

# Towards an Ideal Rowing Technique for Performance

## The Contributions from Biomechanics

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### Abstract

At international standard, sculling (two oars) and rowing (one oar) are competed on-water over 2000m. Race time is the critical measure of performance and is determined from mean skiff velocity during a race. Although a high proportion of race training is completed on-water, rowing ergometers are commonly used for performance testing, technique coaching, crew selection or for training during poor weather. Rowing biomechanics research has aimed to identify characteristics of successful sculling and sweep rowing strokes; however, biomechanical predictors of 2000m rowing performance are indistinct in the literature. If specific biomechanical parameters distinguish between ability levels and successful or unsuccessful techniques, these attributes can be considered when modifying

technique or predicting future rowing performance. The kinematics and kinetics of the sculling and rowing movements have been described on ergometers, on-water and for novice and elite male and female rowers, but there is limited research on the ideal technique or how a rower's anthropometry or boat set-up could help improve/optimize their rowing performance. Currently viewing the technique and providing verbal feedback is the primary tool used by a coach to help improve a rower's technique and performance. The greater use of customised telemetered sensors on the rowing skiff can assist the coach and biomechanist with judging when performance (skiff velocity) improves with some form of intervention.

Rowing ergometers, such as the Concept2, can reliably physiologically simulate a 2000m race.<sup>[1]</sup> Ergometers can also reproduce parts of the body action in the biomechanical stroke patterns (mostly for the lower limbs), but ergometers do not allow good reproduction of trunk and upper limb body patterns compared with on-water rowing or sculling due to the central pulley system most often used. Methodological issues in assessing on-water rowing technique are starting to be addressed with development and improvement of computer hardware and software telemetry systems that allow recordings of force profiles from the pin and foot-stretcher, oar position, boat velocity and boat orientation from all rowing disciplines. Biomechanical variables gained in the competitive environment should provide information on factors that predict performance.

The review of the mechanics of the sculling stroke cycle identified high correlations between outcome measures such as stroke length, stroke rate and boat velocity,<sup>[2,3]</sup> but the link with internal and external forces and kinematics causing these outcome measures is at times ambiguous. Kinetic and kinematic profiles during a stroke cycle are dependent upon sex,<sup>[4-6]</sup> skill level,<sup>[7]</sup> rowing sub-discipline<sup>[8,9]</sup> and potentially seat allocation<sup>[3]</sup> when in a team boat. The time course of force production, in association with oar position, body segment velocities and contribution of other crew members affect performance. Additionally, a rower's anthropometry and boat set-up also contribute to performance.

Rowing technique contributes to rowing performance, but it is still unclear what aspects of technique can predict on-water rowing performance.

There are no clear guidelines available to coaches, selectors or rowers on the ideal biomechanical rowing stroke for a given rower of determined anthropometric characteristics.

## 1. How Much Does Rowing Technique Contribute to Rowing Performance?

The physiological<sup>[10-14]</sup> and anthropometrical<sup>[15-19]</sup> attributes of highly skilled scullers and rowers have been described. Although the ability to distinguish rowers by these characteristics rather than race time is important, knowing which of these characteristics will accurately and reliably predict current and future 2000m on-water sculling (two oars) or rowing (one oar) performance is essential for coaches and selectors. For reasons of practicality and repeatability, research to investigate predictors of performance has primarily been completed using rowing simulators. Physiologically, maximal oxygen uptake (L/min) and maximal aerobic power are significantly correlated to 2000m<sup>[20,21]</sup> or 2500m ergometer performance.<sup>[22]</sup> Additionally, successful rowers are taller, heavier, and have greater upper and lower limb lengths, breadths and girths.<sup>[16,23]</sup> The relative contribution of these characteristics of rowing technique to overall race performance is not known. Coaches are spending more time on technique training – but there are no guidelines on what is an ideal rowing technique for an individual of specific anthropometrical dimension or crew combination. Therefore, the coach is challenged with identifying a technique and the movement pattern that best fits all rowers in a boat given their skill and

developmental level. From the analysis of the sculling and rowing strokes, skill-based movement patterns of elite performers are being identified and provide a guide for novice or developing rowers and coaches. Comparisons with the elite performers also allows for identification of weak performance areas within an individual and/or crew and can provide another dimension to talent identification programmes. If biomechanical parameters could distinguish between ability levels<sup>[7]</sup> and successful or unsuccessful techniques, these attributes could be considered when predicting rowing performance.

This paper discusses the contributing factors to a qualitative model of rowing performance, and reviews and summarises published data on the mechanics of the sculling stroke cycle with the aim of identifying measurable biomechanical variables that may predict performance. The following points provide a summary of the current research regarding biomechanics and rowing performance.

- Rowing simulators do not reliably simulate physiological aspects of on-water rowing; however, only one study has investigated whether the kinematics and kinetics of these two activities are the same. Elliot et al.<sup>[4]</sup> reported no significant differences in joint kinematics and a high correlation ( $r = 0.98$ ) in force-length curves.
- Higher stroke rate<sup>[2,3]</sup> and longer stroke drive lengths<sup>[3]</sup> will result in greater average boat velocity.
- Reduced intra-stroke fluctuations in boat velocity,<sup>[24,25]</sup> as stroke rate increases<sup>[3]</sup> may be an indicator of performance level.
- Greater force on the handle is generated when the drive phase is initiated with extended elbows and the finish position is reached with the elbows close to the trunk.<sup>[26]</sup>
- Sequential sequencing of the lower limbs, trunk and arms may lead to a more effective rowing stroke<sup>[27-30]</sup> and, therefore, greater average boat velocity.
- Measured drive to recovery ratios range from 0.9 to 1.7<sup>[31]</sup> and are strongly negatively correlated to stroke rate<sup>[3]</sup> and average boat velocity.
- Peak oar force increases with stroke rate,<sup>[3]</sup> is greater when the handle is pulled at the umbilicus level,<sup>[26]</sup> is significantly greater in males<sup>[4-6]</sup> and may be asymmetrical between oars during on-water sculling.<sup>[4,32]</sup>
- Peak oar force occurs earlier in the drive phase and closer to the bow of the boat as stroke rate increases.<sup>[3,33]</sup> The ability to maintain peak oar force application when the oar is perpendicular to the boat may be an indicator of performance level.
- Mean propulsive power output per kilogram of body mass, propulsive work consistency, stroke to stroke consistency and stroke smoothness successfully distinguish rowers of three different ability levels.<sup>[7]</sup>
- Measured peak foot-stretcher forces range from 299N to 600N<sup>[8,9,32,34,35]</sup> and may vary between stroke and bow feet.<sup>[32]</sup>
- Successful male rowers can be identified by specific anthropometrical measures (e.g. height and weight),<sup>[16,17,36]</sup> whereas female rowers tend not to conform to a particular body shape.<sup>[17]</sup>
- Guidelines are available relating to best oar positions, lengths and new blade design possibly for the improvement of rowing performance.
- The foot-stretcher design and orientation is subjective in nature with limited research<sup>[37]</sup> investigating optimal positions and the influence these may have on performance.

The following review of the literature expands on the summary points above, reviewing kinetic and kinematic profiles during a stroke cycle and the methodological issues in assessing rowing technique.

### 1.1 Literature Reviewed

Literature was located using two computer databases (Medline, and SPORTSDiscus) in addition to manual journal searches. The computer databases provided access to sports-oriented and biomedical journals, serial publications, books, theses, conference papers and related research published since 1948. The keywords searched included: 'row\*', 'scull\*', 'kinematic', 'kinetic', 'ergometer',

'electromyography', 'EMG', 'force', 'performance' and 'predict\*'. Articles that were not published in English and/or in scientific journals refined literature searches were excluded. The criteria for inclusion were:

- the paper must have addressed at least one biomechanical component of the sculling or sweep rowing stroke;
- the paper must have used uninjured scullers or rowers. Age, sex and ability levels were not excluding factors;
- the paper may have been a review of previous research.

## 2. Methods to Measure Rowing Biomechanics

### 2.1 Instrumentation

Rowing instrumentation has improved noticeably in the last 10 years. Advances in microtechnology have allowed on-water analysis of force application profiles from the feet and oar to be frequently reported in the literature.<sup>[4,38,39]</sup> A comprehensive review by Spinks<sup>[40]</sup> investigated the change in rowing data collection procedures since the 1950s. Baird and Soroka<sup>[41]</sup> and Cameron<sup>[42]</sup> used modified strain gauges and photographic analysis, respectively, whilst more recent studies have utilised advanced telemetry systems to provide detailed real-time analysis and feedback of on-water boat orientation and velocity; and oar, pin and foot-stretcher forces.<sup>[9,43]</sup>

Shakespear<sup>[44]</sup> stated that traditionally, rowers were "...assessed by the art and skill of the coach"; however, with advances in boat instrumentation systems additional quantitative information is available to the coach or selectors. Selecting rowers with similar force profile characteristics was thought to most likely result in a successful rowing crew compared with a crew with different force profile characteristics.<sup>[33,45-47]</sup> However, recent research by Smith and Draper<sup>[9]</sup> and McBride<sup>[3]</sup> has indicated that differences in the timing and magnitudes of force application may aid a pair crew in minimising lateral boat deviations and, therefore, improve their chances of success (see section 5). More studies are

required to determine what force profiles of rowers in a sculling crew are associated with successful performance.

