

# Biomechanics feedback for rowing

RICHARD M. SMITH<sup>1\*</sup> and CONSTANZE LOSCHNER<sup>2</sup>

<sup>1</sup>School of Exercise and Sport Science, Faculty of Health Sciences, The University of Sydney and

<sup>2</sup>New South Wales Institute of Sport, Sydney, Australia

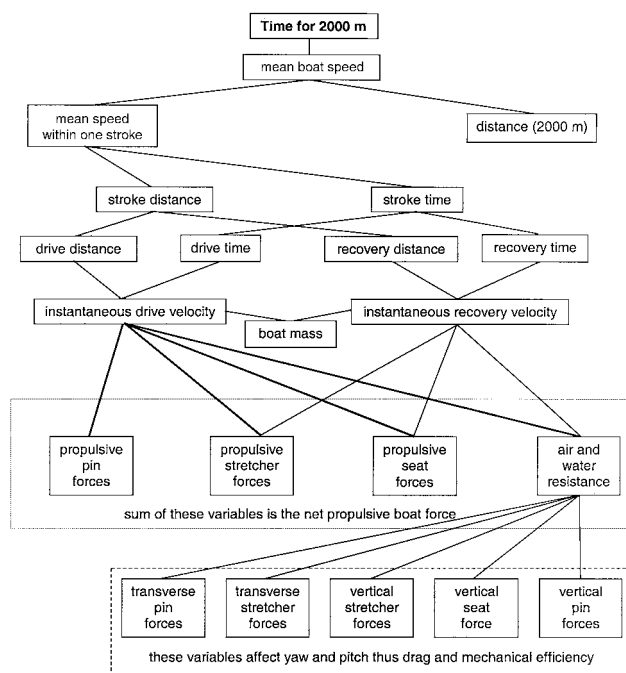
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Factors that affect boat speed are important determinants of rowing performance and should form the basis of feedback to rowers and their coaches. Biomechanical analysis of rowing has led to variables that are causally linked to boat speed. With modern technology, these variables can be measured and feedback can be presented instantaneously on-water, or be presented simultaneously with video after the event. This paper demonstrates the links between the criterion of success in rowing, the time for completing 2000 m and the forces acting on the boat, and describes an instrumentation system for providing feedback of these variables to rowers and coaches. These feedback techniques have been used with rowers from national to Olympic competition standard. Aspects of technique have been linked to the determinants of boat speed and several examples are presented here. The motor learning literature supports the effectiveness of kinetic information feedback for the improvement of motor skill and provides a relevant conceptual framework for the improvement of rowing performance. However, although rowers and their coaches value this feedback, further research must be undertaken to establish a sound basis for comparing the effectiveness of such feedback compared with traditional styles, such as verbal feedback of performance.

*Keywords:* biomechanics, feedback, motor learning, rowing, sculling.

## Introduction

Success in competitive rowing is achieved by taking the shortest time to complete a 2000 m course. This time is mathematically linked to the average speed of the boat. Thus, factors that affect boat speed are important determinants of rowing performance and should form the basis of feedback to rowers and their coaches. A biomechanical analysis of rowing (Korner and Schwanitz, 1987) revealed key variables that determine the speed of the boat (Fig. 1). Following the breakdown of variables from top to bottom in this figure leads to the forces that affect boat speed: propulsive pin (rowlock) forces, propulsive stretcher (foot plate) forces, and water and air resistance. The sum of these is the net boat force. Water resistance will also be affected more indirectly by unbalanced transverse and vertical pin, stretcher and seat forces, as these affect the attitude of the boat and thus the cross-sectional area and skin surface area presented by the boat to the water. These unbalanced



**Fig. 1.** Biomechanical analysis of boat motion showing the dependence of time to 2000 m on measurable variables.

\* Address all correspondence to Richard Smith, School of Exercise and Sport Science, The University of Sydney, PO Box 170, Lidcombe, NSW 1825, Australia. e-mail: r.smith@cchs.usyd.edu.au

forces are also implicated in energy loss through wave creation. Factors that rowers can manipulate are the magnitude and timing of forces on the oar handles, seat and stretcher and the coordination of body segment motion. The oar handle force, in turn, affects the pin force through the lever and hydrodynamic system of the oar. Overall performance then depends on the rower's fitness and ability to optimize the application of forces. Feedback about the application of those forces should play an important role in the optimization process.

