A NEW MODEL OF ROWING BASED ON SIMPLE PHYSICS

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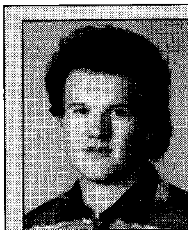
A formalism based on simple physics that predicts the variation in boat velocity throughout the rowing stroke is presented and is applicable to all classes of rowing. Predicted boat velocity-time profiles throughout the rowing stroke closely match experimental profiles in both shape and amplitude. The formalism also identifies a primary cause of boat deceleration at the start of the power phase (blade in the water) as a detrimental lever action of the oar. This detrimental lever action occurs when the net rowing force acts in an opposite direction to the intended direction of boat travel, irrespective of hydrodynamic drag contributions. The detrimental lever action is minimised if the line of action of the force applied to the oar-handle by the rower is maintained as parallel to the long-axis of the boat as possible, a finding consistent with current coaching strategies. For oar-handle forces applied at 10, 20, 30 and 40° to the long-axis of the boat, the lever system is predicted to operate detrimentally at catch angles above 67, 49, 35 and 27° respectively for an oar length of 3.4 m and rowlock-to-centre-of-hands length of 1 m. The findings provide additional quantified insight into observations and predictions made by other authors (e.g., Pope, 1973; Martin & Bernfield, 1980) and indicate that relatively large catch angles, e.g., 60 to 65°, may in some respects be detrimental to rowing performance.



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Introduction

Studies into the optimisation of rowing technique through modeling are of interest because of the many rowing techniques that have been used since the first documented regatta for oared boats held in 13th century Venice (Dodd, 1992). Dal Monte and Komor (1989) provide a comprehensive review of studies up to 1985. Sanderson and Martindale (1986), Millward (1987) and Brearley and de Mestre (1996, 1998) are more recent studies, all of which develop Newtonian ($\Sigma F = m \times a$) equations of motion by considering the forces acting on a rowing boat.

The model rowing equations presented by Sanderson and Martindale (1986) are solved analytically to investigate the effect of rower size and energy expenditure, while the rowing equations presented by Millward (1987) and Brearley and de Mestre (1996) are solved numerically to model known phenomena such as the variation in boat velocity throughout the rowing stroke. Brearley and de Mestre (1998) model steady state rowing conditions to study the effects of oar flexing.

The present study develops a model equation of rowing based on simple Newtonian physics but differs from the above-mentioned studies, particularly in its derived relationship between the force applied to the rowlock by the oar and the force applied by the feet to the boat, which are the two primary rower-generated forces that act on the boat. Of particular interest is the use of this model equation to provide insight into the cause of the known deceleration at the start of the power phase (blade in the water) and to suggest strategies to minimise this deceleration.

Theory

Power phase

This section briefly outlines the development of an equation of motion for all classes of rowing during the power phase of the rowing stroke.

The primary rower-generated, two-dimensional forces that act on the oar and boat during the power phase, in a plane parallel to the water surface, are respectively shown in Figures 1a and 1b.

The symbols used throughout the text that are associated with Figures 1a and 1b are defined as follows:

h = distance from the rowlock to the centre of the hands,

l = length of the oar from the centre of the blade to the centre of the hands,

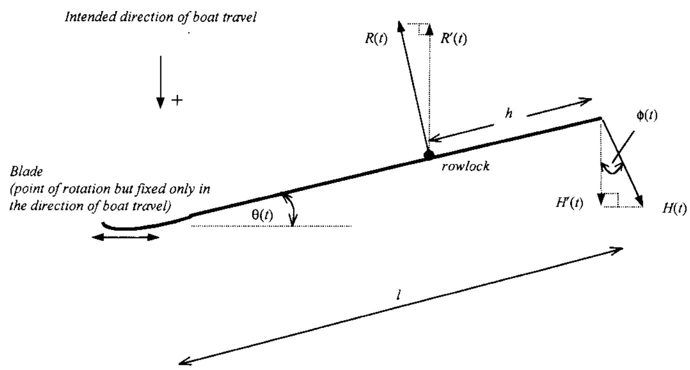

Figure 1a. The primary rower-generated, two-dimensional forces acting on the oar in a plane parallel to the water surface. H(t) is the force applied to the oar-handle and R(t) is the force applied by the rowlock to the oar.

