (2005) where a description of the experimental method can be found. The data includes a measurement of the oar angle in the vertical plane, from which we can determine the maximum vertically downwards angular acceleration of the oars before the catch as 8.8 rad/s^2 (right oar) and 11.2 rad/s^2 (left oar). Since these are significantly greater than the 5.5 rad/s^2 due to gravity alone[8], it is clear that the rower is actively lifting the handle at the catch, as Bourne (1925) had concluded was necessary.

Fig. 2 shows Kleshnev's data for the oar horizontal (sweep) angle, as a function of time over one cycle, and also the path of the oar-blade in the vertical plane near the catch (distance forward of square and height above water). The cycle time is

[6]By system speed we mean the speed of the centre of mass of the entire system consisting of hull, oars and rower. The centre of mass is the point where the entire system could, in theory, be balanced on a single trestle. We speak of the speed of the system, rather than the hull, because it is the entire system which must be moved from start to finish line. The rower in sliding-seat rowing is not fixed in position in the hull and therefore the centre of mass of the system moves within the hull. Over one cycle the average hull speed is equal to the average centre-of-mass speed. Of course, since a race is over when the bow crosses the finish line, there is one instance, on the last stroke of a race only, when the hull speed, rather than the centre of mass speed, may be significant. The hull might shoot forward, as the rower moves sternwards, at just the right moment to win a very close race.

[7]For example: 'To effect a clean blade entry into the water, the hands should allow the weight of the oar to raise the handle [...]' (Redgrave 1995, p. 60)

[8]Considering the oar to be a uniform diameter pole of mass $m = 2$ kg and overall length $L = 288$ cm, with an in-board length of 88 cm, the distance of the oar's centre of mass from the gate is $r = L/2 - 0.88$ $= 56$ cm. The mass moment-of-inertia for rotation about the gate is $I_g = mL^2/12 + mr^2 = 2$ kg m^2. The gravity force (acceleration due to gravity $g = 9.8$ m/s^2) applies a turning moment about the gate of $mgr \approx$ 11 kg m^2/s^2 and the angular acceleration is $mgr/I_g = 11/2 \approx 5.5$ rad/s^2.

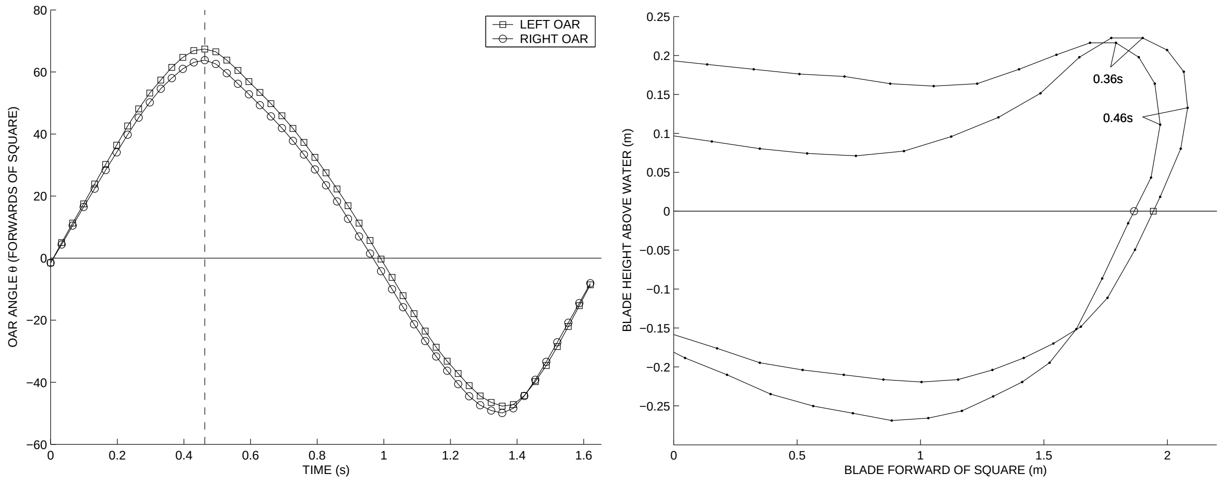

Figure 2: Left: Variation of bow-ward oar angle θ (over one cycle time $\tau = 1.65$s). Zero point for time axis is when the oars are nearly square to the hull during the recovery. Maximum θ occurs at $t \approx 0.46$s (vertical dashed line). Right: Path of blade relative to boat near catch. The blades begin moving vertically downwards towards the water at $t \approx 0.36$s. The approximate point of first contact of blade with water (height zero) is shown as $\circ$ (right oar) and $\square$ (left oar).