Rowing is a periodic movement that begins with the catch, then the drive phase, the finish, the recovery phase and back to the catch. The catch involves placing the blade of the oar in the water, ready for the build up of force. The muscle actions that extend the ankle, knee, hip and lumbar joints and flex the shoulder, elbow and wrist joints control the drive phase which follows the catch. The finish is defined by the removal of the blade from the water. The recovery phase is the return of the rower from the body-extended position of the finish to the flexed posture of the catch. This combination of actions, once optimized, must be repeated as precisely as possible for more than 200 strokes during the competition. Competent rowing, then, requires good stroke-to-stroke consistency.

The learning of any motor skill requires some information feedback, which, in conjunction with practice, is one of the most important elements of motor learning (Newell, 1976; Salmoni *et al.*, 1984). Information feedback is used to modify performance so that particular motor behaviours can be achieved for specified performance objectives. Almost any valid feedback will improve the performance of a novice rower. The elite rower, however, will require very accurate information for the detection of errors in a performance that is already proficient. This feedback can be intrinsic or extrinsic; the latter can consist of knowledge of results or knowledge of performance. Knowledge of results allows performers to examine their efforts in relation to an externally defined goal. However, such information feedback provides only goal-related information and ignores knowledge of performance, which is information about how the action was completed (Newell and Walter, 1981). Furthermore, Newell and Walter (1981) maintained that the provision of kinetic information feedback is preferable to mere knowledge of results and that feedback should occur as soon after performance as possible. There is growing support for the use of force and position information feedback to facilitate the acquisition and optimization of motor skills (Newell *et al.*, 1985; McLean and Lafortune, 1988; Broker *et al.*, 1993). In particular, Spinks and Smith (1994) used a template and concurrent visual feedback of the force on the handle and angular position of the handle of a

rowing ergometer to investigate whether such feedback could improve the consistency of the rowing performance. The results of their study indicated that, at least for ergometer rowing: (1) concurrent visual feedback may be used to modify patterns of work output during maximal rowing and to enhance maximal rowing performance; (2) there is biomechanical support for the even pace race strategy in competitive rowing; and (3) examination of the force-angle profile may allow coaches to identify those biomechanical factors which limit rowing performance.

The dynamical systems perspective on motor learning provides a relevant conceptual framework for the improvement of rowing performance. This perspective emphasizes the interaction of the learner with the biomechanical parameters of the motion – the forces and resulting kinematics. The learner relates to the laws of nature so they can be used to create the required organization for a closer approach to the movement goal. The learning process is an exploration of 'perceptual-motor work space' (Newell *et al.*, 1989). The implementation of these ideas involves providing the motor experiences that allow the learner scope for exploration (novice athletes) and the opportunity for using highly specific information for refinement of movement (elite athletes). Thus, sports scientists and coaches aim to provide accurate perceptual information that can guide the learner towards optimal movement states.

The measurement of force and position information about the rower and boat provides a unique opportunity for high-quality augmented feedback, including concurrent visual feedback. A more quantitative classification of rowing styles may be based on an analysis of the shape of the torques or forces generated by the rower on the oar handle or the oarlock (Dal Monte and Komor, 1988). The information provided by oar torque or force analysis is important for the evaluation of rowing technique and crew selection (Angst, 1984; Angst *et al.*, 1985; Gerber *et al.*, 1985). Advances in computer technology and electronics have allowed the development of sophisticated computer-aided measurement systems for on-water assessment of rowing capacity and skill (Gerber *et al.*, 1985; Bachev *et al.*, 1989; Christov *et al.*, 1989; Duchesnes *et al.*, 1989; Smith *et al.*, 1994).

As one of the main propulsive units, the torques or forces applied to the oar by the rower had been the biomechanical focus until a few years ago. Many technique variables can be illustrated by the force-angle profile (Fig. 2). Simple and portable technology, which can be mounted on any oar and boat, can be used to measure force on the oar and angle of the oar. Most of these systems measure the bending strain in the oar that is a consequence of the normal oar force only. A significant force, which also has a propulsive com-