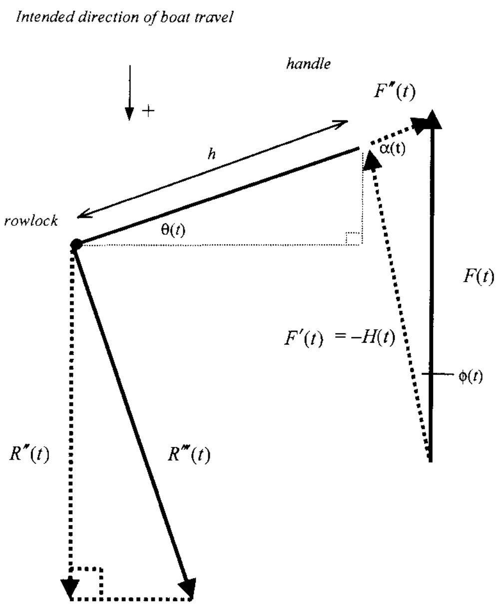

Figure 1b The primary rower-generated, two-dimensional forces acting on the boat in a plane parallel to the water surface. F(t) is the foot force and R‴(t) is the force applied by the oar to the rowlock. Shown is the relationship between H(t) and F(t).

t = time from the onset of the current power phase,

$\phi(t)$ = angle at which the oar-handle force is applied measured relative to the intended (positive) direction of boat travel ($|\phi(t)|$ is used within all equations),

ϕ_{catch}= initial and maximum value of $\phi(t)$,

$\theta(t)$ = angle made by the oar and a line perpendicular to the direction of boat travel ($|\theta(t)|$ is used within all equations and $\phi(t) \to$ zero as $\theta(t) \to$ zero is assumed),

θ_{catch} = initial and maximum value of $\theta(t)$,

$F(t)$ = force applied by the feet to the boat,

$F'(t)$ = component of $F(t)$ parallel to $H(t)$ (defined below),

$F''(t)$ = component of $F(t)$ parallel to the oar,

$H(t)$= force applied to the oar-handle at the centre of the hands $= -F'(t)$,

$H'(t)$= component of $H(t)$ in the positive direction of boat travel,

$R(t)$ = force applied by the rowlock (at a right-angle) to the oar,

$R'(t)$ = component of $R(t)$ in the negative direction of boat travel,

$R'''(t)$= force applied by the oar to the rowlock $= -R(t)$, and

$R''(t)$ = component of $R'''(t)$ in the positive direction of boat travel $= -R'(t)$.

Water reaction forces on the blade are not shown. The convention used is that $G(t)$ represents $\tilde{G}(t)$ or $|\tilde{G}(t)|$ in context, for any given vector, $\tilde{G}(t)$.

Assuming that the position of the blade remains fixed in the direction of boat travel establishes the following lever equation, with the blade as the point of rotation:

$$lH'(t) = -(l-h)R'(t). \tag{1}$$

Since the blade moves perpendicular to the direction of boat travel, only force components in the direction of boat travel are considered related through a lever relationship in establishing Equation 1. (Force components perpendicular to the direction of boat travel contribute to wasted effort and Celentano et al. (1974) show that as much as 22% of rowing effort may be wasted.)

Since $R'(t) = -R(t)\cos\theta(t)$ and $H'(t) = H(t)\cos\phi(t)$, Equation 1 may be written

$$H(t) = \frac{(l-h)}{l}\frac{R(t)\cos\theta(t)}{\cos\phi(t)}. \tag{2}$$

This approach whereby the blade is assumed fixed only in the direction of boat travel is given credence by the fact that if the blade is also assumed fixed perpendicular to the direction of boat travel, then Equation 2 would take the form

$$H(t) = \frac{(l-h)}{l}\frac{R(t)}{\cos(\theta(t)-\phi(t))}. \tag{3}$$

Equation 3 implies that it is advantageous for a rower to apply force on the oar-handle with a non-zero value of $\phi(t)$ which does not agree with practical rowing.

The assumption of a fixed blade in the direction of boat travel is ideal (Affeld et al., 1993). Supporting this assumption, Brearley and de Mestre (1996) observe only minor blade movement through the water. Martin and Bernfield (1980) also observe that deceleration of the boat due to relative motion (slipping) between the water and the blade is generally not evident, which lends confidence to the assumption of a fixed blade in the direction of boat travel. Additionally, any slipping of the blade is largely taken into account by Equation 2 since a loss in blade efficiency will manifest as changes in the (ideally) experimentally measured profiles of $R(t)$, $\theta(t)$ and $\phi(t)$.