$\tau = 60/36.3 = 1.65$ seconds. Fifty data points were taken in each cycle (and averaged over many cycles). The time resolution of the data is $1.65\text{s}/50 \approx 0.03$s. The zero point for the time axis is set to the moment when the oars are close to square to the hull, while the rower is sliding sternwards during the recovery. At $t = 0.46$s the rotation of the oars changes direction (*i.e.* this is the moment when the rotational speed of each oar was measured as zero just before the catch). The blades make maximum angles forward of the square position of 67° (left oar) and 64° (right oar).

The path of the oar blade was calculated from the measured oar angles in the horizontal and vertical planes, and the distance from the gate to the mid-point of the blade. Because of a possible slight rocking of the hull from side to side the gates/pivots of each oar are not necessarily at the same heights above the water at the catch as was assumed when the oar vertical angles were calibrated. Hence where the calculated blade path shown in Fig. 2 (right) crosses the zero height line is not an accurate indication of the moment of first contact of the blade with the water. We can use Kleshnev's measurement of oar bending to get a better estimate of the moment of first contact, which we will refer to as the moment of catch. When the blade first touches the water, a reaction force from the water is exerted on the blade and bending strains develop in the oar shaft.

2.1 Row-in angle and delay time

Here we estimate what we will call the delay time t_d and the row-in angle ϕ_r. The row-in angle is the angle swept through the air by the oar between the moment it changes direction relative to the hull (the turn-around) and the moment of catch. The delay time is the corresponding time required for the oar to sweep through this

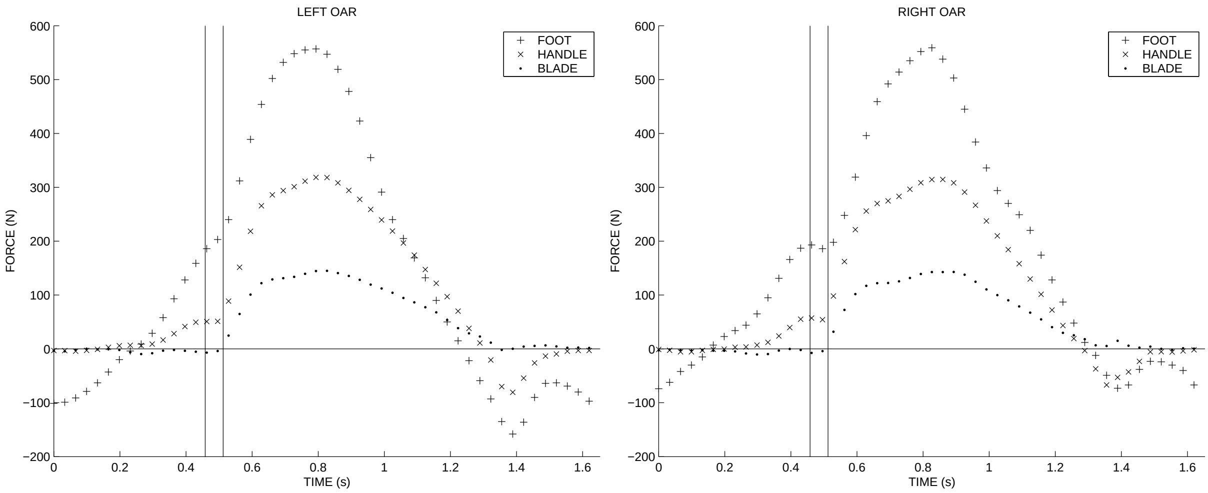

Figure 3: The measured foot force, and handle and blade forces on the oar calculated from the measured bending, over the cycle. The first vertical line (at $t = 0.46$s) shows the moment when the oar changes direction at the catch, and second vertical line (at $t = 0.51$s) indicates the estimated first contact of the blade with the water. The difference is the delay time $t_d \approx 0.05$s, during which the oars are being rowed through the air.

angle. This delay can be seen in the oar-bending and foot-stretcher force[9] data which Dr. Kleshnev has supplied, which can be converted to a force on the handle and a force on the blade. As shown in the Appendix, the linear and rotational inertia of the oar must be taken in to account when calculating the handle force and blade force which give rise to the measured bending of the oar. As a result, the handle and blade forces are not given by constant multiples of the measured bending strains; the rotational inertia of the oar is significant just before the catch and at the release when the oar undergoes significant angular acceleration.