### 2.2 Ergometer versus On-Water Sculling and Sweep Rowing

An ergometer can be friction loaded or air braked and may be used for training during poor weather, technique coaching, crew selection and performance tests. Additionally, ergometers allow for research in a controllable and technically simpler environment than the outdoors. The findings from research investigating the ability of an ergometer to simulate on-water sculling or sweep rowing technique typically support the use of ergometers; however, research by Martindale and Robertson<sup>[48]</sup> have shown significant differences in segment energies between the two activity modes. Table I provides a summary of studies that have directly compared ergometer technique to on-water sculling or sweep rowing technique.

Rowing simulators such as the Stanford, Gjesing, RowPerfect and Concept2 ergometers have been compared with either other ergometers or on-water rowing. A less frequently used simulator is a rowing tank where a rower sits on a custom-designed platform between two water tanks with the foot-stretcher fixed and seat on a slide. The blade(s) is moved through the water circulating at pre-defined speeds within these tanks. Peak and average power produced during tank rowing is significantly ( $p < 0.05$ ) greater yet correlated ( $r = 0.71$  and  $0.77$ , respectively) to similar measures obtained from a Concept2 ergometer.<sup>[51]</sup> The relationship between power produced whilst rowing on a Concept2 and on-water is not reported in the literature. Asymmetries in timing of peak force application on the right and left foot-stretcher measured during on-water sweep rowing (non-oar side leg reached peak prior to oar side leg) were reportedly reversed during tank rowing.<sup>[8]</sup> It was suggested that the inconsistency in timing of peak foot-stretcher force application may be a factor in the poor correlation (correlation coefficient not reported) between tank and on-water sweep rowing performance.<sup>[8]</sup> Tank rowing combined with instrumented oars may provide a skill-

**Table I.** Studies indicating similarities and differences between ergometer and on-water rowing

| Study                                  | Sample   | Methods  | Results and conclusions   |
|--|--|--|---|
| Elliot et al. <sup>[4]</sup>           | 4 male and 4 female national junior rowers   | Video taped during 500m on-water sculling (single) and ergometer rowing (RowPerfect) at stroke rates of 24, 26, 28 strokes/min<br>Maximum force, stroke length (scull angle) and trunk, thigh, leg and knee angles were determined for each rower in each condition                            | Significantly greater knee flexion occurred at the catch on-water compared with on the RowPerfect ergometer at 24 strokes/min. No other significant kinematic differences were reported<br>High levels of consistency were observed between force traces on-water and on the RowPerfect ( $r = 0.01-0.93$ )   |
| Lamb <sup>[27]</sup>                   | 30 male national rowing trialists level  | Drive phase of 1 stroke was analysed during on-water and ergometer rowing<br>The rowing movement was defined as 2 vector loops<br>Linear velocities of 5 segments were used to determine their contribution to total linear oar velocity and differences between ergometer and on-water rowing | No significant differences in the contribution of the trunk, upper leg and lower leg to total linear oar velocity<br>Kinematics of the arm and forearm were significantly different at the catch and finish between activity type. This was due to specific oar movement at these 2 stages during on-water rowing<br>Ergometer rowing simulates on-water rowing                                     |
| Martindale & Robertson <sup>[48]</sup> | 1 male and 1 female international rowers; 1 male and 1 female inexperienced competitive rowers | 1 stroke was analysed from rowing on a stationary Gjessing and wheeled Gjessing ergometer and during on-water single sculling<br>Stroke rate was at, above and below each individual race pace   | Significant differences between ergometer and on-water sculling due to the exchange of energy between the boats and the subject   |
| Schneider & Hauser <sup>[49]</sup>     | 24 rowers (sex and ability level not stated)   | Total mechanical power and propulsive power were calculated for 12 crews in coxless pairs completing 2000m on-water and ergometer races  | Mean total power expenditure during an on-water race correlates well with mean power during a rowing ergometer test ( $r = 0.63$ ; $p = 0.01$ , $df = 16$ )   |
| Struble et al. <sup>[50]</sup>         | 6 male and 2 female college level rowers   | 2 strokes were analysed from on-water rowing in a pair and custom designed ergometers that simulated sweep oar rowing for a single and a pair  | Hand velocity vs time during all 3 conditions was similar (no significance reported)<br>More gradual time to peak hand velocity than either ergometer (no significance reported)<br>Rowers produced hand displacement plots on the sweep oar ergometer designed for pair rowing that were most similar to on-water rowing<br>The land-based rowing simulator most closely simulated on-water rowing |

based analysis of an individual's technique in a controlled environment; however, the relationship between skill-based variables and on-water sculling and sweep rowing must be determined. The costs involved in building and maintaining indoor rowing tanks may prohibit their widespread use.

Air-braked ergometers are preferred over friction-loaded ergometers, which do not account for frictional resistance of the ergometer's transmission. Friction-loaded ergometers result in 10% errors in workload calculations<sup>[52]</sup> and are reported to inadequately simulate resistance characteristics of on-water sculling or sweep rowing.<sup>[53]</sup> Commonly used air-braked ergometers are the Gjessing, Concept2 and RowPerfect, which have a freely moving seat on a central rail and a central flywheel chain, ensuring a symmetrical movement pattern<sup>[54]</sup> that is most similar to on-water sculling. However, it is common practice for scullers and rowers to complete land-based training sessions and monitoring tests on the same ergometers.

Many researchers have used the Gjessing ergometer as a tool for assessing physiological<sup>[12,46,53,55-59]</sup> and biomechanical<sup>[6,46,47,60]</sup> aspects of sweep rowers and scullers. Physiological testing of 11 elite rowers on a Gjessing and Concept2 ergometer found that ergometer type did not affect physiological parameters; however, average power output was significantly greater (9.3%) on the Concept2.<sup>[53]</sup> The difference in power output may have been due to greater absorption of energy in the Gjessing<sup>[53]</sup> or differences in rowing technique on the two ergometers. Christov et al.<sup>[46]</sup> indicated that the handle velocity profile of the Concept2 was most similar to on-water rowing compared with the Gjessing ergometer. Further research is required to compare rowing technique on the Gjessing and Concept2 ergometers. Comparing the Gjessing with on-water sculling, Martindale and Robertson<sup>[48]</sup> reported significant differences in segment energies for two experienced (one female and one male) and two inexperienced (one female and one male) scullers. It was concluded that a wheeled ergometer allowed rowers to work at strokes similar to racing levels.

The Concept2 ergometer is currently the most frequently used air-braked ergometer for the simulation of on-water sculling and sweep rowing. The widespread use of the Concept2 is evident by the inception of the Concept2 Indoor Rowing Olympics in 1981. The Concept2 is reported to be highly reliable when testing well-trained rowers (2%, 95% CI 1.3, 3.1)<sup>[1]</sup> and national level competitive rowers (1.3%, 95% CI 0.8, 2.9)<sup>[61]</sup> during 2000m races. The high reliability of rowers' performance on the Concept2 ergometer is thought to be present due to the ergometer being inherently stable, requiring no calibration and the rowers being accustomed to completing 2000m time trials on the ergometer.<sup>[1]</sup> A moderate positive correlation ( $r = 0.74$ ) between 2000m performance time on a Concept2 and during on-water 2000m standing start time trials has been reported.<sup>[62]</sup> The concept II ergometer appears to be a valid and reliable measure of on-water performance; however, no research has compared the kinematics and kinetics between on-water and Concept2 rowing.

Unlike the Gjessing and Concept2, the foot-stretcher and flywheel on the RowPerfect ergometers freely move as one in an effort to match the inertial forces exerted on a rower whilst on-water.<sup>[63]</sup> Elliott et al.<sup>[4]</sup> reported that the shapes of force-displacement curves for eight (four male and four female) national junior and under-23 heavyweight rowers performing at 24, 26 and 28 strokes/min on a RowPerfect and during on-water sculling to be highly correlated ( $r = 0.98$ ). On-water sculling at 24 strokes/min resulted in a significantly smaller knee angle at the catch, meaning the subjects were achieving a more compact position compared with on the RowPerfect at the same stroke rate. No other significant differences in trunk, knee or leg angles at the catch or finish were reported for any stroke rating. An earlier study by Buck et al.<sup>[5]</sup> reported the successful instrumentation of a RowPerfect and Concept2 (standard and wheeled) in an effort to compare magnitude and timing of force production. Peak horizontal handle force, time to peak handle force and time to peak horizontal foot-stretcher force were not significantly different between the

three ergometers; however, peak horizontal foot-stretcher force was 44% ( $p = 0.00$ ) greater on the RowPerfect than on a standard Concept2 when rowing at race pace. Comparing the results from Buck et al.<sup>[5]</sup> with the same variables from on-water rowing "...will reveal the relative specificity of each ergometer to on-water rowing". Recently a study<sup>[61]</sup> comparing reliability of 500m and 2000m rowing performance on the Concept2 and RowPerfect has been completed and found rowers' mean power output to be less variable on the Concept2 ergometer (500m = 2.8%, 95% CI 2.3, 3.4; 2000m = 1.3%, 95% CI 0.8, 2.9) than the RowPerfect ergometer (500m = 3.0%, 95% CI 2.5, 3.9; 2000m = 3.3%, 95% CI 2.2, 7.0).

The Stanford rowing ergometer is designed to simulate on-water sweep oar rowing in an eight-oared shell through its mechanical design and set-up. The Stanford can be set for oars on the stroke or bow sides and induces trunk rotation throughout the stroke cycle (rowing simulation). Few observable differences in the contribution of lower body segments to total linear oar velocity were reported when 30 national heavyweight rowers rowed on a Stanford ergometer and on-water.<sup>[27]</sup> However, the contributions of the upper arm and lower arm to total linear oar velocity during the drive phase (0–100%) were significantly different during 10–20% and 80–90% of the drive phase, respectively. These differences are most likely due to the lack of specific arm movements required at the catch (blade placement) and finish (feathering) during rowing on the Stanford.