$H(t)$ is ultimately generated by the rower pushing against the boat with force $F(t)$ which acts primarily through the feet in the negative direction of boat travel. $H(t)$ is therefore considered the effective reaction force of $F'(t)$, where $F'(t)$ and $F''(t)$ add vectorially to form $F(t)$ as shown in Figure 1b. For $H(t)$ to be the effective reaction force of $F'(t)$, $F''(t)$ must not produce torque about the rowlock which acts as a fixed point of rotation with the boat as the frame of reference. Hence, $F''(t)$ acts parallel to the oar and geometric considerations ($\alpha(t)=90°+\theta(t)-\phi(t)$ in Figure 1b) give the following equation for $F(t)$ as a function of $H(t)$:

$$F(t) = -H(t)\frac{\cos(\theta(t)-\phi(t))}{\cos\theta(t)} . \tag{4}$$

Combining Equations 2 and 4 now allows $F(t)$ to be expressed in terms of $R(t)$, $\theta(t)$, $\phi(t)$, l and h:

$$F(t) = \frac{(h-l)}{l}\frac{R(t)\cos(\theta(t)-\phi(t))}{\cos\phi(t)} . \tag{5}$$

The derived relationship between $F(t)$ and $R(t)$ in Equation 5 automatically accounts for the movement of the rowers during the power phase and therefore offers a simple alternative to other models of rowing (e.g., Pope, 1973; Sanderson & Martindale, 1986) where the analysis of rower movement is more complex. As is practically necessary, $F(t)$ increases with $\phi(t)$ for constant (non-zero) $\theta(t)$ and $R(t)$. Experimental evidence that also supports Equation 5 is discussed in the results.

$R''(t)$, the reaction (of $R'(t)$) force component, acts on the boat to promote motion in the positive direction of boat travel and is given by

$$R''(t) = R(t)\cos\theta(t) . \tag{6}$$

$R''(t)$ is referred to as a primary rowing force on the boat in the positive direction of travel rather than a force component for further discussion.

The final force that acts on the boat and which needs to be taken into account is hydrodynamic drag, $D=D(\rho,v,C_v,L,V,D_W)$. From established rowing literature (Pope, 1973; Dal Monte & Komor, 1989), D can be shown to be given by

$$D=\left(\tfrac{1}{2}\rho v^2 C_v\sqrt{2\pi L V}\right)+D_w , \tag{7a}$$

where ρ is the water density; v is the velocity of the boat relative to the water; C_v is a nondimensional viscous drag coefficient proportional to Reynolds number and dependent on the smoothness of the boat; $\sqrt{2\pi L V}$ is the wetted surface area of the boat where L is the boat length and V is the volume of water displaced by the boat; the bracketed term represents viscous drag; and D_w is the wave drag which is a function of Froude number. Also, since $V = m/\rho$, where m is the combined mass of the rowers, boat and oars, Equation 7a can be expressed in the following form which shows the dependency of D on m:

$$D=\tfrac{1}{2}v^2 C_v\sqrt{2\pi L m\rho}+D_w . \tag{7b}$$

D_w makes a relatively small contribution to Equation 7b and represents approximately 12 and 8% of D for single scull and eights respectively (Dal Monte & Komor, 1989). Although D_w exhibits a complex dependency on the shape of the boat, Pope (1973) shows that to a good approximation, D_w is proportional to v^2 and therefore accounts for D_w by the introduction of a multiplicative correction factor. Following this approach, D may be simplified to

$$D\approx\tfrac{1}{2}\zeta v^2 C_v\sqrt{2\pi L m\rho} , \tag{8}$$

where ζ is a factor ranging from 1.14 (single) to 1.08 (eights). The sign of D is implied within all hydrodynamic drag equations such that action is against the direction of boat motion. The effect of air drag is not included.

The expression for D may be further simplified by fitting a polynomial equation to resistance data obtained from towing tanks or pools with forced water flow, as is the approach by Millward (1987) and Brearley and de Mestre (1996). Based on such data, Millward models hydrodynamic drag on a single scull as the third-order polynomial D=-0.0672.v^3+3.67v^2 Wellicome (1967) measures drag as a function of velocity for three rowing boats. Combining the findings from the Millward and Wellicome studies with the results of a similarity analysis between classes of rowing boats (McMahon, 1971) allows coefficients a and b, for equations of the form

$$D\approx av^3+bv^2, \tag{9}$$

to be approximated for other classes of boats. Coefficients calculated for a range of rowing classes are given in Table 1 and are used to model D for the present study. The approximations made with respect to D and air drag are not critical for the present study since the primary aim, upon the development of a model equation of rowing, is to obtain a physical understanding of boat deceleration at the start of the power phase.

Table 1 Coefficients a and b for approximating hydrodynamic drag (D^a av^3+bv^2) for various boats.