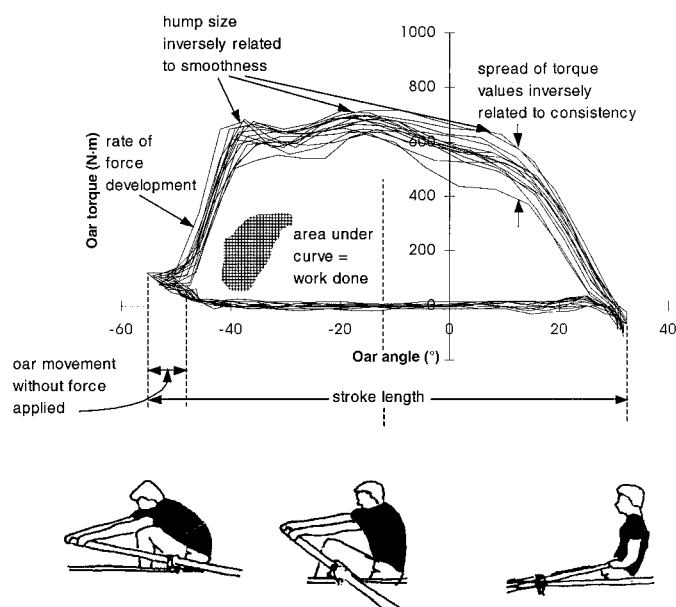


Fig. 2. Torque-angle profile of a club rower.

ponent, is transmitted along the long axis of the oar to the pin. Furthermore, these simple systems do not measure another important variable, the stretcher force. Significant mechanical interface problems have to be solved to measure accurately pin and stretcher forces and the portability of the solution is reduced. However, all the forces that have a significant effect on boat speed must be measured or deduced in an instrumentation system designed for comprehensive feedback.

The aim of this study was to provide examples of how useful biomechanical feedback can be obtained from a system that measures all the forces that have a significant effect on boat speed. Available technology presented a choice between a system that could be mounted on any boat and a system that would be dedicated to a measurement boat. The requirement of portability for the first option led to decreased accuracy and less information. The permanent instrumentation of a single scull (a one-person boat with two oars) and a pair (a two-person boat with one oar per person) was found to be the best compromise. This allowed us to test all scullers and sweep-oar rowers. Examples of performance feedback from both boats are given below.

## Methods

### Participants

The participants who provided the case study results reported here were drawn from elite and sub-elite rowers training with the New South Wales Institute of Sport. Each rower was required to row for 250 m at

20, 24, 28 and 32 strokes  $\cdot$  min<sup>-1</sup> and at race pace in windless conditions on an Olympic standard rowing course.

### Instrumentation

A single scull and pair boat were instrumented with sensors that measured important performance variables. Pin force data were sensed using three-dimensional piezoelectric transducers (Kistler, Switzerland). The pin was mounted on the rigger and was the axis of rotation for the gate or rowlock that holds the oar. Only the boat propulsive force was recorded from the stretcher or footplate with two shear-beam load cells [Applied Measurement, Australia (single scull); Transducer Techniques, USA (pair)]. The vertical and horizontal oar angles were measured by low-friction potentiometers and a fibreglass arm attached to the inboard end of the oar so that the oar was free to rotate around its longitudinal axis. A magnetic turbine, pick-up coil and frequency-to-voltage converter were used to track boat speed, including intra-stroke fluctuations. Three accelerometers (Analog Devices, USA) and three gyroscopes (Murata, Japan) sensed the acceleration and orientation of the boat along and around the three axes of the boat. Seat position was measured with a cable and drum potentiometer (Aerospace Technologies). All variables were sampled at 100 Hz and the data were telemetered (pocketLAB, Digital Effects) to a shore-based receiver and laptop computer (4700CT, Toshiba) that streamed the data to disk while displaying the results in graphical formats in real time chosen by the

coach. The results presented on the laptop screen could be simultaneously superimposed on video of the rower. On the boat, the transmitter transferred the same data through a serial link to two palmtop computers mounted over the stretcher within easy viewing distance of the rower. The palmtops could be programmed to display the same graphical information as the coach's laptop.

After collection, the data were loaded into analysis software and a sequence of strokes was selected for which all variables were time-normalized and -averaged. A written report was generated with tables of discrete variables and plots of the important variables against time and oar angle. Efficiency-related variables such as the ratio of boat speed to rower power output were reported.