Performance reliability needs to be determined for the Gjessing and Standford ergometers. A 2000m trial on a Concept2 rowing ergometer is the most appropriate ergometer protocol supported by the literature for testing the influence of an intervention on a rowers' performance.<sup>[1,61]</sup> Unlike the RowPerfect ergometer, a clear analysis of biomechanical similarities or differences between the Concept2, Gyessing or Stanford ergometers and on-water sculling or sweep rowing has not been completed.

### 3. A Deterministic Biomechanical Model of Rowing Performance

Race time is the critical measure of a sculler's performance and is determined by race distance and average boat velocity. 2000m races are standard at international regattas; therefore, boat velocity is the controllable determinant. The mechanical determinants of producing average boat velocity are indicated in the deterministic biomechanical model of rowing (see figure 1).

#### 3.1 Boat Velocity

Boat velocity should remain as constant as possible during a stroke cycle (i.e. limited acceleration or deceleration changes) to minimise the effects of drag on the boat from the water and to a lesser extent air mechanics. Due to the density of water at +4°C being approximately 770 times greater than the density of air at 0°C, air resistance is often ignored. The effect of fluid (water) around the hull of the boat is made up of pitch, hull and skin resistance.<sup>[64]</sup> In a coxed eight, pitch resistance accounts for 4% of total resistance and refers to the pressure around a boat being greater when it is rowed compared with at rest, due to changes in horizontal and vertical boat orientations.<sup>[64]</sup> The long narrow hull shape of a rowing boat is designed to reduce the fluid resistance when the bow enters the water and to ensure a good release of the water at the stern of the boat. Hull resistance accounts for 8% of overall resistance.<sup>[64]</sup> Skin resistance provides the greatest resistance (88%) to forward propulsion of the boat. The boundary layer (layer of agitated water molecules around the hull) increases as the water moves from the bow to the stern, eventually becoming frictional wake as it follows the boat for some time.<sup>[64]</sup> Fluid resistance increases approximately proportional to the square of the boat's velocity.<sup>[2]</sup> Therefore, there is greater fluid resistance at higher boat velocities.

Figure 2 illustrates a typical velocity-time curve of a single scull during one stroke (based on data from Martin and Bernfield<sup>[2]</sup>). Greatest boat velocity occurs during the recovery phase when the oars are out of the water and the rowers' mass is moving in the opposite direction to the boat.<sup>[2,65,66]</sup> The catch

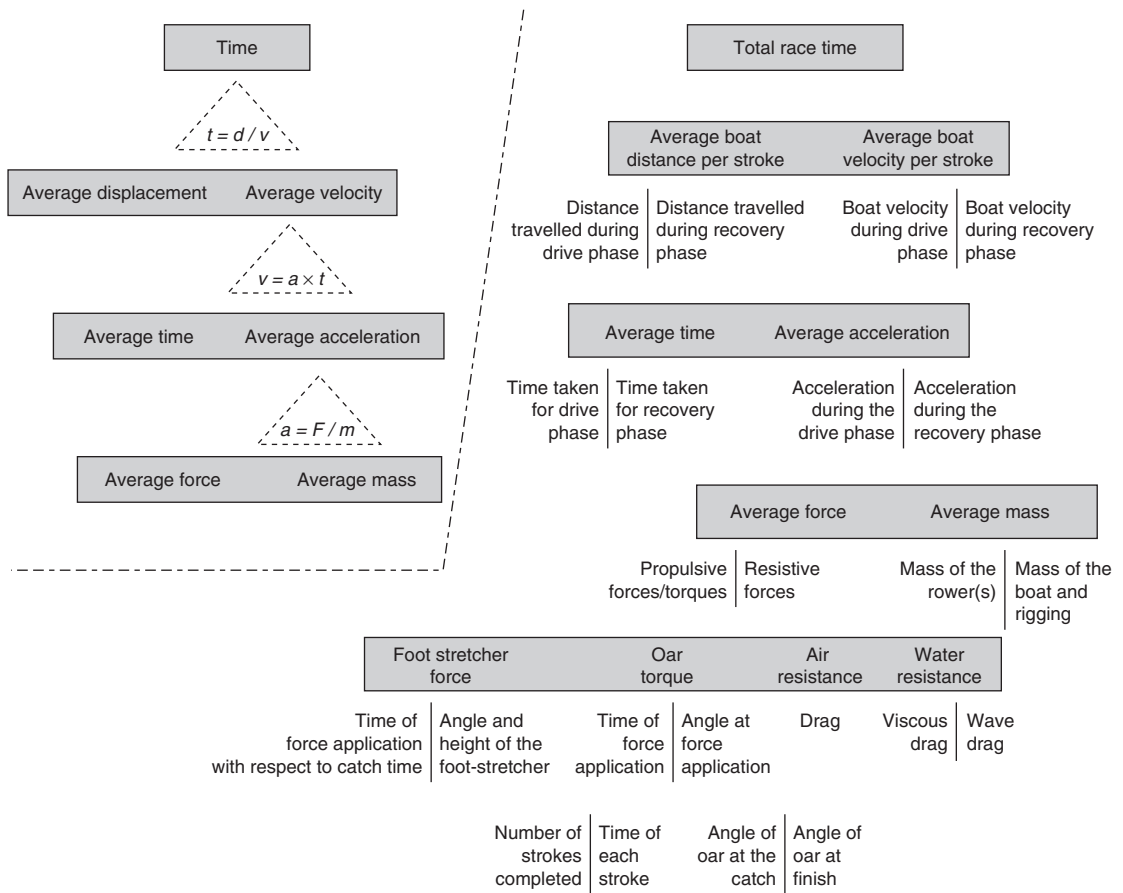


Fig. 1. A deterministic model showing the basic mechanical factors of rowing that influence performance.

and initial drive phase of the stroke are characterised by low boat velocity, which has been attributed to: (i) a delay in the ability of the rower to overcome water resistance<sup>[2]</sup> and inertia of the system;<sup>[67]</sup> (ii) the relative velocity of the boat and oars;<sup>[65]</sup> (iii) the need to change the movement direction of the oarsman;<sup>[68]</sup> and (iv) the time spent in the stern of the boat prior to placing the blades in the water<sup>[2]</sup> (see figure 2). The ability of the sculler to limit the reduction in boat velocity during the catch and initial drive phase may be an indicator of performance level. Aujouannet and Rouard<sup>[67]</sup> reported that the interval between the catch and minimum boat velocity was highly positively correlated ( $r = 0.95$ ) with average boat velocity for the entire stroke cycle over 50m. The researchers divided the velocity-time

curves of six national and international sculling specialists into three phases:

- phase 1: time of catch to time of slowest boat velocity;
- phase 2: time of slowest boat velocity to time of greatest boat velocity;
- phase 3: time of greatest boat velocity to time of catch.

The international scullers were reported to increase boat velocity during phase 1 and maintain this velocity during phase 2 compared with the delayed increase in boat velocity at phase 3 by national rowers. In an effort to limit the reduction in boat velocity at the catch, Simeoni and colleagues<sup>[69]</sup> reported an overall increase of 0.3 m/sec in average boat velocity when the oar angle at catch was re-



duced from  $-60^\circ$  to  $-44^\circ$  ( $0^\circ$  depicts an oar perpendicular to the boat). It was concluded that boat velocity increased due to the elimination of boat deceleration at the catch and during the start of the drive phase. However, stroke rate is a determinate of boat velocity and was not controlled, leading to difficulty in isolating a reduced catch angle as the cause of increased boat velocity.<sup>[2]</sup>

The effect of roll, pitch and yaw of a boat on boat velocity<sup>[70]</sup> was examined in 13 single scullers over 20 strokes at four different stroke rates. Yaw, pitch and roll refer to the boat's orientation about its x-, y- and z-axis, respectively, and are investigated to provide a measure boat stability throughout the stroke cycle. A boat balanced about all three axes will be less hydrodynamic drag and will be energetically more efficient for the rower.<sup>[70]</sup> The pitch of the boat was affected primarily by the bow-ward and stern-ward movement of the rower along the longitudinal or y-axis of the boat. The range of motion about the y-axis varied between  $0.3$ – $0.5^\circ$  and this change in pitch was moderately correlated to the scullers mass. The bow of the boat reached its lowest point when the rower was in the catch position initiating the recovery phase. Yaw, or movement of the boat about its x-axis occurred primarily at the catch phase when forces were applied to the blades and foot stretchers. Movement ranged from  $0.1$ – $0.6^\circ$ , which equated to  $0.5$ – $3.0$ cm of movement at the bow. The roll of the boat or movement about its z-axis was between  $0.3$ – $2.0^\circ$  and started just after

the catch phase. Loschner et al.<sup>[70]</sup> concluded that there was a high relationship between boat orientation and boat run and that the greater the changes in boat orientation the greater the effect on boat velocity. However, unfortunately these relationships were not quantified with correlation coefficients.

### 3.2 Stroke Velocity

Average boat velocity is the average of each individual stroke's velocity. Stroke velocity is the product of the stroke length (distance of blade travel) and time. Stroke drive velocity (m/sec) is the blade stroke drive displacement (m) – known as stroke drive length – divided by the blade stroke drive time (seconds), i.e. the time from catch to the finish (when the blade leaves the water). The total blade stroke time (from catch to catch) is divided into the drive time and the recovery time with the ratio between these times known as the drive to recovery ratio. Rowers tend to place more emphasis on the stroke time than on the stroke length during competition, as when stroking at very high rates it is hard to maintain a good stroke length.

