Mechanics and Energetics of Rowing

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Chapter 1

General Introduction

GENERAL INTRODUCTION

August 1, 1715; Six apprentice watermen are lined up in their traditional rowing vessels on the river Thames, right under the London Bridge. Normally they serve as the 18th century equivalent of a water taxi, transporting customers from one shore of the Thames to the other. But today is different. Ahead of them lies a 4 miles and 7 furlongs race, which will be held against the tide! It's a prestigious race too. The origins of the race lie a little earlier that year. On his way to one of London's many theatres, Thomas Doggett, a then famous Irish actor fell overboard during one of his crossings of the Thames. He was rescued by one of the watermen. In gratitude, he offered a prize for the fastest waterman in his first year of service. The winner will receive the watermen's red coat and a silver badge, in honor of the ascension of the throne of George I, earlier that year. The race marked the start of a century's long tradition.[26]

The 'Doggett's Coat and Badge' is the oldest recorded rowing race in the world. The race still exists in nearly identical form, making it one of the oldest sporting events in continued existence. In the early years, it took the watermen over 2 hours to complete the course, implying that, relative to the shore, they where rowing at an average speed of just over 1 m/s. In 2008, it took Olaf Tufte just under 7 minutes to complete the 2000 meters of Beijing's Lake Shunyi and become Olympic Champion. Tufte rowed at an average speed of 4.8 m/s, nearly 5 times as fast as the first winners of the Coat and Badge races!

Energy and Power

Both the rowers in the Beijing Olympic final and those of the first Coat and Badge race need energy to row. The human body can be seen as an engine, with adenosine tri-phosphate (ATP) as its source of energy[2]. In the muscles, ATP is being split up in ADP and phosphate and subsequently resynthesized. During the split up of ATP, energy is released. This liberated energy is used to drive crossbridge cycling in the muscle fibers[2], resulting in force generation in the muscle fibers. When muscle fiber length changes, mechanical energy is exchanged between muscle fibers and their environment.

When forces are exerted on the environment and the points of application of those forces move in relation to any frame of reference, mechanical energy is exchanged with the environment (e.g.[27]). When considering the rower, forces are exerted between the foot stretcher and the feet and between the handles and the hands. Both stretcher and handles move relative to the earth, thus, mechanical energy is exchanged between the rower on the one hand and boat and oars on the other hand. For every joule of mechanical energy generated by muscle fibers, at least about 4 joules of metabolic energy needs to be liberated[2]. In other words, the gross efficiency (e_{gross}), being the ratio between mechanical to metabolic energy[2], of human motion cannot be higher than 0.25[9].

To gain insight into the generation and dissipation of energy, the power balance is a useful tool[11]. In its simplest form, the instantaneous mechanical power balance for any passive system (meaning no energy is added to the system) can be written as:

$$\Sigma P_{external} = dE/dt^{[29]}$$
<div align="right">Equation 1.1</div>

In words, equation 1.1 states that the sum of all external power terms of a system ($\Sigma P_{external}$); i.e. the total mechanical power exchanged with the environment; equals the rate of change of the kinetic energy of that system (dE_{kin}/dt).

When mechanical power is generated from within the system, the system considered becomes an active system and equation 1.1 should be extended as follows:

$$\Sigma P_{external} + \Sigma P_{internal} = dE/dt^{[11]}$$
<div align="right">Equation 1.2</div>

Here $\Sigma P_{internal}$ represents the sum of internal power production.

In the case of endurance sports, the athlete produces mechanical power, represented by $\Sigma P_{internal}$ in Equation 1.2. Power production (P_{rower}) results from the aforementioned

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turnover from metabolic power ($P_{metabolical}$) into mechanical power. This can be expressed as:

$$P_{internal} = P_{rower} = e_{gross} \cdot P_{metabolical}[11]$$ Equation 1.3

Where e_{gross} stands for gross efficiency; i.e the ratio between $P_{internal}$ and P_{rower}.

The Power Equation in Endurance Sports

Obviously, the investigation of rowing as a competitive sport can be approached from several angles, of which the power equation is just one. The physiology of the rower[5, 21], his movements[16], or the forces he exerts on, for instance, the handles[17, 24] or foot stretcher[13, 15] have been the topic of many studies. Often, (multiple) regression analysis were performed to identify performance determining factors[4, 22]. Performing a regression analysis might help to identify what is important in rowing. However, these methods do not always provide answers to *why* some factors are important for performance. Moreover, a priori it might be difficult to decide which factors to include in the regression analysis. We argue that in periodic tasks where a large amount of mechanical power is exchanged with the environment, the use of the power equation as presented in equation 1.2 is an attractive method to use. The equation can be applied to any (sub) system and can thus incorporate both the biological system (in this case the rower) and the mechanical system (in this case oars and boat)[11]. Central in the analysis of performance is always the goal, which in most cases will be to maximize average velocity. It is the task of the athlete to maximize the mechanical power flow to processes associated with this average velocity, and to maximize the average velocity at given mechanical power transfer (i.e. by optimizing drag parameters[19]). The mechanical power equation has been successfully applied in sporting activities such as skating[12] and cycling[14], but also wheelchair riding[28]. Due to its nature, the equation is less informative for events such as long-distance running (where little mechanical power is exchanged with the environment) or non-periodic tasks such as soccer or hockey.