Boat type	a ($N{\cdot}s^3{\cdot}m^{-3}$)	b ($N{\cdot}s^2{\cdot}m^{-2}$)
Single	-6.73×10^{-2}	3.67
Double	-1.01×10^{-1}	5.51
Fours	-1.61×10^{-1}	8.81
Eights	-2.35×10^{-1}	12.9

Incorporating the primary forces acting on the boat in the positive and negative directions of travel, $R''(t)$, $F(t)$ and D, given respectively by Equations 6, 5 and 9, into Newton s second law, $\Sigma F=m\times a$, generates the following differential equation of motion during the power phase of rowing for a total of N oars:

$$m\frac{dv}{dt}=NR(t)\left(\cos\theta(t)+\frac{(h-l)\cos(\theta(t)-\phi(t))}{l\cos\phi(t)}\right)-av^3-bv^2 . \tag{10}$$

Recovery phase

The theory used to describe the recovery phase assumes half-cycle sinusoidal motion of the rowers' displacement described by:

$$x = A\cos\left(\frac{\pi}{\tau_r}t_r\right), \quad (11)$$

where x is the displacement of the rowers relative to the centre sitting position, A is the amplitude of motion, τ_r is the duration of the recovery phase and t_r is the time from the onset of the recovery phase.

Differentiating Equation 11 twice to obtain the rowers acceleration and multiplying by —M, where M is the combined mass of the rowers, gives the reaction force exerted by the rowers on the boat throughout the recovery:

$$m\frac{dv}{dt} = \frac{M\pi^2 A}{\tau_r^2}\cos\left(\frac{\pi}{\tau_r}t_r\right) - av^3 - bv^2. \quad (12)$$

Examination of Equation 12 reveals that during the first half of the recovery, rower motion promotes boat movement in the positive direction of travel, whereas the opposite is true during the second half of the recovery.

Incorporating Equations 12 and 9 into $\Sigma F = m \times a$ generates the following differential equation of motion for the recovery phase:

$$F(t) = \frac{M\pi^2 A}{\tau_r^2}\cos\left(\frac{\pi}{\tau_r}t_r\right). \quad (13)$$

Equation 13 is the same as the recovery phase equation presented by Brearley and de Mestre (1996) except that Brearley and de Mestre use an alternative simplified expression for D.

Total rowing equation

Combining Equations 10 and 13 for the power and recovery phases respectively, yields the following equation for one complete rowing stroke:

$$m\frac{dv}{dt} = \delta_{power,\,n} NR(t)\left(\cos\theta(t) + \frac{(h-l)\cos(\theta(t)-\phi(t))}{l\cos\phi(t)}\right) + \delta_{recovery,\,n}\frac{M\pi^2 A}{\tau_r^2}\cos\left(\frac{\pi}{\tau_r}(t-\tau_p)\right) - av^3 - bv^2, \quad (14)$$

where n is the current phase (power or recovery) and τ_p is the duration of the power phase. The Kronecker delta, $\delta_{n',n}$, equals one or zero and simply turns a term on or off during a particular phase (i.e. $\delta_{n',n}$ = 1 and 0 for $n' = n$ and $n' \neq n$ respectively). Equation 14 is a differential equation that is easily solved to give v as a function of t using a fourth-order Runge-Kutta routine that is standard within software packages such as Matlab and ODE Architect.

Results and discussion

Boat velocity throughout the rowing stroke

The boat velocity throughout the rowing stroke for the first 11 strokes as predicted by Equation 14 for a coxless pair (2×95 kg rowers and 28 kg boat) is shown in Figure 2. Constant input parameters are A = 0.36 m, l = 3.4 m, h = 1 m, τ_p=0.9s and τ_r=1.2s (i.e., 28.6 strokes per minute). Time-varying inputs $R(t)$, $\theta(t)$ (θ_{catch} = 60°) and $\phi(t)$ (ϕ_{catch} = 20°) and calculated D profiles are shown in Figure 3. Input parameters are based on experimental data for a coxless pair at race-pace (Australian Institute of Sport (A.I.S.), 1995) and practical observations in

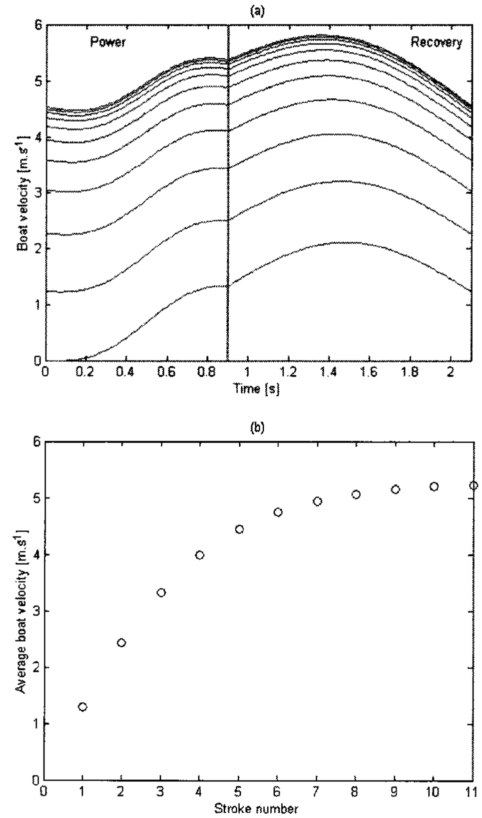

Figure 2 Simulation of the (a) instantaneous and (b) average boat velocity for the first 11 strokes for a coxless pair. τ_p = 0.9 s, τ_r = 1.2 s, rower mass = 95 kg, boat mass = 28 kg. The vertical line represents transition from power to recovery phase.