### Modelling

The forces and moments acting on the boats were considered in the horizontal plane only (Figs 3 and 4). The propulsive forces acting on the boat were the stroke and bow pin forces ( $F_{propulsive}^{stroke\ pin}$ ,  $F_{propulsive}^{bow\ pin}$ ), the stretcher force ( $F_{propulsive}^{stretcher}$ ), the seat force ( $F_{propulsive}^{seat}$ ) and the fluid resistive forces ( $F_{propulsive}^{air\ resistance}$ ,  $F_{propulsive}^{water}$ ) (equation 1). The rolling resistance of the seat wheels was not measured in this experiment and the propulsive seat force was considered to be zero. The transverse forces acting on the boat were the pin forces ( $F_{transverse}^{stroke\ pin}$ ,  $F_{transverse}^{bow\ pin}$ ) (equation 2). We assume that the rowers achieved balance in the transverse forces they applied to the boat. Therefore, the transverse water resistive forces acting on the boat were assumed to have a net value of zero and were not included in the free body diagram or the equation. Equation (3) describes the effect of the sum of the moments acting on the boat. In the case of the pair boat, the stretcher force is the sum of the bow rower's stretcher force and the stroke rower's stretcher force (Fig. 4). Whereas  $d_{transverse\ moment\ arm}^{stroke\ pin}$  and  $d_{transverse\ moment\ arm}^{bow\ pin}$  are the same for the single scull (Fig. 3), they are different in the pair boat because of the different seating arrangement (Fig. 5).

The horizontal plane equations of motion for a single scull and pair boat are as follows:

$$m^{boat} a_{propulsive}^{boat} = F_{propulsive}^{stroke\ pin} + F_{propulsive}^{bow\ pin} + F_{propulsive}^{seat} + F_{propulsive}^{stretcher} - (F_{propulsive}^{air\ resistance} + F_{propulsive}^{water}) \quad (1)$$

$$m^{boat} a_{transverse}^{boat} = F_{transverse}^{stroke\ pin} + F_{transverse}^{bow\ pin} \quad (2)$$

$$I_z^{boat} \alpha = F_{propulsive}^{bow\ pin} \times d_{propulsive\ moment\ arm}^{bow\ pin} - F_{propulsive}^{stroke\ pin} \times d_{propulsive\ moment\ arm}^{stroke\ pin} + F_{transverse}^{bow\ pin} \times d_{transverse\ moment\ arm}^{bow\ pin} - F_{transverse}^{stroke\ pin} \times d_{transverse\ moment\ arm}^{stroke\ pin} - M_z^{water\ reaction} \quad (3)$$

## Results and discussion

The integrated system, known as Rowsys2, provided concurrent visual feedback to the rower. The coach was able to make suggestions about the required change in pattern of force development or boat behaviour, and both rower and coach could observe whether the change had been made. The rower was able to associate the objective information with his or her own proprioception. Furthermore, the data were saved to disk and a report was available for further feedback and discussion after the test session. This report contained derived variables such as power and a partial sum of boat forces that were not available in real time.

### Examples from single sculling and pair rowing

The first example compares skilled and unskilled male heavyweight pair rowers. The overall pattern of pin propulsive force development, for both pairs of rowers (Fig. 5), was as expected with force rapidly increasing soon after the catch and decreasing towards the finish. Little force was evident during the recovery phase. The main difference between the two pairs of rowers was in the timing of the forces. For the skilled pair, the stroke rower reached peak force earlier than the bow person after applying a greater force than the bow rower between 10 and 20% of the stroke. Subsequently, the bow rower applied a greater force than the stroke rower up to the finish. The opposite was the case for the unskilled pair. The skilled pair compensated for the unbalanced moment that would arise in a pair if the applied forces had the same magnitude and timing. The unskilled pair did not.

To understand this in more detail, consider the direction and application point of the pair pin forces in the horizontal plane at about 10% of the complete stroke (Fig. 4). If the distances of the two pins from the centre line of the boat were the same for bow and stroke, the moment arms for the two propulsive forces would be equal. If the magnitudes of the forces were the same, those forces would cause equal but opposite moments about the centre of mass of the boat. The net moment caused by the propulsive forces would be zero. However, the transverse pin forces both caused anti-clockwise moments. If we assume that the transverse seat and stretcher forces were negligibly small, a net anti-clockwise moment would have been caused by the pin forces (equation 3). In the second half of the drive phase, when the transverse forces on the pins changed from inwards to outwards, the same argument would apply but the net moment would be reversed. However, to avoid this, the stroke rower should develop their propulsive force first, followed by the bow rower as in Fig. 5a. Feedback of the relative timing and magnitude