These forces over the cycle are shown in Fig. 3. There is a delay after the moment of maximum reach, before the blade forces increase above zero between $t = 0.50$s and $t = 0.53$s. We therefore estimate the moment of contact (for both oars) as midway between these times at $t = 0.51 \pm 0.16$s. The estimated error (± 0.16s) is merely half the time resolution of Kleshnev's data. The delay time for both oars is thus

$$t_d = 0.51s - 0.46s = 0.05s \pm 30\%.$$

The estimated error is rather large at 30% because the delay time is not much larger than the time resolution of the data. The oar angles at this moment (the catch angles θ_c) are 63° for the left oar and 61° for the right oar. The row-in angles are

$$\phi_r = 67^\circ - 63^\circ = 4^\circ \quad \text{(left oar)}, \quad \phi_r = 64^\circ - 61^\circ = 3^\circ \quad \text{(right oar)}.$$

[9]The rower faces the stern, and the soles of the feet apply pressure to the hull in the sternwards direction. The inclined 'foot plates' are fixed to the hull by a load bearing cross beam known as the foot-stretcher. Kleshnev measured the force applied by each foot of the rower to the foot-stretcher.

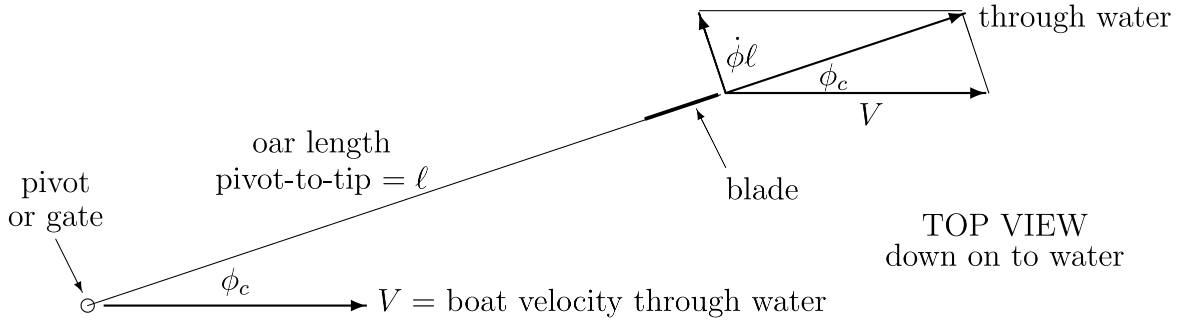

Figure 4: The velocity of the oar/blade tip relative to the water, at the catch, is the sum of two velocities: the forward motion of the boat relative to the water V and the sideways motion of the tip (in the direction 90° to the blade face). The latter has a magnitude of $\dot{\phi}\ell$, where $\dot{\phi}$ is the rotational speed of the oar and ℓ is the distance from the pivot to the tip. The resultant blade tip velocity is the diagonal of the 'parallelogram of velocities' as shown. To slice cleanly into the water without generating a pressure force on either side of the blade, the blade tip velocity must be parallel to the oar shaft, as shown, giving $\dot{\phi}\ell = V \sin \phi_c$.

3 Blade motion relative to the water

There is no indication in Fig. 3 of a significant back-splash force (a negative blade force) from the moment of turn-around to the moment of first contact. To determine whether the sculler under consideration would be expected to cause back-splash at the catch, we calculate the oar rotational speed required to prevent back-splash. Fig. 4 shows a plan view looking down on the oar, at the moment the blade tip enters the water. It is convenient to define the angle $\phi_c = 90° - \theta_c$ which the oar makes with the forward direction of the boat at the catch. To avoid back-splash entirely, the blade tip velocity must be parallel to the oar shaft as it enters the water, so that the blade is instantaneously moving through the water in a direction parallel to the face of the blade. Of course, the thickness of the blade, as well as the curvature of the blade in the horizontal plane, will displace some water on both sides of the blade but this would produce small but approximately equal and opposite sideways forces on the blade. An oar entering the water with the velocity shown in Fig. 4 should produce what Richardson (2005) describes as the correct entry. Thus