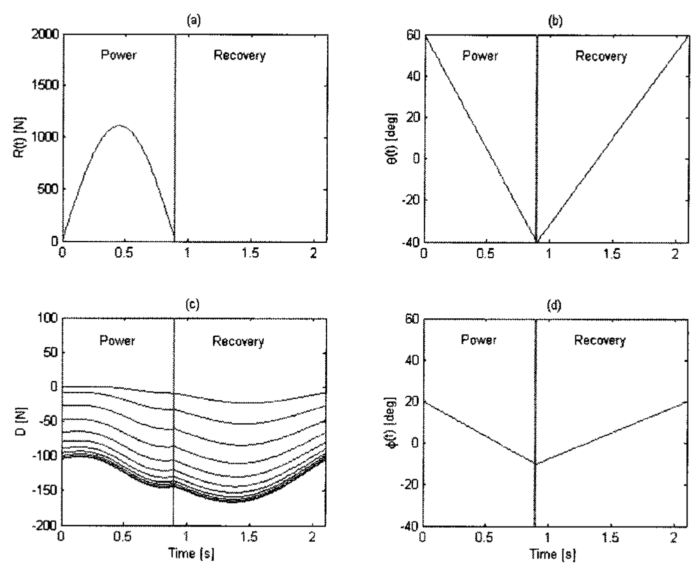

Figure 3 Time-varying inputs (a) R(t), (b) q(t) and (d) f(t), and (c) hydrodynamic drag, $D \approx \Delta(\rho, v, C_V, L, V, D_w)$ for the simulation in Figure 2.

the case of $\phi(t)$. For the purpose of the present study, $R(t)$ is modeled as a half-cycle sinusoid. However, Equation 14 readily accepts actual $R(t)$ profiles.

The calculated average boat velocity in Figure 2b converges to 5.27 $m \cdot s^{-1}$ which supports the validity of the model (5.36 $m \cdot s^{-1}$ is the current world championship first place average boat velocity for heavy-weight men).

Figure 4 shows the calculated average boat velocity throughout the first 11 strokes for other classes of rowing (single scull, double scull, quads and eights) based on minimum rower and boat masses for heavy-weight men as specified by the International Rowing Federation (F.I.S.A.). The manner in which the calculated attained average boat velocities increase through the above-mentioned rowing classes also validates the model (5.1, 5.6, 6.0 and 6.3 $m \cdot s^{-1}$ are respective current world championship first place average boat velocities).

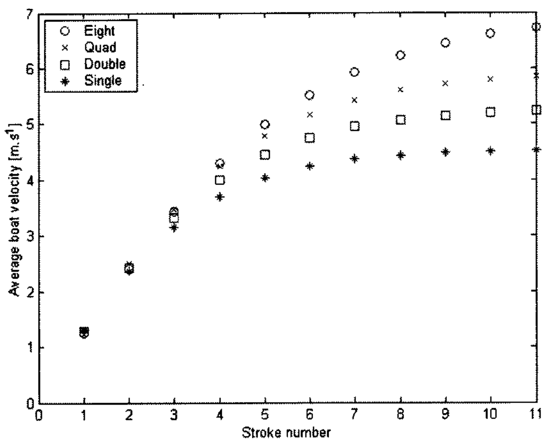

Figure 4 Average boat velocity calculated for the first 11 strokes for single scull, double scull, quad and eight.

The shape of the boat velocity-time profiles in Figure 2a closely matches the experimental measurements for a single scull (Affeld et al., 1990) and an Olympic eight-person crew (Martin and Bernfield, 1980). The minimum in the calculated velocity-time profile for the 11th stroke (in particular) demonstrates deceleration of the boat at the start of the power phase. The position of this minimum is dependent on rowing style (see Martin and Bernfield for an explanation of the shape of the profile).