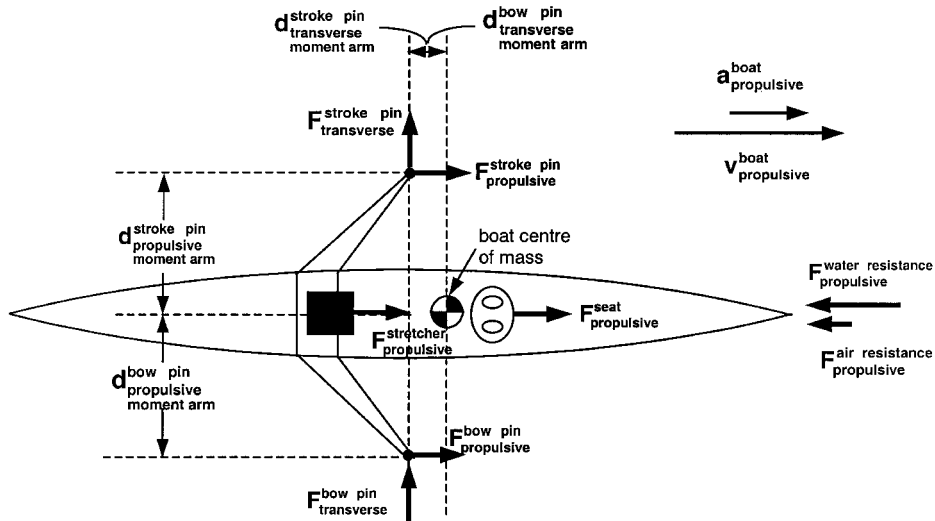


Fig. 3. Free body diagram of the single scull.

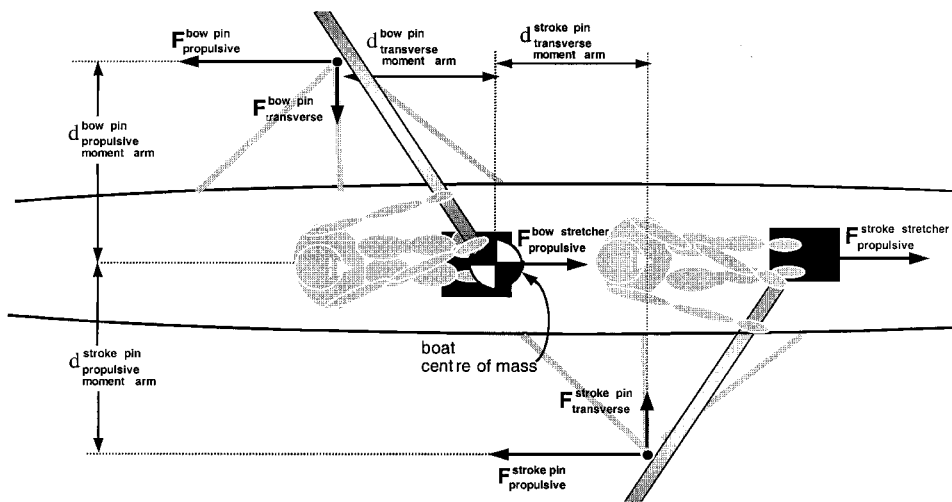


Fig. 4. Pin and stretcher forces acting on a pair boat and their moment arms about the boat centre of mass in the horizontal plane.

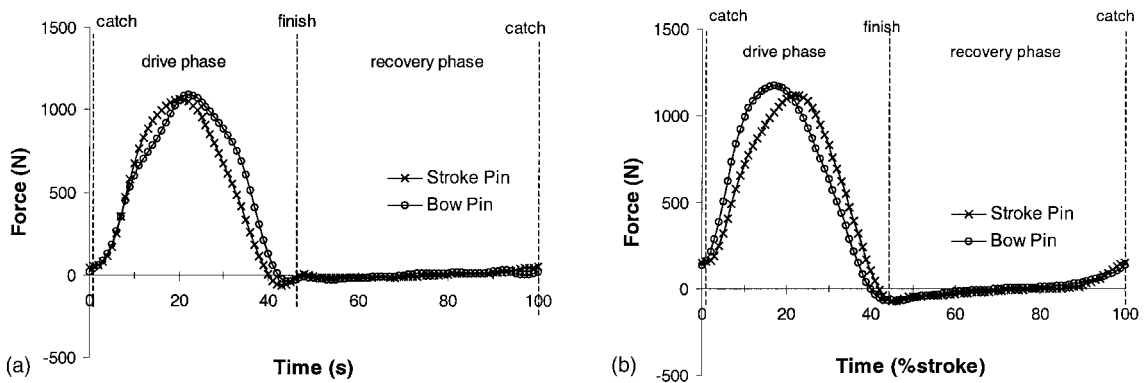


Fig. 5. Relative timing between the stroke and bow pin propulsive forces in a pair for skilled (a) and less skilled (b) rowers. The curves are time-normalized and averaged data for 12 consecutive strokes at  $30\text{ strokes} \cdot \text{min}^{-1}$ .