#### 3.2.1 Stroke Rate

The stroke rate (strokes/min) is the number of strokes divided by 1 minute of time. A 1-minute period divided by the number of strokes will give the time per stroke. Tonks has estimated that the average stroke rate of an elite single sculler during a 2000m race is 34 strokes/min. Anywhere from 1000m out from the finish, but more normally from the final 300m, an all-out sprint starts with a high stroke rating. All crews will have their own efficient stroke rate. Gearing of the blade in the boat allows female rowers to rate the same as men even if they are not as strong.

Stroke rate is significantly correlated ( $r = 0.66$ – $0.76$ ) to average boat velocity with correlation coefficients reported from  $r = 0.66$ <sup>[2]</sup> to  $r = 0.76$ <sup>[3]</sup> The different strengths of the stroke rate-velocity relationship reported by Martin and Bernfield<sup>[2]</sup> and McBride<sup>[3]</sup> may be due to different stroke rate ranges tested ( $3.5$  vs  $15.7$  strokes/min range), or may indicate that two- and eight-seat boats respond differently to stroke rates due to weight and drag char-

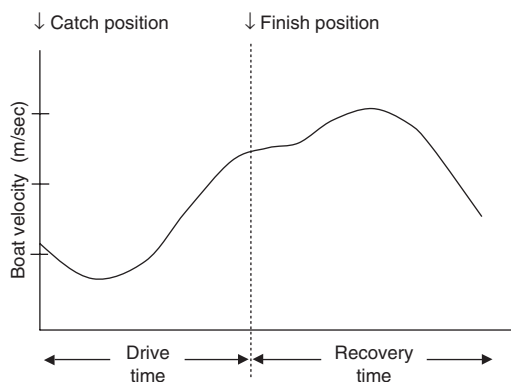


Fig. 2. A typical force-velocity time curve during on-water sculling in a single scull.<sup>[2]</sup>

acteristics. McBride<sup>[3]</sup> reported a linear increase in boat velocity as stroke rate increased from 20 to 32 strokes/min in four equal intervals and finally at race pace (average stroke rate = 35.7 strokes/min).

Due to hydrodynamic drag on a boat being approximately proportional to the square of the boat's velocity,<sup>[2]</sup> it is expected that the stroke rate-velocity relationship would plateau at some point where the drag on the boat becomes too great and gains in boat velocity become more difficult.

Due to the cyclic nature of rowing, each stroke has its own temporal pattern that will contribute to final average boat velocity. Intra-stroke fluctuations in boat velocity have been identified as a fundamental factor when evaluating rowing performance<sup>[24]</sup> and are associated with less successful technique.<sup>[25]</sup> As stroke rate increased, the amplitude of intra-stroke fluctuations in boat velocity significantly ( $p = 0.00$ ) increased by 44.3% ( $r = 0.84$ ) in 13 pair sweep rowing boats.<sup>[3]</sup> Martin and Bernfield<sup>[2]</sup> also reported increased intra-stroke fluctuations in boat velocity when stroke rate increased from 37.5 to 39.6 strokes/min.

Earlier studies have assumed that any intra-stroke fluctuations in boat velocity would be equally distributed about the average boat velocity.<sup>[65,68]</sup> During a single stroke cycle, research by McBride<sup>[3]</sup> and Martin and Bernfield<sup>[2]</sup> has shown greater boat velocity reductions ( $-33.04\%$  and  $-24.4\%$ , respectively), than increases ( $+19.35\%$  and  $+18.6\%$ , respectively) with respect to average boat velocity. The greater reductions in average boat velocity will require greater force application at the catch to increase boat velocity during the drive phase. It appears that although higher stroke rates are essential for increasing boat velocity, the maintenance of a constant boat velocity or reductions in the amplitude of intra-stroke fluctuations may be an indicator of successful performance.

### 3.2.2 Stroke Drive Distance (Stroke Length)

The stroke drive distance, known as stroke length, is determined as the total arc the blade moves through from blade entry at the catch until the blade is fully removed at the finish and is reported in degrees. Stroke length was significantly correlated

( $r = -0.99$ ) to stroke rate, and through association, average boat velocity ( $r = -0.99$ ) when the crew averages of 13 pair rowers were regressed with five stroke rates.<sup>[3]</sup> It was unclear whether the reported significant change in stroke length of 2.2° or 2.5% over the five different stroke rates actually had a real effect on on-water sweep rowing performance.

Force application is most inefficient at the catch and finish positions due to increased transverse force application<sup>[71]</sup> and, therefore, a reduction in stroke length of this magnitude may be acceptable and possibly desirable if stroke rate and, therefore, average boat velocity increased. Further research is required to determine what magnitude of decrease in stroke length and, therefore, time of force application will have a negative effect on performance.

The ability to produce a high boat velocity with limited fluctuations throughout each stroke is key to successful rowing performance.<sup>[3]</sup> The generation of consistent boat velocity depends on the rowers' ability to generate power, skill to maintain a stable boat throughout the stroke cycle and chosen stroke-length/stroke-rate relationship.<sup>[2,24,70]</sup>

## 4. The Body Movements During the Sculling Stroke Cycle

To determine an ideal rowing technique, it is essential to firstly understand the movement patterns of the stroke cycle and the underlying forces. Kinematics represents the overall movement pattern of the sculling motion, which is the result of internal and external forces acting on the rower-boat system. The overall movement shape is what a coach views and, therefore, manipulates to produce a more powerful and efficient stroke cycle. Although many researchers<sup>[4,29,48,72-74]</sup> have previously investigated the joint and segments motions during ergometer rowing, limited publications explicitly report 2- or 3-dimensional joint angles and or ranges of motion during ergometer rowing.

For technical reasons, the rowing stroke is frequently analysed in two dimensions on an ergometer;<sup>[4,27,31,50,75-77]</sup> however, some researchers have attempted on-water video analysis.<sup>[4,27,50,78]</sup> Trunk, thigh and shank positions were not significantly

different at the catch and finish positions on-water or on the RowPerfect for eight national junior rowers.<sup>[4]</sup> However, at the catch (24 strokes/min), 3.1% greater knee flexion (1.6°,  $p < 0.01$ ) was achieved on-water compared with on the RowPerfect.<sup>[4]</sup> For a similar sample of nine junior world championship rowers at 20 strokes/min, Hume et al. reported a knee angle on the RowPerfect of  $53 \pm 3.7^\circ$  (personal observation), very similar to the  $52.5 \pm 2.0^\circ$  reported by Elliott et al.<sup>[4]</sup> Stroke rate has not been found to significantly affect joint kinematics when using a RowPerfect<sup>[4]</sup> or Concept2<sup>[74]</sup> ergometer or when sculling on-water.<sup>[4]</sup>

The high incidence of lower back pain amongst scullers and rowers,<sup>[79-84]</sup> in part due to the amount of time a rower spends in a flexed position, the number of rowing stroke cycles completed, and the forces on the body during the rowing stroke<sup>[82]</sup> has led to the assessment of the lumbo pelvic angle (included angle between the pelvis and lower back) at the catch. It has been suggested<sup>[84]</sup> that rowers should adopt a less flexed lumbar spine posture, particularly at the catch phase when the oar is placed in the water.<sup>[84]</sup> In this respect, if the pelvis could be rotated more anteriorly, less motion would be required in the lumbar spine. During on-water sculling ( $n = 4$  elite scullers) and sweep rowing ( $n = 4$  elite rowers) Soper et al. (personal observation) reported lumbo pelvic angle to be  $138 \pm 15^\circ$  and  $139 \pm 19^\circ$ , respectively. In comparison, world junior rowers on a RowPerfect ergometer had an average lumbo pelvic angle of  $154 \pm 10^\circ$  indicating less flexion at the catch (personal observation) and possibly a reduced risk of low back pain.<sup>[84]</sup>

During ergometer rowing using a central pulley system (Concept2, Gjessing or RowPerfect), symmetry can be assumed between left and right side.<sup>[54]</sup> No other studies have investigated the symmetry of the movement; however, Halliday et al.<sup>[74]</sup> reported flexion/extension, abduction/adduction and significant internal/external rotation movements of upper and lower limbs from following 3-dimensional analysis. Halliday et al.<sup>[74]</sup> were the first to provide joint ranges of motion during ergometer rowing in three dimensions. Due to the small sample size ( $n = 5$ ) and

large variations (up to  $50^\circ$ ) reported in segment movements, further research is needed before it is accepted that the error involved in 2-dimensional analysis out-ways the benefits of 3-dimensional analysis, including additional time and costs.

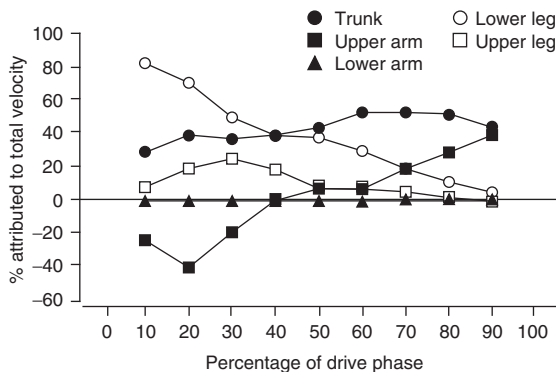
At the catch, the rowers' hips and knees are in a flexed position preparing for the drive phase. Bompa<sup>[26]</sup> compared three catch positions graphically and categorised positions according to 'very packed' (the leg extension transmits the force), 'moderately packed' (said to be most efficient) and 'minimally packed' (allows for extended stroke length due to increased trunk flexion but decreases seat slide length and range of knee extension). Limited research has directly reported any relationship between joint kinematics and changes in performance measures such as boat velocity. Research by Bompa<sup>[26]</sup> has shown that rowers ( $n = 11$ ) who kept their elbows close to their trunk at the finish position produced 131.1N (30.1%,  $p < 0.05$ ) greater force on the handle compared with rowers with their elbows pointed outwards. Similarly, rowers who initiated the drive phase with extended elbows ( $180^\circ$ ) generated 38.4N or 6.3% greater force than those with flexed ( $150^\circ$ ) elbows.