Effect of θ(t) and ϕ(t) on the resultant rowing force

We are interested in the condition under which the resultant rowing force in the direction of boat travel, $R''(t)+F(t)+D$, is negative. The model predicts a negative resultant rowing force when

$$NR(t)\cos\theta(t) \ < \ NR(t)\frac{(l-h)\cos\big(\theta(t)-\phi(t)\big)}{l\cos\phi(t)} + av^3 + bv^2 \, . \quad (15)$$

From Equation 15, the critical value of $\theta(t)$ for which the oar lever system undergoes a transition from the production of a

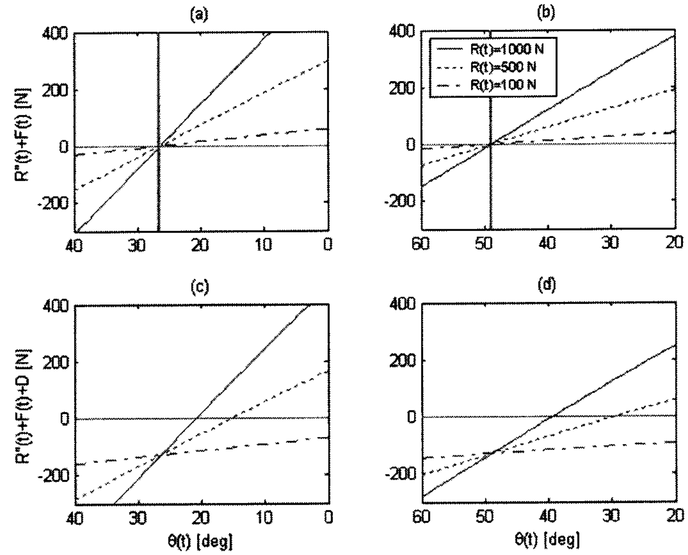

Figure 5 The effect of θ(t), on the resultant rowing force, R''(t)+F(t)+D, for constant R(t) of 100, 500 and 1000 N. R''(t) is the force applied to the rowlock in the direction of boat travel. Results are shown for ϕ(t) set to (a) 40° and (b) 20° in the absence of D, and (c) 40° and (d) 20° with D. The x-intercepts identified in (a) and (b) are critical oar angles.

negative to a positive resultant rowing force may be calculated for selected constant values of $\phi(t)$, $R(t)$ and D. Figures 5a and 5b show resultant rowing force transitions for $\phi(t)$ set to 40 and 20° respectively and $R(t)$ set to 100, 500 and 1000 N in the absence of D.

Figures 5a and 5b demonstrate that $\theta(t)$ values above 27 and 49° produce negative resultant rowing forces, irrespective of D, for $\phi(t)$ = 40 and 20° respectively, a condition we call detrimental operation of the oar lever system. Critical $\theta(t)$ values for other $\phi(t)$ values are given in Table 2. The results in Table 2 highlight the importance of maintaining $\phi(t)$ as parallel to the long-axis of the boat as possible, as advocated by current coaching practices. When D is set to 130 N (corresponding to = 5.2 $m \cdot s^{-1}$) it dominates the $R(t)$ = 100 N curves in Figures 5c and 5d, demonstrating that once the oar lever system ceases to operate detrimentally, it is important to attain a large rowlock force to counter the effects of D, a finding consistent with observed $R(t)$ profiles.

Hence, the model identifies a primary cause of boat deceleration at the start of the power phase as a detrimental action (as distinct from a less efficient action which also causes deceler-

Table 2 Critical θ(t) for various values of ϕ(t) for l = 3.4 m and h = 1 m. If θ(t) is greater than the critical θ(t) a negative resultant rowing force occurs irrespective of hydrodynamic drag contributions.

$\phi(t)$ (degrees)	Critical $\theta(t)$ (degrees)
0	-
10	67
20	49
30	35
40	27

ation) of the oar lever system. This finding provides additional insight into the three causes given by Martin and Bernfield (1980). Furthermore, the model predicts that this detrimental lever action may be avoided by a reduction in θ_{catch}, which will in turn reduce ϕ_{catch}. Supporting this prediction is the fact that Rowing Australia (1997) recommend θ_{catch} values of between 45 and 55° for sweep oar rowing and 55 to 60° for sculls and these values are lower than those observed for some rowers (e.g., 60 to 65°). Also, though not advocating a general reduction in θ_{catch}, Sanderson and Martindale (1986) state that the range of oar motion is reduced for scullers with comparatively fast sprints, while Pope (1973) shows that if the stroke is shortened as a consequence of increasing the stroke frequency, then θ_{catch} should be reduced rather than the oar angle at the start of the recovery phase.

Note that changes in technique that involve a reduction in θ_{catch} may require a subsequent increase in stroke frequency and are also limited by other interdependent factors such as the ease of blade placement in the water. For a shortened slide forward, the position of the footrests may also need adjustment to allow maximum leg drive and this may have practical limitations in terms of boat rigging and balance. Moving the rowlocks slightly forward in relation to the rowers is another strategy to counter the detrimental lever action of the oar since this will reduce θ_{catch} and ϕ_{catch}.