> Correct entry at the catch creates a splash which is a perfect V [...] Too much backsplash means the blade entry is checking the boat run [...] No backsplash means the blade has moved toward the stern before entering the water [...] (Richardson 2005, p. 159)

It should be noted however, that if there is no back-splash then the oar has rotated horizontally (around the gate-pin) up to *at least the minimum angular velocity necessary to avoid checking the hull with the blade.* This minimum angular velocity[10] of the oar, required to prevent back-splash is

$$\dot{\phi}_m = \frac{V}{\ell} \sin \phi_c. \tag{1}$$

[10]The rate of change of oar angle ϕ is called the rotational speed or 'angular velocity' (radians/second or rad/s) and is denoted by $\dot{\phi}$. The rate of change of angular velocity (rate of change of $\dot{\phi}$) is the angular acceleration (radians/second/second or rad/s^2) and is denoted by $\ddot{\phi}$.

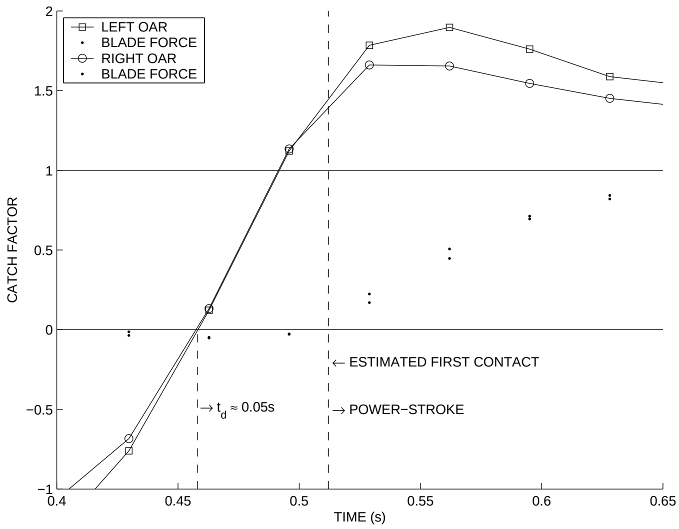

Figure 5: The 'catch-factor' $C = \dot{\phi}/\dot{\phi}_m = \dot{\phi}\ell/\left(V\cos\phi\right)$ for both oars. $C = 0$ when the oar changes rotational direction. At $C = 1$, *i.e.* $\dot{\phi} = (V/\ell)\sin\phi$, the blade could enter the water without producing a net back-splash force. The blade force is shown to an arbitrary scale. The moment of first contact (at $t \approx 0.51$s), occurs when $C \approx 1.43$. The oar has been 'rowed-in' for a time of approximately 0.05s.

We define the ratio $\dot{\phi}/\dot{\phi}_m$ as the 'catch factor'

$$C = \frac{\dot{\phi}}{\dot{\phi}_m} = \frac{\dot{\phi}\ell}{V\sin\phi}. \tag{2}$$

Note that V and ϕ, not just $\dot{\phi}$, vary with time. Fig. 5 shows the catch factor (*i.e.* a measure of the oar rotational speed) near the moment of catch. At the oar turn-around just before the catch, $C = 0$ (*i.e.* no rotational speed, $\dot{\phi} = 0$). For a catch factor $C = 1$, the oar is rotating at the minimum speed to enter the water cleanly. The moment of catch, at $t = 0.51$s, is indicated; this occurs at a catch factor of C ≈ 1.43. In other words the oar rotational speed is 43% greater than the minimum required to avoid checking the boat through back-splash. The blade force data (to an arbitrary scale) is superimposed on the figure, to emphasize that there is no significant checking (negative) force at the catch, and to show that the moment of first contact has been estimated as mid-way between two data points for the blade force, and is thus subject to the uncertainty of ±0.16s. If the moment of contact is as early as $t = 0.50$s, the catch factor would be $C \approx 1.13$, and if it is at late as $t = 0.53$s, the catch factor would be $C \approx 1.72$.