#### 4.1 Segmental Coordination

When comparing segment velocities of novice and skilled rowers, Nelson and Widulle<sup>[29]</sup> reported novice rowers to have a greater delay between peak angular velocities of the knee and trunk than skilled rowers. Delay in peak segment angular velocities resulted in a smaller sum of knee and trunk velocity when the oar was perpendicular to the shell. In support of this, Hume and Soper<sup>[30]</sup> have reported that sequential movement patterns are common for New Zealand's elite scullers and rowers but this clear sequencing pattern, i.e. no delay between peak velocities, is often not evident in the technique of novice or development level rowers.

Lamb<sup>[27]</sup> determined during sweep oar on-water and sweep oar ergometer rowing the lower leg angular velocity contributed 76% and 68% to total linear oar velocity, respectively. In order of greatest to least contribution, the remaining linear oar velocity

was developed from the trunk, upper leg, lower arm and finally upper arm velocity (see figure 3). Trunk velocity contribution maximised at approximately 70% of the drive phase, surpassing the contribution at this point of lower leg velocity as the rower moved toward the bow of the boat.<sup>[27]</sup> This delayed trunk movement supports the conclusions of Lamb<sup>[27]</sup> and Nelson and Widule<sup>[29]</sup> who reported that the lower limbs are responsible for initiating the drive phase through knee extension followed sequentially by trunk movement. The rowing fraternity have termed this sequential order of body segment movements the 'Rosenberg style' due to Al Rosenberg's (US national team coach 1975–76) comments<sup>[29]</sup> that when a stroke is performed correctly, the legs followed by the lower trunk, mid-trunk, arms and wrist segments will accelerate the boat. In partial support of the Rosenberg style, Kleshnev and Kleshnev<sup>[28]</sup> reported that consecutive segment movements produced greater power than synchronous segment movements; however, synchronous movements produced a more mechanically efficient rowing pattern ( $n = 62$  experienced oarsmen). The authors concluded that the movement choice should be based upon a rower's individual musculature and biomechanical features of their style. Similarly, following 1 month of intensive training, female rowers showed a tendency to have a higher effective work output which was attributed to better sequencing of the main muscle groups.<sup>[47]</sup>



**Fig. 3.** A comparison of trunk, upper and lower arm and leg component velocity during on-water rowing.<sup>[27]</sup>

In contrast to the Rosenberg style, Williams<sup>[85]</sup> had previously reported that the trunk should initiate the drive phase followed sequentially by the legs. This order of body segment movement aimed to provide stability at proximal joints before movement occurred in distal joints. Support for this style of sculling and sweep rowing is currently limited.

#### 4.2 Drive to Recovery Ratio

The stroke length can be divided into the stroke drive length and the stroke recovery length. The relative time to complete the stroke drive length and the stroke recovery length is known as the drive to recovery ratio.

Tonks has subjectively observed variations in the timing of body segment movements and the drive phase to recovery phase ratio. Redgrave<sup>[86]</sup> suggested a 1 : 2 drive to recovery phase ratio to enable a rower to optimise the run of the boat during each stroke cycle. However, the measured drive to recovery ratios have been much lower than 2. During on-water sweep oar rowing<sup>[2,3]</sup> and ergometer rowing<sup>[31]</sup> the drive to recovery ratios ranged from 0.9 to 1.7, illustrating a relatively faster recovery phase than recommended by Redgrave.<sup>[86]</sup>

As stroke rate increases, the absolute time in the drive and recovery phases of the stroke cycle decreases; however, greater reductions occur in the recovery phase.<sup>[2,41,87]</sup> With reference to total stroke time, McBride<sup>[3]</sup> reported a 40% increase ( $p = 0.00$ ) in percentage drive-phase time when stroke rate increased from 20 to 35.7 strokes/min. The ratio of drive phase to recovery phase was strongly negatively correlated ( $r = -0.98$ ) to stroke rate. In addition, increases in average boat velocity resulted in increases in the percentage of total drive time during on-water sweep rowing ( $r = 0.73$ ),<sup>[2]</sup> on-water sculling<sup>[87]</sup> and on an ergometer.<sup>[87]</sup> Although percentage leg drive time is significantly related to average velocity, Martin and Bernfield<sup>[2]</sup> suggested a constant drive time irrespective of the overall stroke time may be indicative of a limit in the maximum rate of knee and hip extension during the stroke cycle to maintain the required level of force. This is supported somewhat by the classic isometric force-

velocity relationship that indicates decreases in muscular force as velocity of muscle shortening increases.<sup>[88]</sup>

Optimising the drive to recovery ratio by slowing down a rower's recovery phase has been cautioned as a performance strategy, due to the influence it may have on boat velocity fluctuations.<sup>[3]</sup>

## 5. Forces During the Sculling Stroke Cycle

Greater peak force application on the blades has been associated with greater boat velocity.<sup>[3]</sup> External and internal forces contribute to the boat velocity.

### 5.1 External Forces

Maximal total force application occurs through appropriate sequence and timing of force by body segments. Propulsive power (product of force and time) must be produced to overcome the drag forces of the hull, sculler and blades through the water and air and ultimately produce boat velocity. Hydrodynamic resistance to the hull is the predominant drag force and increases approximately to the power of two as boat velocity increases.<sup>[89]</sup> The large intra-stroke fluctuations in boat velocity occur due to the intermittent force application at the foot-stretchers and oars resulting in boat acceleration and deceleration during the drive and recovery phases, respectively.

Research has investigated force application on the oar from a single scull on-water,<sup>[8,32,45,90-94]</sup> a Concept2 ergometer,<sup>[31,95]</sup> a Gjessing ergometer,<sup>[6,60]</sup> a rowing tank,<sup>[35]</sup> or other rowing simulators.<sup>[7,77,96]</sup> Only one study<sup>[33]</sup> has attempted to determine blade force as opposed to handle or pin force. Relatively limited research has been conducted investigating foot-stretcher forces during on-water sweep rowing<sup>[8,91]</sup> and sculling,<sup>[8,32]</sup> tank rowing<sup>[35]</sup> and Concept2 ergometers.<sup>[95]</sup> Currently no guidelines are available to coaches or selectors on how to use force application profiles to reliably or accurately predict a rower's current or future on-water sculling or sweep rowing performance.

### 5.1.1 Oar Force Profiles

At 32 strokes/min, average peak propulsive pin force equalled  $1120 \pm 104\text{N}$  for five international level coxless pairs.<sup>[9]</sup> For well trained, competitive coxless pairs, average oarlock force equalled  $841.3\text{N}$  at 20 strokes/min and significantly ( $p = 0.001$ ) increased (12%) to  $942.0\text{N}$  at 35.7 strokes/min (maximal rating).<sup>[3]</sup> Similarly, research by Roth et al.<sup>[90]</sup> has graphically shown greater peak force of experienced coxless pairs when stroke rate increased from 20 to 32 strokes/min. Peak propulsive oar forces for three elite female scullers were between  $465\text{--}600\text{N}$  over 500m at race pace. Recent research by Elliot et al.<sup>[4]</sup> calculated the blade force during on-water sculling by positioning a linear proximity transducer on the outboard of each oar, closer to the blades. Force readings were substantially smaller ( $107.3\text{--}187.0\text{N}$ ) than previously reported handle or pin force values. Changes in right blade maximum force increased 8.9% and 9.7% when stroke rate increased from 24 to 28 strokes/min ( $p = 0.02$ ) and 26 to 28 strokes/min, respectively.<sup>[4]</sup> Equivalent changes in left oar forces were 1.0% and 2.7%.

On a RowPerfect ergometer, handle forces ranged from  $318\text{--}541\text{N}$  for four male and four female national junior or under-23 rowers at 24, 26 and 28 strokes/min.<sup>[4]</sup> The male participants produced a minimum 23.8% greater force at each required stroke rate than their female counterparts.<sup>[4]</sup> Similarly, experienced national level male rowers produced significantly greater ( $p$ -value or magnitude not provided) power output at race pace compared with females of the same competitive level.<sup>[5]</sup> Greater peak force recordings for males compared with females were also reported following a series of five and ten maximal effort strokes and a 6-minute maximal effort row on a Gjessing ergometer by 81 elite male and 21 elite female heavyweight rowers.<sup>[6]</sup>

Due to the inboard length of the oars used during sculling, the oar handles must overlap when the blades are perpendicular to the boat, resulting in upper body asymmetry. Boats are most commonly rigged so that when the handles overlap the left hand will be on top of the right hand. This asymmetry

may lead to the large discrepancy reported<sup>[4,32]</sup> in stroke and bow side force. Loschner and Smith<sup>[32]</sup> reported that three female elite scullers had  $91.0 \pm 20.6\text{N}$  (19.5%) greater force on the bow side pin compared with the stroke side pin. Similarly, Elliott et al.<sup>[4]</sup> reported bow oar force of eight rowers sculling to be 11.7%, 9.5% and 4.0% greater than stroke oar force at 24, 26 and 28 strokes/min, respectively (significantly greater for 24 and 26 strokes/min,  $p < 0.01$ ). Greater force application on one blade may result in greater yawing (movement about the longitudinal axis of the boat), which is reported to negatively correlate to boat velocity.<sup>[70]</sup>

McBride<sup>[3]</sup> reported well trained stroke seat rowers ( $n = 10$ ) produced 13.8% greater ( $p = 0.031$ ,  $p = 0.3$ , Bonferroni adjusted alpha level) peak oarlock force than bow seat rowers ( $n = 10$ ). Similarly, at 32 strokes/min, Roth et al.<sup>[90]</sup> has previously reported significantly greater (9.0%,  $p < 0.05$ ) power by the stroke seat rowers compared with the bow seat rowers. In contrast to the research by McBride<sup>[3]</sup> and Roth et al.<sup>[90]</sup> Smith and Draper<sup>[9]</sup> have reported greater peak propulsive pin forces from bow seat rowers; however, the magnitude of the difference was 4.0% and non-significant ( $p = 0.26$ ).