Figure 6 further supports the validity of the model by showing the variation in $R''(t)$, $-F(t)$ and $R''(t)+F(t)$ for time-varying $R(t)$, $\theta(t)$ and $\phi(t)$, as per Figure 3, for ϕ_{catch} values of 10, 20, 30 and 40°. The calculated $F(t)$ profiles are similar to the experimental measurements of Loschner and Smith (2000) by the manner in which the profiles follow $R''(t)$. $F(t)$ profiles (not shown) calculated for A.I.S. (1995) experimental $R(t)$ profiles closely match the measurements of Loschner and Smith in a similar manner. Loschner and Smith show that $-F(t)$ in practice may exceed $R''(t)$ at the start of the power phase (a phenomenon associated with boat deceleration) and this ϕ_{catch}-dependent characteristic is also displayed in Figure 6 by regions to the left of the vertical lines in (a) to (c). Additionally, in Figure 6 when $\phi(t)$ is zero (ideal for efficient rowing), $-F(t)/R''(t)$ is predicted by Equations 5 and 6 to equal $(l-h)/l = 0.70$. Supporting this predicted value, Loschner and Smith measure $-F(t)/R''(t)$ to be 0.69 ± 0.10 (mean ± SD) at the point of peak force production for six instrumented rowlocks and footrests.

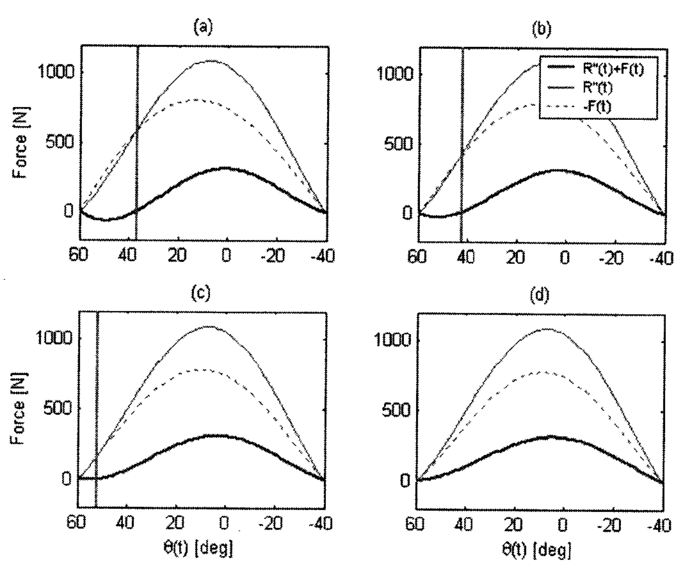

Figure 6 $R''(t)$, $-F(t)$ and the resultant rowing force in the absence of D, R≤(t)+F(t), during the power phase for ϕ_{catch} of (a) 40°, (b) 30°, (c) 20° and (d) 10°. R≤(t)+F(t) is negative to the left of the vertical lines.

Effect of oar dimensions on boat velocity

Though not the primary topic of investigation for the present study, the effect that changes in l and h have on $-F(t)/R''(t)$ during the power phase is of interest. Figure 7 shows that $-F(t)/R''(t) = (l-h)/l$ is minimised by a decrease in l and an increase in h. However, although the minimisation of this ratio in one respect represents efficiency, the use of a relatively short l and long h by a rower will not necessarily increase boat velocity, since such dimensional changes have an interdependency on factors such as stroke length, stroke frequency and $R''(t)+F(t)+D$. For example, a decrease in l and an increase in h will decrease the stroke length, which may have a detrimental effect on the boat velocity if the range of oar motion and stroke frequency remain constant. Hence, the effect of oar dimensions on the resultant rowing force and boat velocity remains a topic for future research.

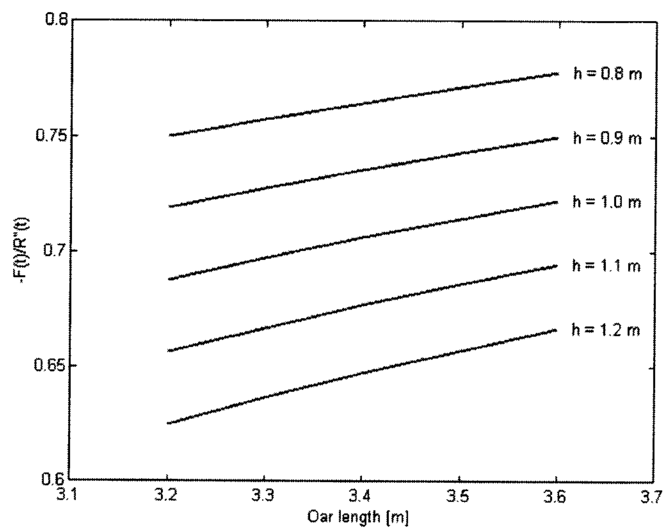

Figure 7 Ratio of $-F(t)$ to $R''(t)$, calculated for $\theta(t) = \phi(t) = 0$ for various values of oar length, l, and rowlock-to-centre-of-hands length, h.