4 Row-in angle for smaller catch angles θ_c

For a given hull speed V and out-board oar length ℓ, the minimum required angular velocity $\dot{\phi}_m$ to avoid back-splash is increased for smaller values of θ_c. If we assume a constant angular acceleration $\ddot{\phi}$ of the oar from the moment of turn-around to the moment of catch we can estimate the delay time t_d as

$$t_d = \dot{\phi}_m / \ddot{\phi} \tag{3}$$

and the row-in angle ϕ_r as

$$\phi_r = \frac{1}{2}\dot{\phi}_m t_d = \frac{\dot{\phi}_m^2}{2\ddot{\phi}} \ . \tag{4}$$

The angular acceleration measured for the left oar of the scull was 25.2-22.4 rad/s^2 before the catch and 27.9-23.5 rad/s^2 for the right oar. We take $\ddot{\phi} = 24$ rad/s^2 as an estimate of the horizontal acceleration that this rower imparts to the oar in the air immediately before the catch. Thus we can estimate the minimum oar angular velocity required (Eq. 1) to avoid checking the hull through back-splash (*i.e.* to achieve a catch factor $C = 1$), and thus estimate the minimum delay time and row-in angle for different catch angles. These values are shown in the table below for catch angles θ_c of 65° to 45°.

catch angle		req'd angular vel.	req'd delay time	req'd row-in angle
θ_c	$\phi_c = \theta_c - 90°$	$\dot{\phi}_m = (V/\ell)\sin\phi_c$	$t_d = \dot{\phi}_m/\ddot{\phi}$	$\phi_r = \frac{1}{2}\dot{\phi}_m^2/\ddot{\phi}$
65°	25°	0.898 rad/s	0.037 s	0.96°
60°	30°	1.063 rad/s	0.044 s	1.34°
55°	35°	1.219 rad/s	0.051 s	1.77°
50°	40°	1.366 rad/s	0.057 s	2.24°
45°	45°	1.503 rad/s	0.063 s	2.70°

Table 1. From Eqs. 1, 3 and 4, with $V = 4.25$ m/s, $\ddot{\phi} = 24$ rad/s^2, $\ell = 2$ m.

The required row-in angle is nearly three times as large (2.70° *vs.* 0.96°) for a catch angle θ_c of only 45° compared to 65°, while the required delay time nearly doubles from 0.037s to 0.063s.

5 Estimated back-splash force

The fear of slowing the hull by applying any sternwards pressure on the foot-stretcher before the blade is engaged with the water looms large in the literature of rowing technique. For example

> No power should be applied to the [foot-] stretcher until the spoon [*i.e.* blade] is covered [*i.e.* fully immersed]. If power is applied earlier than this, it will cause the boat to slow because the power being applied to the [foot-] stretcher is trying to force the boat backwards. (Redgrave 1995, p. 61)

So great is this fear that some books encourage the rower to achieve back-splash at the catch as a sign that the rower has moved the blade vertically (relative to the hull) into the water at the point of maximum reach. In some cases it is even proposed that the blade should be travelling forward relative to the hull as it enters the water. For example

> ... As the athlete approaches full extension the handle moves up, bringing the blade down toward the water. The blade is still travelling toward the bow as it begins to enter the water. (Richardson 2005, p. 157)

If in fact, the horizontal motion of the blade (relative to the hull) could be arrested long enough for the blade to enter the water while moving only downwards relative to the hull, the blade will be moving forward over the water with the hull speed, at an angle of attack to the oncoming water of ϕ (the angle between the oar shaft and the forward direction). We can estimate the force, for unit area of blade, on the back surface of the blade as it hits the water as

$$P_D = C_D \times \frac{1}{2}\rho V^2$$

where $\rho = 1000$ kg/m^3 is the density of water, V is the hull speed through the water and C_D is the drag coefficient for this angle of attack. For the case of the sculler considered above, $V = 4.53$ m/s, and the dynamic pressure is $\frac{1}{2}\rho V^2 \approx 10.3$ kPa (105 g/cm^2). The drag coefficient for a flat plate immersed so its top edge is level with the water surface has been measured by Caplan and Gardner (2005). The angle of attack is $\phi \approx 25°$ for which the measured drag coefficient was $C_D \approx 0.5$. The force/unit area of the blade is $P_D = 0.5 \times 10.3 = 5.1$ kPa (53 g/cm^2) acting in the sternwards direction.