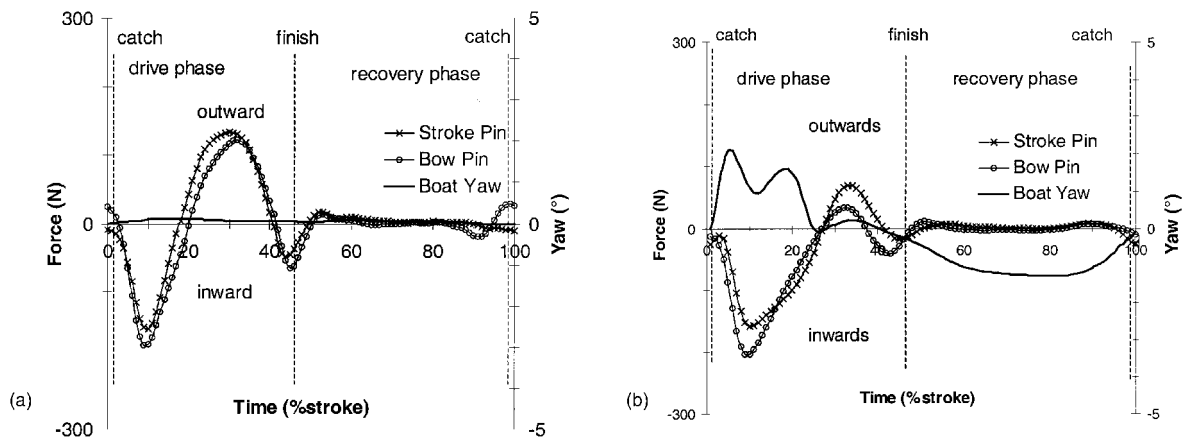


Fig. 6. Transverse force as a function of percent of stroke for pairs of skilled (a) and unskilled (b) rowers.

of the pin forces in a pair boat can help pair rowers optimize their force application to minimize unbalanced moments on the boat about a vertical axis that would cause yaw and high water drag.

Figure 4 demonstrates how the transverse force alternates from an inwards-directed force in the first part of the drive phase to an outwards-directed force in the second part of the drive phase. Timing differences were observed between pairs (a) and (b) for the transverse forces (Fig. 6) as well as for the propulsive forces illustrated in Fig. 5. The effect of inappropriate timing of the propulsive and transverse forces on the yaw (rotation about a vertical axis) of the boat by pair (b) was to move the boat up to  $2^\circ$  off course. This would require a correction using the steering mechanism of the boat and increase the drag of the water on the boat. If this pair of rowers swapped seat positions, it is possible they would row more effectively.

A further implication of the transverse force is that the oar handle force must also have a transverse component. As the oar handle displacement also has a transverse component, energy is absorbed that is not used for propulsion. This is a consequence of having a lever system for propulsion. The ratio of propulsive to total energy expenditure by the rower at the oar handle is a component of the mechanical efficiency equation for rowing and is different for different rowers.

Pair (a) exerted an upwards force on the boat immediately at the catch (Fig. 7) and a downwards force towards the finish. The pin supported the weight of the oar during recovery. The vertical force is influenced by the pitch of the oar blade and can be used to assess whether the blade is pitched correctly.

Results from biomechanical testing of a world junior women's champion single sculler illustrated propulsive pin and stretcher forces and their combined action on the boat (Figs 8 and 9). Both pin and stretcher forces

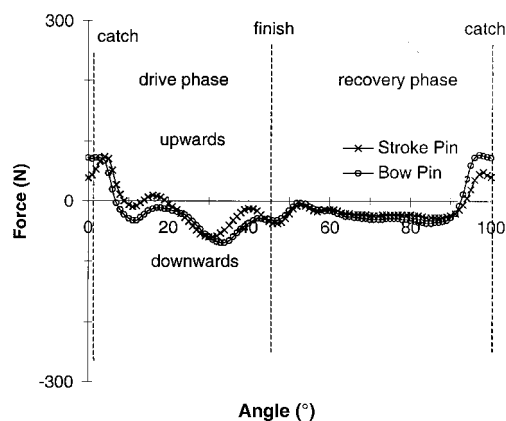


Fig. 7. Vertical pin force for the same skilled rowers as in Figs 5 and 6.