Effect of R(t) and rowing power on boat velocity

The model predicts an increase in average boat velocity if a rower decreases power in the early stages of the stroke, hence reducing the contribution from the forward-most rowing position where the lever action can be detrimental, and increases power when the oar lever system operates more efficiently. This result is displayed by Figure 8 which compares calculated boat velocity-time profiles for the first stroke for $R(t)$ modeled on a sine function (as per Figure 3a) and a sine-squared

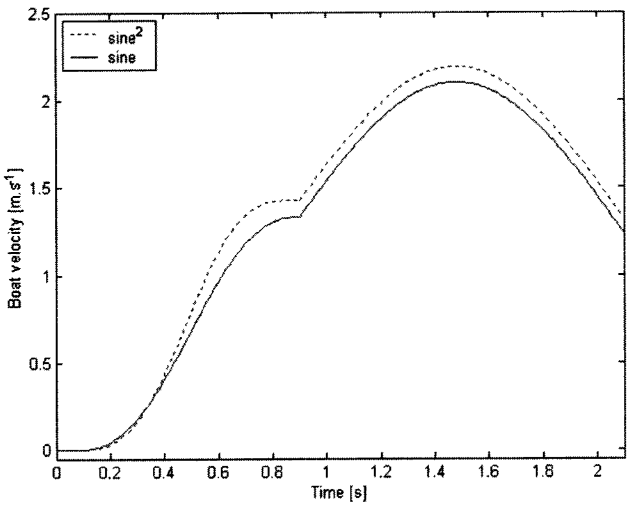

Figure 8 First-stroke velocity profiles for R(t) based on sine and sine-squared functions with the same impulse.

function with the same area (impulse). The sine-squared-based profiles for all strokes converges to an average velocity of 5.47 m·s^{-1} (3.8% higher than for the sine case).

Hence, Figure 8 highlights that the shape of $R(t)$ can be just as important as the amplitude of $R(t)$, a result consistent with the findings of Martin and Bernfield (1980) and Millward (1987).

Limitations

The physical model presented has some limitations, namely (i) the model is two-dimensional and does not consider out-of-plane forces that can significantly contribute to wasted rower effort (Celentano et al., 1974); (ii) a simplified expression for D that does not allow for variations in the combined rower and boat mass within each class is used for calculations, (iii) the blade is assumed fixed in the direction of boat travel throughout the power phase; and (iv) the use of half-cycle sinusoidal modeling of rower motion. However, these limitations do not alter the principal findings associated with the mechanics of the oar lever system throughout the power phase.

Future research idea for consideration

A possible research concept generated by the findings of the present study is the development of a rowlock system that moves laterally throughout the rowing stroke so that the oar moves continuously towards and away from the boat as the magnitude of $\theta(t)$ increases and decreases respectively, thereby minimising $\phi(t)$ at all times.

Conclusion

This study presents a simple mathematical formalism that predicts boat velocity-time profiles that closely match experimental profiles in shape and amplitude and identifies a primary cause of boat deceleration at the start of the power phase as the detrimental operation of the oar lever system. For oar-handle forces applied at 10, 20, 30 and 40… to the long-axis of the boat, the lever system is predicted to detrimentally operate for θ_{catch} values above 67, 49, 35 and 27… respectively for h = 1 m and l = 3.4 m.

To counter this detrimental action of the oar lever system, it is recommended that a rower apply the oar-handle force as parallel to the long-axis of the boat as possible. The detrimental action may also be countered if θ_{catch} is reduced with a subsequent increase in the stroke frequency and adjustment of the foot rests to enable maximum leg drive. However, these changes are likely to affect interdependent factors such as the ease of blade placement in the water, boat balance and rigging requirements. Another suggested counter-strategy is to move the rowlocks slightly forward in relation to the rowers.

It is also recommended that a rower apply minimal rowing force when the oar operates in a region defined as detrimental. Once the oar lever system is no longer detrimentally operating, it is recommended that a rower then attain a large rowlock force to overcome the effects of hydrodynamic drag. Although a number of limitations are identified for the model presented, these limitations do not alter the above conclusions and recommendations.

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