Since many elite rowers tend to hold the oar handle loosely just before the catch, this pressure would probably set the oar in motion relative to the boat and hence relieve the pressure somewhat. Nevertheless if only one fifth part of the blade area of 46cm $\times$ 20cm, entered the water while this pressure was acting, the back-splash drag force would be 94 N (9.6 kgs) per blade. From the blade force data, we can calculate the propulsive impulsive of the forward component of the blade force for one oar, over the entire cycle as

$$\overline{B \sin \phi} \tau \approx 64\text{Ns},$$

where the $\overline{B \sin \phi}$ is the average forward propulsive force over the entire cycle. If we assume that the back-splash drag force acted for as little as 0.03 seconds, the negative impulse would be $94N \times 0.03s = 2.8$Ns, which represents a loss of almost 4.4% of the propulsive impulse. The propulsive impulse must balance the negative impulse of the drag force (which is proportional to $\overline{V}^2$) and the fractional loss of average boat speed would be half the fractional loss of impulse[11], or 2.2%. This corresponds to approximately 44m over a 2000m race, which is significant.

If such a back-splash force were generated by Kleshnev's single sculler for 0.03s seconds, it would show up in the blade force as something like the dashed line shown in Fig. 6. It is clear that no such negative force appears in the actual data. All the data shows consistently that the rower has, in fact, accelerated the oar to a speed where there is no back-splash, *i.e.* the elite sculler has in fact 'rowed the oar in'.

6 Discussion

From the path of the blade in the vertical plane shown in Fig. 2 (right) we can see that the rower has started to lift the handle to bring the blade down towards the water at least 0.1s before the oar reaches its extreme position at the turn-around.

[11]Let the impulse be $I \approx a\overline{V}^2$, where a is a constant. We have $\delta I = \frac{dI}{d\overline{V}}\delta\overline{V} = 2a\overline{V}\delta\overline{V}$ and $\delta I/I = 2a\overline{V}\delta\overline{V}/\left(a\overline{V}^2\right) = 2\delta\overline{V}/\overline{V}$.

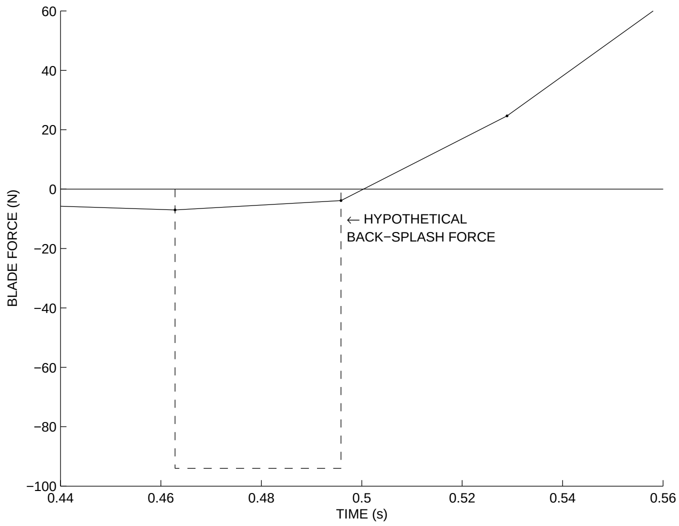

Figure 6: A section of the blade force history near the catch for the right oar of the scull. The dashed line shows the hypothetical back-splash force acting on 1/5 of the blade area, for a time of 0.03s.

Nevertheless he takes another 0.05s after the turn-around before making contact with the water, and rows the oars through the air for three or four degrees of arc. It seems unlikely that this elite rower could not achieve back-splash if he wanted to. We do not know if this rower is aiming consciously to avoid back-splash by his rowing-in action. It might be that he is aiming for a quick catch, which many coaches recommend, and has instinctively adjusted his motion to avoid back-splash; the feel of nearly 10 kgs of back-splash force (magnified to about 20 kgs at the handle) would probably provide enough negative feedback to teach the body to avoid it.