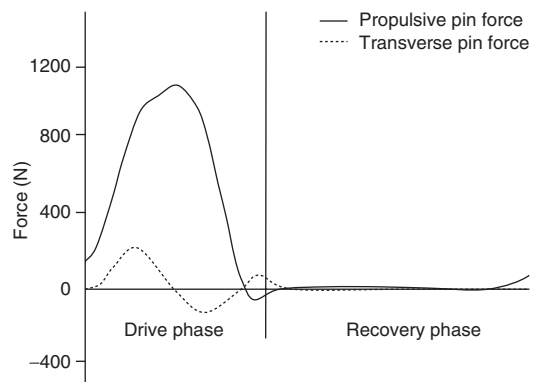
The height of pull on an ergometer handle during upper-body-only rowing has been shown to significantly affect force output.<sup>[26]</sup> Twenty-eight percent greater force was developed when 18 subjects pulled isometrically on an ergometer handle with a strain gauge in series at the umbilicus level compared with the pectoralis level. These results are supported by previous research<sup>[26]</sup> that reported 27.9% greater force when the handle was pulled at the umbilicus level. The lowest peak force output occurred when the handle was pulled at shoulder level.

Fatigue has been shown to decrease the magnitude of applied force during on-water sweep rowing; however, the consistency of shape was preserved following 22 minutes of continuous rowing.<sup>[45]</sup> Limited research has investigated the effects of fatigue on skill-based parameters.

It has been suggested that to optimise the force-length relationship of lower limb muscles, the sculler or rower should aim to achieve peak force when

the blades are perpendicular to the boat.<sup>[2,31]</sup> No research is currently available that supports the proposition that the force-length relationship, as occurs for maximal isometric contractions,<sup>[88]</sup> is present during a dynamic activity such as sculling and sweep rowing. However, during rowing the blade(s) travel through an arc in the water during the drive phase of each stroke cycle resulting in both a propulsive (acting parallel to the long axis of the boat) and a transverse (acting perpendicular to the boat) force. The transverse force introduces a rotational component and is maximal at the beginning and end of the drive phase.<sup>[9]</sup> Peak force occurring when the blades are perpendicular to the long axis of the boat optimises propulsive force<sup>[3]</sup> due to the transverse force component being zero<sup>[9]</sup> (see figure 4). Three typical force-time profiles on the oarlock were presented by Korner<sup>[97]</sup> and showed peak force occurring prior to, at or following completion of 50% of the drive phase. The three variations of force application and the various possibilities within these extremes show an emphasis by the rowers on different aspects of the stroke and can be derived from different sculling or sweep rowing styles.

At a training stroke rate of 20 strokes/min, McBride<sup>[3]</sup> reported peak oarlock force occurred  $10.9^\circ$  prior to the blade being perpendicular to the boat for well trained rowers in coxless pairs. At a higher stroke rate of 30 strokes/min, peak propulsive oar force for elite female scullers occurred  $29.0^\circ$ – $14.0^\circ$  prior to the blade being perpendicular to the boat.<sup>[32]</sup>



**Fig. 4.** Magnitude of propulsive and transverse forces during a sculling stroke cycle in a single scull.

As stroke rate increases, peak oar force occurs earlier in the drive phase, closer to the bow of the boat.<sup>[3,33]</sup> McBride<sup>[3]</sup> reported peak pin force occurred 3.4% or 3.0° ( $p = 0.008$ ) earlier in the stroke cycle when stroke rate increased from 20 strokes/min to 35.7 strokes/min (race pace). The change in oar angle at peak force application as stroke rate increases is detrimental to performance as a greater percentage of this force is acting to rotate the boat as opposed to propelling it forward.

Dwyer<sup>[98]</sup> reported that the position of peak oar force varied between ergometer (Concept2), tank and on-water sweep rowing. In contrast, Buck et al.<sup>[5]</sup> reported no significant difference in the timing of peak horizontal handle force measured on a RowPerfect (23.1%), standard Concept2 (22.9%) and a Concept2 on wheels (23.7%).

The timing of peak force has been shown to vary with rower seat position<sup>[3,9,90]</sup> and skill level.<sup>[35]</sup> Stroke seat rowers are reported to reach peak force 2.4% of the total stroke cycle ( $p = 0.07$ )<sup>[9]</sup> or 3.8° earlier ( $p = 0.115$ )<sup>[3]</sup> than bow seat rowers. The discrepancy in timing of force application was reported to aid the crews in limiting lateral boat deviations by producing a clockwise moment (looking from above) that counteracted the anticlockwise moment generated by the transverse forces. It is suggested the rowers may have adapted to specific seat positions within a crew and may become accustomed to specific timing requirements.<sup>[90]</sup> These findings argue against the procedure of selecting crews based on similar force-time curve characteristics.<sup>[33,45]</sup>

A rower with a higher skill level is reported to achieve peak force approximately 15° prior to the blade being perpendicular to the boat; however, unskilled rowers reportedly achieve peak force in the second half of the drive phase when the seat is in the most forward position.<sup>[35]</sup> The delay in reaching peak oar force by the unskilled rowers will limit the transfer of mechanical energy to the oar and result in decreased oar impulse compared with the skilled rowers.

Despite research having identified particular aspects of a force-time profile that are indicative of

technical efficiency,<sup>[7,40,99]</sup> individual rowers can still be identified by their personal profiles. The idea of an individual's oar force-time profile being representative of a signature has been suggested<sup>[4,8,45]</sup> due to small intra-individual and large inter-individual variability.<sup>[4,46,94]</sup> In an activity that is thought to require high levels of synchronicity, members of an elite German eight sweep rowing crew displayed a large amount of inter-individual variability in force-time profiles, illustrating a lack of uniformity.<sup>[91]</sup> Similarly, when one member of a sweep rowing four was substituted with another rower, the force-time profiles of the remaining three rowers were unchanged<sup>[45]</sup> indicating no adjustments were made for a crew member's different force profiles. The lack of similarities between elite rowers' force-time profiles in part contradicts the research by Smith and Spinks<sup>[7,99]</sup> who were able to group rowers by performance level based on their oar force-time profiles. The comprehensive study by Smith and Spinks<sup>[7,99]</sup> identified four independent skill-based variables that discriminated between male novice ( $n = 9$ ), good ( $n = 23$ ) and elite ( $n = 9$ ) rowers. Multiple discriminant function analysis determined that of the four variables analysed (mean propulsive power output per kilogram of body mass [PPK], propulsive work consistency [PWC], stroke to stroke consistency [SSC], and stroke smoothness [SMO]), PPK most clearly distinguished between ability levels. However, PWC, SSC and SMO all contributed ( $p < 0.001$ ) to the classification of rowers into their correct ability category. Although a clear correlation between the skill variables and on-water performance was not identified, the positive relationship observed between the novice, good and elite rowers and the skill-based variables provides some rationale for their inclusion in performance prediction models.

Although oar force profiles have been examined with respect to the level of the rower (novice vs elite), bow versus stroke forces, the effect of the height of pull or fatigue, the position of the blade, and the force signature, there still remains many unanswered questions regarding the usefulness of

force profile information in predicting rowing performance.

### 5.1.2 Foot-Stretcher Force Profiles

The foot-stretcher provides a solid base (with respect to the boat) against which the athlete can apply force to produce forward propulsion of the boat. Measurements of foot-stretcher forces are relatively limited with respect to the previously reviewed oar forces. At the catch, foot-stretcher forces are reported to range from 100 to 392N depending on whether data were collected during tank rowing,<sup>[35]</sup> on-water sweep rowing by elite coxless pairs<sup>[9]</sup> or 'good' single scullers.<sup>[8]</sup> Foot-stretcher forces are reported to peak between 299 and 600N during the drive phase.<sup>[8,9,32,34,35]</sup> The large variation in peak foot-stretcher forces recorded may be due to analysis of sweep rowers versus scullers, on-water versus simulator rowing or the skill level of participants.

The magnitude of applied foot-stretcher forces during on-water sculling by elite female scullers differ between stroke and bow side feet by as much as 55N (18.4%).<sup>[32]</sup> The side of greatest force application was not consistent for all subjects. During on-water sweep rowing in coxless pairs, Korndle and Lippens<sup>[8]</sup> graphically showed an approximate 33% or 200N greater force application on the oar-side leg compared with the non-oar-side leg. Following similar analyses of scullers, Korndle and Lippens<sup>[8]</sup> reported that due to the asymmetrical nature of sweep rowing, discrepancies in the magnitude of force application to each foot-stretcher were 'more significant' in rowers.