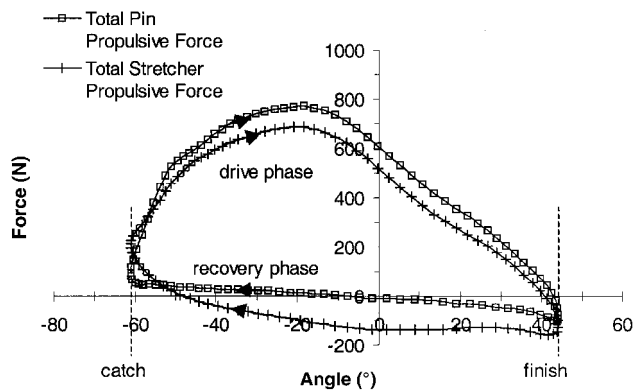
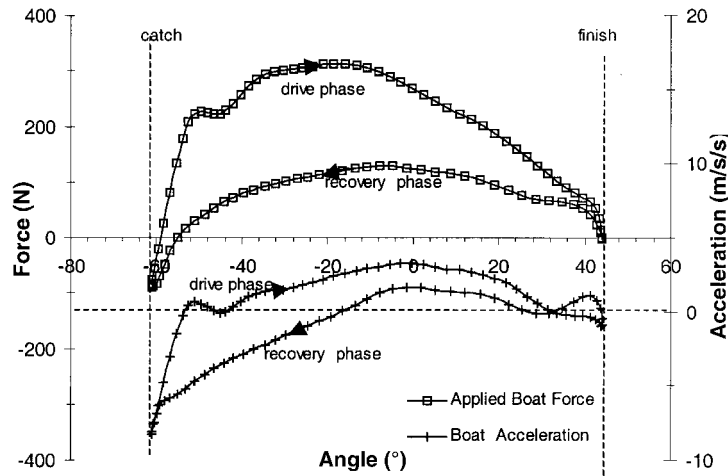


Fig. 8. The sum of the stroke and bow pin forces and the sum of the stretcher propulsive forces as a function of oar angle. The sign of the stretcher force has been reversed to make the comparison between the two forces more obvious. The rower was the world junior women's champion single sculler. The stroke rate was  $30 \text{ strokes} \cdot \text{min}^{-1}$  and the results shown are for the average of 15 strokes.



**Fig. 9.** The applied boat force (the sum of the propulsive pin and stretcher forces) and the boat propulsive acceleration for the world junior women's champion single sculler versus oar angle.

are shown in Fig. 8 with the same sign for easier comparison. During the drive phase, the pin forces exceeded the stretcher forces except for a few degrees each side of the catch. It is during those few degrees before and after the catch that the rower's body mass must be accelerated towards the bow of the boat as the body flexes and then extends. In the recovery phase, the stretcher force has significant magnitude and can be equal to or greater than the drag force (equation 1), thus maintaining boat speed or even accelerating the boat.

These propulsive pin and stretcher forces are shown combined in Fig. 8, together with boat propulsive acceleration. The magnitude of the applied force was in line with the results of Korner and Schwanitz (1987: 91). The acceleration should reflect the net boat force, whereas the sum of the propulsive pin and stretcher forces does not include air and water resistance. The seat is assumed to exert no force in the propulsive direction. The seat is mounted on wheels, which, in reality, would have some rolling resistance.

Deductions can be made about rowing technique through observation of seat speed. The ischial tuberosities remain in contact with the seat throughout the rowing cycle. The motion of the head, arms, thighs and trunk will be closely related to seat motion. Thus, to a first approximation, seat motion could be taken to represent the motion of a significant proportion of the rower's body mass. The advantage of making this assumption is that the effect of the rower's technique on energy or momentum exchange can be approximated. During the drive phase, kinetic energy is stored in the rower's body as it is accelerated towards the bow of the boat. During the recovery phase, this kinetic energy can be returned to the boat through the stretcher forces (Zatsiorski and Yakunin, 1991). Overall mechanical energy expenditure is minimized if the fluctuations in

boat speed are minimized. During the recovery phase, the rower has some control over fluctuations in boat speed through the stretcher force. Accelerating the body segments towards the stern of the boat in the recovery phase requires a reaction force on the stretcher. To maintain a constant boat speed, a constant reaction force is required to balance exactly the drag force of the water and air on the boat. Using the model outlined above, a seat speed that increased steadily towards the stern would provide such a reaction force. An example of two different recovery techniques follows.