The motivation for the advice of achieving back-splash is frequently said to be to avoid any backwards foot-force on the hull while the blade is not engaged in the water, or to reduce it to a minimum. Fig. 3 shows that the foot-force increases long before the catch as the rower's motion (on the sliding seat) towards the stern is stopped and reversed. Note also that the handle force is greater than zero before the catch; the handle is pulling on the rower's hand as the legs decelerate the rower. That is, the oar has inertia which must be overcome by the decelerating force, which is transmitted to the handle by the arms acting as 'tie-ropes'. If one waits for the maximum extension of the blade towards the bow, and then tries to lower the blade instantly into the water, without drawing the hands closer to the body, and without opening the angle between the upper body and the legs, the leg force which is already acting before the turn-around will accelerate the blade sternwards as it descends to the water, *i.e.* the leg force will row the oar in even if the rower is careful not to increase this force until the oar is engaged with the water.

Many rowers do in fact seem to achieve back-splash and some may have actually lifted their hands so early as to make the oar hit the water before the turn around, *i.e.* with the blade moving towards the bow. It may well be sensible, as a rower's skill develops, to ask the rower to aim for a quick entry of the oar into the water and to increase the leg force only when the oar makes contact with the water; a quick entry allows the propulsion force to be generated for a longer fraction of the cycle.

But it seems perverse that rowers be told to produce back-splash, something which many will instinctively feel is wrong[12].

To avoid the braking effect of back-splash the oar must be rowed through the air by some minimum amount. We do not consider that this needs to be actively coached (except in an effort to 'unlearn' back-splash); it just comes instinctively. The larger the catch angle, the shorter the time, and the smaller the movement of the oar, that are required to avoid back-splash. We believe this is a major benefit of the large catch angle.

Acknowledgement

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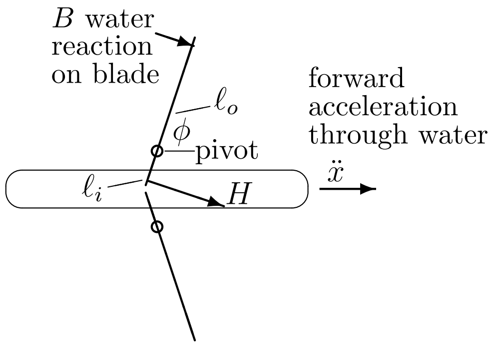
[12] An example of intuitive knowledge of this sort of problem was given to us by a seventeen year old boy. Skate-board riders sometimes propel themselves by pushing on the ground with the finger tips. Every skate-boarder knows that the hands must be moving backwards relative to the board before the fingers make contact with the ground. No skate-boarder lowers the fingertips vertically downwards (relative to the board) and waits until contact is made before moving the hands backwards. One could sit on the skate-board and 'row' backwards and the same principle applies – the hands must be moving relative to the board as ground contact is made, and the addition of a sliding seat to the skate-board would make no difference to this principle.

Appendix: Equations of motion for rotating oar



The component of water force on the blade (normal to the oar) is B, acting at a distance ℓ_o from the pivot. The component of handle force normal to oar shaft is H at distance ℓ_i from the pivot. Each force is applied a little way from the oar tips.

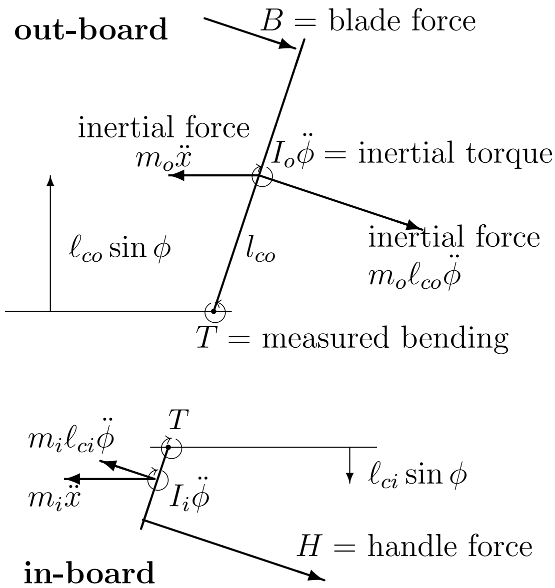


Figure 7: Schematic view of the hull and oars (left figure), and free-body diagrams of one oar (right figure). The free-body diagrams show 'inertial' torques and forces acting. Force components parallel to the oar shaft, and forces at the pivot are not shown.