Zatsiorsky and Yakunin<sup>[34]</sup> cited German and Russian research that reported foot-stretcher force application was initiated 0.15–0.22 seconds prior to the blade entering the water. Similar findings can be derived from figures presented by Korndle and Lippens<sup>[8]</sup> temporally illustrating oar and foot-stretcher forces from single scullers on-water. Although numerical data were not provided, it is evident that force to the foot-stretcher was applied prior to force on the oar. Early foot force application would transfer negative propulsive forces to the foot-stretcher and McBride and Elliott<sup>[39]</sup> suggest that this em-

phasises the importance of leg drive timing at the catch. No research has specifically investigated if the interval between foot-stretcher and oar force application is an indicator of elite performance.

The time of peak foot-stretcher forces during a stroke cycle are most commonly described with respect to the time or angle of peak oar/pin force and are reported to reach peak magnitude prior to,<sup>[8,32,95]</sup> at the same time<sup>[8]</sup> or following<sup>[32]</sup> peak oar forces. Loschner and Smith<sup>[32]</sup> investigated the relationship between pin and individual feet forces during on-water sculling by three international level sculling specialists. Stroke and bow side foot-stretcher forces were compared with their respective oar force. On stroke side, all three participants reached peak foot-stretcher force after (range 2–10°) peak oar force; however, on bow side, two of the three participants reached peak foot-stretcher force prior to peak oar force (7–10°). The authors did not discuss possible reasons for the reported differences. During the drive and recovery phase of the stroke cycle, the left hand passes on top of the right hand when the oars are perpendicular to the boat due to the length of the inboard shaft of the oar. This asymmetrical movement may result in the different timing of peak foot-stretcher force application. To ensure this is a true effect, a greater sample of scullers needs to be assessed with regard to the typical error of measurement for timing of peak foot-stretcher force and peak handle force during on-water sculling. Further research is required before the optimal timing of pin and foot-stretcher forces can be concluded for either rowers or scullers.

It is not currently reported if the discrepancies in timing and magnitude of peak forces applied to the foot-stretcher change with sculling and sweep rowing skill ability level. A comparison of foot-stretcher force-time profiles by skilled and unskilled scullers (classifications were based on rower success at regattas) showed that skilled scullers ( $n = 4$ ) consistently produced negative anterior-posterior force curves during the drive phase of the stroke.<sup>[8]</sup> All unskilled scullers (sample size not reported) produced extremely variable anterior-posterior force curves that initially increased with increasing oar



force. The consistent negative anterior-posterior force curves could not have been an adaptation to a particular coaching style as three different people coached these skilled scullers.

## 5.2 Internal Forces (Muscle Activation Patterns)

Force application measured from the pin, oars and or foot-stretcher is generated through appropriate muscle activation patterns. It is accepted that the linear relationship between integrated electromyogram (EMG) and force during isometric contractions is present during ergometer (Concept2) rowing and, therefore, provides a method of determining those muscles that are not activated appropriately during ergometer activity.<sup>[100]</sup> Researchers have used Gjessing<sup>[101]</sup> and Concept2<sup>[72,100,102,103]</sup> ergometers due to the difficulties of determining muscular activation patterns during on-water sculling or sweep rowing.

Rodriguez et al.<sup>[102]</sup> and Wilson et al.<sup>[101]</sup> used sweep rowing specialists to describe the pattern and intensity of muscular activity whilst on ergometers that did not differentiate between right and left sides. It appears reasonable to assume that similar recruitment patterns and levels of activation would be observed in scullers on the same ergometers. However, it is accepted that differences in muscular activity of the trunk and upper limbs would be measured if EMG were recorded using an ergometer that required trunk rotation at the catch.

Muscular activity in the lower limbs was reported to be low ( $n = 5$  experienced male rowers)<sup>[102]</sup> or  $<50\%$  of maximal ( $n = 9$  lightweight university class male rowers)<sup>[101]</sup> during the catch position with the exception of tibialis anterior<sup>[101]</sup> and vastus medialis.<sup>[102]</sup> Tibialis anterior was involved in ankle dorsiflexion as the shank became more vertical and the vastus medialis muscles acted eccentrically to stop knee flexion and movement of the sculler towards the stern of the boat. The drive phase was characterised by synchronous recruitment of gluteus maximus, vastus lateralis, biceps femoris and gastrocnemius.<sup>[72,101,102]</sup> Maximal levels of muscular activity were reached just prior to (gluteus maximus,

vastus lateralis, biceps femoris) and at (gastrocnemius) peak handle force<sup>[101]</sup> and during mid-drive when the knees were at  $90^\circ$ .<sup>[102]</sup> Wilson et al.<sup>[101]</sup> defined co-contraction as occurring when the EMG levels of two muscles were simultaneously  $>50\%$  of their individual peak activity. The knee flexor moment created by the biceps femoris, acting as a hip extensor and knee flexor was overcome by the vastus lateralis acting as a knee extensor.<sup>[101]</sup> Co-contraction is often reported to reduce mechanical efficiency<sup>[104]</sup> in sport; however, during sculling and rowing the knee and hip must be forcefully extended during the drive phase, requiring co-contraction of the quadriceps and hamstring muscle groups.

Throughout the drive phase, intra-individual variability was greatest for gluteus maximus and least for biceps femoris activity.<sup>[101]</sup> Average peak biceps femoris activity, reported as a percentage of group peak biceps femoris activity was  $80\%$ , illustrating some degree of variability of peak activity. On average, one standard deviation represented  $10\text{--}20\%$  of the signal for each muscle.<sup>[101]</sup> One stroke cycle was analysed by Rodriguez et al.<sup>[102]</sup> who observed that few differences were observed between strokes.

At the end of the drive phase, a steady decline in activity of vastus lateralis and medialis,<sup>[102]</sup> biceps femoris and gluteus maximus,<sup>[72,101]</sup> and gastrocnemius<sup>[101,102]</sup> has been reported. The exception to this was reported by Wilson et al.,<sup>[101]</sup> who graphically showed rectus femoris and tibialis anterior activity increasing during the final third of the drive phase and reaching near peak activity at the finish. Tibialis anterior maintained this high level of activation into and throughout the recovery phase. The increase in rectus femoris activity may occur to eccentrically assist in slowing extension of the hip while tibialis anterior prepares for ankle dorsiflexion and assists in stopping movement of the body into the bow of the boat.

Jaszczak<sup>[103]</sup> compared peak muscle activity during ergometer rowing and maximal effort static contractions. Eight rowers (four world class and four national level) completed maximal voluntary contractions of the elbow, shoulder, knee, hip and trunk flexors and extensors followed by maximal effort

rows on a Concept2 ergometer at 32, 36 and 40 strokes/min. Using inverse dynamics, the percentage utilisation of each muscle group during ergometer rowing was compared with total static torque generation. The knee, hip and shoulder extensors utilised the greatest potential strength for the world-class and national-level rowers. Hip extensors reportedly utilised 110–120% of potential strength. Utilisation of shoulder extensors, although high in the world-class rowers, was 35–40% less than the national level rowers. This may indicate that the world-class rowers more efficiently utilised their larger muscle groups (knee and hip extensors) than the national-level rowers, and were not taking it on the hands as it is commonly referred to amongst the rowing fraternity. Muscle strength may not be as important as the ability to coordinate upper and lower body activity<sup>[102]</sup> in optimising performance.

Fatigue may affect the ability to coordinate upper and lower body activity during ergometer rowing. Kyröläinen and Smith<sup>[72]</sup> reported earlier activation of rectus femoris, vastus medialis and vastus lateralis and significantly greater ( $p = 0.001$ ) integrated EMG in all main acting muscles following 3.58 minutes of maximal effort rowing. Throughout the 4.5-minute trials, subjects were able to maintain stroke rates of 28, 30 and 32 strokes/min; however, the authors concluded that the subjects "...were progressing towards a fatigued state as the IEMGs of the main acting muscles increased without corresponding increasing power output".<sup>[72]</sup> Stroke rate alone had no effect on EMG magnitude or timing.<sup>[72]</sup>

The EMG activity from ergometer studies cannot be compared with on-water activity. It is currently assumed that the Concept2 and Gjessing ergometers simulate similar EMG patterns to on-water sculling or sweep rowing but no research has investigated the relationship between muscular activity patterns or magnitudes and 2000m performance.

## 6. Factors Affecting Kinematics and Kinetics of Rowing

The anthropometric characteristics of the athlete and boat set-up can also affect the kinematics and kinetics of rowing.

### 6.1 Anthropometry

The study of anthropometry can relate the structure of the athletic body to the specialised function needed for various tasks and can also be used to understand the limitations of such relationships.<sup>[105]</sup> These associations are of interest to rowing biomechanists and coaches and can be used in the identification of rowing potential. Table II summarises key papers that have investigated the anthropometrical profiles of scullers and rowers. Researchers specifically trying to identify the key predictors of performance in rowing have compared a rowing population to a normative population<sup>[16,23]</sup> or compared the population based on class<sup>[106,107]</sup> or skill level.<sup>[16,17,23]</sup>

Using 72 national level Australian rowers (31 males, 46 females), a range of physiological and anthropometric tests were administered<sup>[17]</sup> and highly ranked rowers were compared with lower ranked rowers. Anthropometric variables included: mass; standing and sitting height; body segments lengths; breadths and girths; and total skinfolds. The results demonstrated that the highly ranked males were taller and heavier, had a smaller sum of total skinfolds, had longer forearms and thighs, a greater biceps girth and had smaller hips with respect to their shoulder width. Contrasting these significant anthropometric differences, females of differing performance ability were found to be of similar shape and size in all aspects. Whether female rowers can be distinguished by other determinants of performance such as their physiology or biomechanical profiles is unknown. It may be suggested that the competitive environment in 1990 was stronger for male than female rowers and that anthropometrical differences therefore played a bigger role in performance outcomes. If a similar study was completed now, 14 years later, a similar finding may be reported for the female rowers.