The seat of sculler A remained stationary (Fig. 10) from the finish of the drive phase until about 65% of the stroke. She then accelerated down the slide until 85% of the stroke, whereafter she decelerated. The effect of this motion on the speed of the boat was to cause a peak velocity at 85% of the stroke. Sculler B began her acceleration down the slide at 62% of the stroke and continued this steady acceleration until 90% of the stroke. The effect was to produce a more constant speed over the recovery phase and a delayed decrease of boat speed.

There is more to performance than minimizing fluctuations in boat speed, for example a high average boat speed. Furthermore, using the seat speed relative to the boat has at least two major shortcomings. First, the seat could be stationary, but the head, arms and trunk could be moving with significant acceleration through flexion or extension at the hip joint. Secondly, the acceleration should be measured from an inertial frame of reference. This can be achieved by adding the boat speed relative to the water to the seat speed. Seat speed revealed the beginning and end of leg extension and flexion, showing how the rowers coordinated their power output.

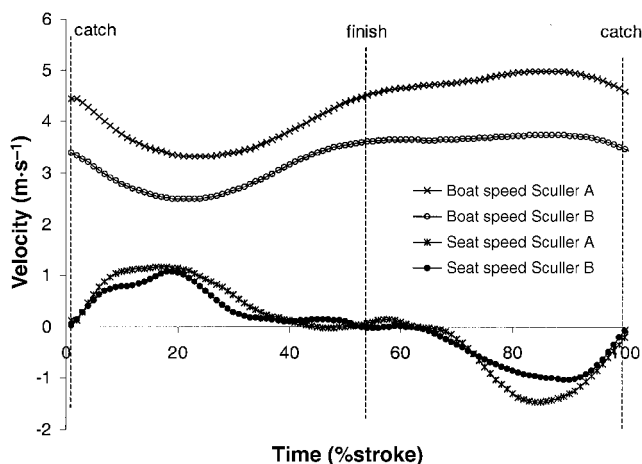


Fig. 10. Boat and seat speed for two single scullers with different recovery styles. Seat speed is relative to the boat.

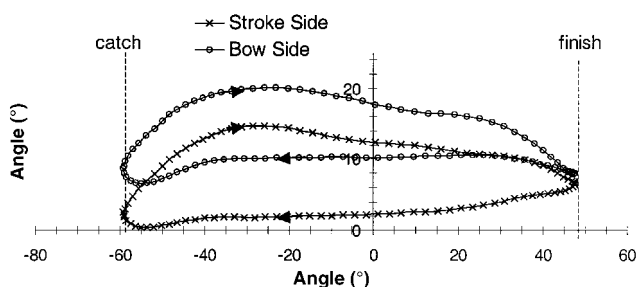


Fig. 11. Hand curves for the stroke and bow side of a single sculler. The horizontal axis is the horizontal oar angle and the vertical axis is the vertical oar angle.

The last example of information provided by the Rowsys2 system is the hand curve (Fig. 11). In single sculling, the inboard length of the oar is such that one hand must pass over the other as the oar passes the perpendicular to the longitudinal axis of the boat. This is evident in the offset of the hand curves in Fig. 10. This sculler's left hand passed over her right. Although the stroke length was the same for both hands, the range of vertical motion was greater for the bow-side oar than the stroke-side oar. The vertical position of the oar handle is also an indication of how deep the blade is in the water, other things being equal.

Although specific applications have been discussed above, in practice the usual style of feedback consists of a four-page report presenting rower and boat rigging constants, plots of variables against time and oar angle, and boat statistics. Less often, real-time feedback is used in the boat or graphs are superimposed on video of the rower and viewed afterwards. Rowers and coaches from club to elite standard responded positively to all the styles of feedback outlined above. This is anecdotal evidence only and rigorous research studies would have to be undertaken to compare the effectiveness of this

style of feedback with other styles. Other hypotheses to be tested include whether this style of feedback improves the understanding among rowers and coaches of the determinants of good rowing performance, and whether the coaching language has been influenced through the widespread examination of this quantitative evidence.

## Conclusions

The on-water rowing instrumentation system described in this paper can provide feedback about the forces that have most influence on boat speed. Kinematic information such as seat position, which is available from the same source, can supplement kinetic information by providing an approximation of the segment motion of the rower's body associated with desirable and undesirable boat forces. The type of feedback and its immediacy are of a style recommended by proponents of the dynamical systems theory of motor learning. Rowers and coaches who have used the system value such feedback; however, further research must be undertaken to provide a sound basis for comparing the effectiveness of this type of feedback compared with more traditional forms, such as verbal feedback of performance.

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