Dr. V. I. Kleshnev has measured the bending strain in the oars as well as the hull acceleration $\ddot{x}$ and the variation of oar angle ϕ with time, from which the angular acceleration $\ddot{\phi}$ of the oar can be determined. A rowing boat and oars are shown schematically in plan view in Fig. 7. The pivots of the oars ('the gates') are rigidly attached to the hull by some rigging which is not shown. The 'free-body' diagrams of each section of one oar are also shown. The oar shaft is 'cut' just on the in-board side of the pivot, where the bending torque T is measured. Forces acting at the gate (pivot-point) are not shown. Components of the blade and handle force parallel to the oar shaft are omitted. The centre of mass of the out-board portion of the oar is located a distance ℓ_{co} and that of the in-board oar at a distance ℓ_{ci} from the gate. All distances ℓ are measured along the oar shaft. The out-board oar mass is m_o and in-board oar mass is m_i.

The inertial forces and torques acting on the centre of mass have been shown in each free-body diagram. The inertial force on the outer oar can be divided into two parts. One of magnitude $m_o\ddot{x}$ is the reaction against the linear acceleration of the hull and gate. The other, of magnitude $m_o\ell_{co}\ddot{\phi}$, is the reaction against the angular acceleration of the oar. There is also an inertial moment $I_o\ddot{\phi}$, opposing the angular rotation, where I_o is the mass moment of inertia of the outboard portion of the oar (about its centre).

We denote the torque (or moment) applied to the out-board oar, about the gate, by the blade force as B_t. It is given by

$$B_t = B\ell_o. \qquad (5)$$

The sum of the moments (torques) taken about the gate is zero. Thus

$$\begin{aligned} 0 &= B_t + I_o\ddot{\phi} + m_o\ell_{co}\ddot{\phi}\ell_{co} - m_o\ddot{x}\ell_{co}\sin\theta - T \\ B_t &= T + (m_o\ell_{co}\sin\phi)\,\ddot{x} - \left(I_o + m_o\ell_{co}^2\right)\ddot{\phi}. \end{aligned} \quad (6)$$

Similarly, the handle force applies a moment

$$H_t = H\ell_i \quad (7)$$

to the in-board oar and we have

$$\begin{aligned} 0 &= H_t - I_i\ddot{\theta} - m_i\ell_{ci}\ddot{\phi}\ell_{ci} - m_i\ddot{x}\ell_{ci}\sin\phi - T \\ H_t &= T + (m_i\ell_{ci}\sin\phi)\,\ddot{x} + \left(I_i + m_i\ell_{ci}^2\right)\ddot{\phi}. \end{aligned} \quad (8)$$

Note that for a static oar, or for an oar with negligible inertia, these reduce to the simple 'lever arm' rule,

$$H_t = B_t = T$$

which gives the handle force as $H = T/\ell_i$ and the blade force as $B = (\ell_i/\ell_o)\,H$.

Kleshnev's sculler used an oar with an overall length of 2.88m. It measured about 0.88m from the handle-tip to the centre of the gate. The estimated dynamical properties of this oar are shown in the table below. The distances ℓ_i and ℓ_o are from the gate to the assumed centres of pressure of the handle force and blade force.

In-board side		Out-board side	
ℓ_i (m)	0.82	ℓ_o (m)	1.77
m_i (kg)	0.61	m_o (kg)	1.39
ℓ_{ci} (m)	0.44	ℓ_{co} (m)	1.00
I_i (kg m^2)	0.039	I_o (kg m^2)	0.463
$I_i + m_i l_{ci}^2$ (kg m^2)	0.158	$I_o + m_o\ell_{co}^2$ (kg m^2)	1.852

The inertial terms (those depending on $\ddot{x}$ and $\ddot{\phi}$) are found to be practically negligible for the in-board part of the oar, but not for the out-board part.

Strictly speaking, these equations apply only if the oar is rotating in a single plane, as when the oar is drawn through the water at approximately a constant depth, with the top of the blade just below or level with the water surface. When the oar is rotating in the vertical plane to move the blade in and out of the water, or rotating round its long axis to feather or square the blade, extra terms (the so called 'gyroscopic' terms) must be included. These terms depend on a detailed calculation of the mass moments of inertia of the oar for rotation about different axes, and the rotation rate of the oar during feathering, which we do not know.

M. N. M.