A more recent study<sup>[16]</sup> of 383 elite male juniors (mean age 17.8, range 15.1–18.6 years) at the 1997 world junior championships supported the previous findings of Hahn<sup>[17]</sup> and reported that the finalists were taller and heavier, and had greater limb lengths, breadths and girths. Additionally, it was

**Table II.** Studies reviewing anthropometry of successful scullers and rowers

| Study                              | Sample                           | Methods   | Conclusions   |
|------------------------------------|----------------------------------|---|---|
| Bourgois et al. <sup>[23]</sup>    | 220 elite male junior rowers     | 90% of all female rowers participating at the 1997 world junior rowing championships were sampled<br>Age 14.6–18.6y   | Elite junior female rowers are taller, heavier, with greater length, breadth and girth dimensions and lower skinfold thickness than female non-rowers of a similar age<br>Elite junior female scullers (n = 108) are taller, heavier, with greater length, breadth and girth dimensions and greater skinfold thickness than female rowers (n = 94)<br>Female finalists (n = 112) are taller, heavier, with greater length, breadth and girth dimensions than non-finalists  |
| Bourgois et al. <sup>[16]</sup>    | 383 elite male junior rowers     | 89% of all male rowers participating at the 1997 world junior rowing championships were sampled   | Elite junior male rowers are taller, heavier, with greater length, breadth and girth dimensions than male non-rowers of a similar age<br>Male rowing finalists had greater length breadth and girth dimensions than non-finalists   |
| Jurimae & Jurimae <sup>[106]</sup> | 20 male national level rowers    | Rowers classified as lightweight (n = 9) and open class (n = 11) according to individual body mass  | Open-class rowers were heavier and had a greater body mass index, lean body mass, thigh cross-sectional area, muscle mass and skeletal mass compared with lightweight rowers<br>No significant differences in skinfold measurements (sum 6 sites) and percentage body fat between sample groups   |
| Hollings & Robson <sup>[107]</sup> | 36 elite male and female rowers  | Rowers classified as male heavyweight, male lightweight or female heavyweight<br>Height, weight, skinfolds, breadths and girths were measured 3 weeks prior to the 1990 world championships | Compared with overseas oarsmen and women NZ heavyweight oarsmen were shorter and lighter; NZ lightweight oarsmen were shorter and heavier; and NZ heavyweight oarswomen were taller and heavier<br>All NZ oarsmen and women had greater endomorphic, less mesomorphic and less ectomorphic components compared with overseas oarsmen and women except lightweight men who had a greater ectomorphic component   |
| Hahn <sup>[17]</sup>               | 77 elite male and female rowers  | All measurements were taken during a 6wk period around the 1988 Australian rowing championships<br>Scullers were distinguished from rowers  | Scullers and rowers were taller and had proportionally longer legs than the general population<br>Scullers and rowers had a slightly above average arm length to total height ratio<br>Highly ranked male rowers were significantly taller and heavier with longer forearms and thighs than lower ranked rowers. Similarly, highly ranked male rowers had a lower total skinfold measurement, smaller hips and a greater biceps girth<br>There was no difference in any anthropometrical variables between highly ranked and lower ranked female rowers |
| Ackland et al. <sup>[36]</sup>     | 296 elite male and female rowers | All measurements were taken during a 4wk period around the 2000 Olympic Games<br>Scullers were distinguished from rowers  | Open-weight male rowers had greater mesomorphy (muscularity) than open-class females and all lightweight categories<br>Open-class females had the highest endomorphy (relative fatness) score, whilst lightweight male and female rowers scored highest on ectomorphy (linearity or slinness)   |

found that the competing population was significantly different from the normative population. Specifically, the junior male rowers were 7% taller, 27% heavier and had significantly greater limb lengths and breadths than the normative population. It is assumed that this greater limb length gives a rower a mechanical advantage by increasing their lever length and time available for force application. Bourgois et al.<sup>[16]</sup> also found junior males rowers to have a longer leg length relative to their stature compared with the normative reference group. This finding has not been supported in elite male rowers.

It would appear that a male's physique is an important determinant of success at world-class competition. Before such claims can be made for female rowers a large-scale research project is required, which ideally is prospective in nature. A longitudinal prospective study will allow the relationship of anthropometrical variables to performance to be determined as a necessary pre-requisite of rowers (e.g. limb lengths) or a developed attribute (e.g. lean body mass).

## 6.2 Equipment

Except for a minimum weight specification for each rowing sub discipline, the construction, design and dimensions of rowing boats and oars are unrestricted by the International Rowing Federation (FISA). Modifications can be made to the design of the hull, oars, blades and foot-stretcher; however, new 'innovation' must be equally available to all competitors, be at a reasonable cost and be safe and environmentally sound.<sup>[108]</sup>

The oars, consisting of the handle, shaft and blade have been modified to improve the performance of elite scullers and sweep rowers. Croker Oars Pty Ltd (New South Wales, Australia)<sup>[109]</sup> state that handles are designed for "...comfort and ease of use..." and have reported that there may be a correlation (r-value not reported) between hand size (measured from the base of the thumb and the tip of the fingers) and preferred grip size. This company provides a simple hand chart relating hand size to grip size to help guide rowers to the most appropriate grip. No research is available to support or

negate this proposition. The shaft of the Croker oar is made from carbon fibre producing an extremely light (1.4–2.7kg) lever that reportedly offers maximum force transfer to the blade. A traditional symmetrical wooden Macon Blade was used by most rowers until 1991 when the Hatchet blade was introduced. The Hatchet is asymmetrical, reportedly more stable under load and minimises vertical movement in the water during the drive phase.<sup>[109]</sup> When using the Hatchet blades, 36.4% greater peak compressive force at the catch was determined at the L5-S1 joint, whereas 15.9% and 28.7% less force was determined for the same joint during the drive and at the finish position.<sup>[76]</sup> The greater percentage of peak compressive force on L5-S1 may be due to the reported reduction in slippage<sup>[110]</sup> of the blade at the catch. By 1993, 90% of the medals awarded at the Rowing World Championships went to rowers using hatchet blades. The impact of the introduction of the hatchet blades on low back pain and injuries over the last decade has not been assessed.

The foot-stretcher is a plate used to position the feet in a boat. Redgrave<sup>[86]</sup> states that "careful adjustment of the foot-stretcher position can optimise the work angle of the knees and ankles to obtain maximum efficiency for the leg drive". The foot-stretcher can be adjusted in three directions: vertically, horizontally and obliquely (changing the rake). The vertical positioning of the foot-stretcher can be determined by placing the balls of the feet only slightly lower than the seat to ensure maximum forward propulsion in the horizontal plane.<sup>[86]</sup> The ideal horizontal position will allow a "...correct finish angle (and) catch angle" by positioning the foot-stretcher relative to the point of oar rotation.<sup>[86]</sup> The rake of the foot-stretcher has been recommended to be between 41–46° but will be dependent upon a rower's ankle range of motion.<sup>[64,86]</sup> Although these guidelines have been developed following substantial on-water experience by members of the rowing fraternity, no research has been completed to investigate different foot-stretcher orientations and on-water rowing performance. An individual's ankle range of motion, lower limb anthropometry and

possibly discipline (sculling or sweep rowing) may affect the optimal foot-stretcher position.

## 7. Conclusions

This paper has reviewed the sculling and sweep rowing strokes from a biomechanical viewpoint in terms of kinematics and kinetics. Research utilising a range of ergometers dominate the literature and provide evidence that force- and velocity-time profiles can distinguish sculler and sweep rowers of different skill levels<sup>[7]</sup> and between elite rowers in different seat positions.<sup>[9,90]</sup> It is currently assumed that rowers classed as novice or intermediate, who are able to develop force-time profiles similar to elite rowers, will improve their own performances. However, research to indicate improvements in performance due to technique or equipment changes are currently limited in the literature.

Based on current research findings, it is difficult to provide clear guidelines regarding optimal biomechanical stroke patterns. Future research should focus on clarifying the following points:

- What is the ideal oar force – angle profile for scullers and rowers in bow and stroke seat positions?
- What percentage decrease in stroke length and therefore time of force application will have a negative affect on performance?
- What is the ideal interval between oar and foot-stretcher force application for a rower, and between different crew members?
- What is the influence of foot-stretcher position on rowing performance and can foot-stretcher position be optimised, as suggested by Redgrave<sup>[86]</sup> and Herberger<sup>[64]</sup> for individual rowers?
- Do changes in body segment movement patterns during rowing relate to changes in performance measures such as boat velocity?
- What are the biomechanical similarities or differences between ergometer and on-water sculling or sweep rowing?
- Can coaches or selectors use force application profiles to reliably or validly predict a rowers' current or future rowing performance?

The kinematics and kinetics of the rowing movement have been described on ergometers, on-water and for novice and elite male and female rowers, but there is limited research on the ideal rowing technique or how a rower's anthropometry or boat set-up could help improve/optimize rowing performance.

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