The Power Equation for Rowing

A first description of the power equation of rowing was given three decades ago by Van Ingen Schenau[10], who pioneered the application of the power equation in endurance sports. The power equation can help understand why Tufte is so much faster than his early predecessors on the Thames. To that aim, equation 1.1 needs to be specified for the specific case of rowing. In both the coat-and-badge race and the Olympic Final, the system of interest consist of a rower, a boat and (a pair of) oars. It is important to identify where in the system boat-rower-oars mechanical power is dissipated to the environment. The major part of mechanical power is dissipated as the result

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of drag force on boat and rower. About 10% of the total drag power is related to air friction, the remainder is related to water resistance[18]. The instantaneous drag force (F_{drag}) is related to the velocity of, in this case, the boat. This relationship is captured surprisingly well by the following simple equation:[3]

$$F_{drag} = -k \cdot v_{boat,water}^2 \qquad \text{Equation 1.4}$$

In this equation, $v_{boat,water}$ is the boat velocity relative to the water and k is a constant, depending on water density, viscosity, streamline and wetted surface of the boat. Boat velocity is assumed to be positive in any case. Power dissipated by F_{drag} (P_{drag}) can subsequently be written as

$$P_{drag} = -k \cdot v_{boat,water}^2 \cdot v_{boat} \qquad \text{Equation 1.5}$$

In this equation, in an earth bound frame of reference, v_{boat} is the boat velocity relative to the earth. Under still water conditions, equation 1.4 reduces to

$$P_{drag} = -k \cdot v_{boat}^3 \qquad \text{Equation 1.6}$$

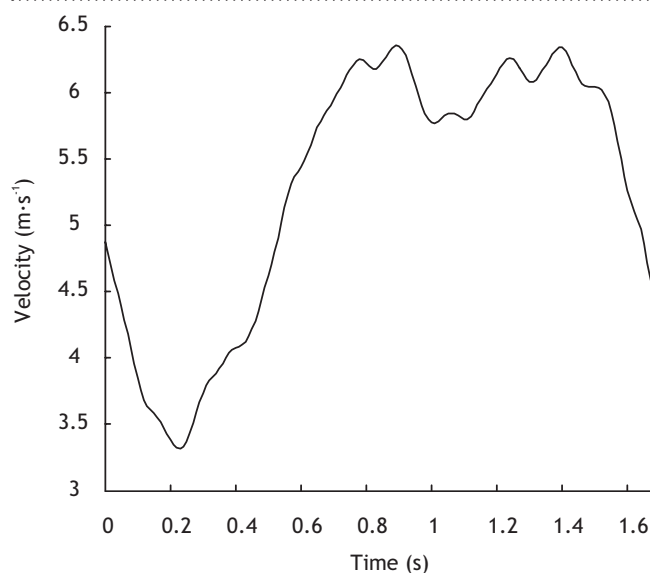*Figure 1.1: Velocity profile of a single scull, rowed by an elite level male rower. The boat was travelling at an average speed of 5.29 m·s^{-1}. The profile shows that fluctuations in boat velocity within one stroke cycle are quite large.*

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Since drag power is related to velocity cubed, this implies that it is most beneficial to row at a constant speed[18]. In rowing, boat velocity fluctuations within a stroke cycle are quite large ([18], see also Figure 1.1). These fluctuations are caused by the fact that propulsion in rowing is not continuous, but mostly by the rower moving back and forth on the slides. Since the mass of the rower is up to 8 times larger than that of the boat (single scull), boat movements are heavily influenced by movements of the rower. The velocity fluctuations lead to a power loss term that is unrelated to average velocity. This power loss is defined by the difference between average drag power and hypothetical drag power that would occur when boat velocity would be constant, and is defined by $\overline{P}_{\Delta v}$. Velocity efficiency ($e_{velocity}$) can be calculated as follows

$$e_{velocity} = 1 - \overline{P}_{\Delta v}/\overline{P}_{rower} \hspace{4cm} \text{Equation 1.7}$$

If the rower minimizes his movements, boat speed fluctuations will be minimal and $e_{velocity}$ will be close to 1. This is a potential dilemma; since not using the sliding seat will mean that the rower cannot use his leg muscles and consequently can produce much less mechanical power.* Thus, there is a potential tradeoff between maximum power production and maximum velocity efficiency.

Rowers use their oars to push off against the water. When they do so, they move a certain amount of water with the blades. This can be observed by the 'puddles' that the blades leave behind in the water after each stroke. Thus kinetic energy is given to the water, and this energy can be seen as a loss[30]. The average amount of power put into moving water with the blades ($\overline{P}_{blade}$) is the second major source of energy dissipation. Accordingly, the efficiency of propulsion ($e_{propelling}$) can be calculated as follows

$$e_{propelling} = 1 - \overline{P}_{blade}/\overline{P}_{rower} \hspace{4cm} \text{Equation 1.8}$$

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* A mechanical solution was found, and used, in the early 1980's by means of the sliding rigger. By installing a stationary seat and using a sliding rigger and foot stretcher construction, the same rowing movement is still possible, but the amount of moving mass is much smaller. Speed fluctuations are therefore also much smaller, and consequently, $e_{velocity}$ will be substantially higher. Using equations 1.1 through 1.6, it can be calculated that with power output remaining the same, a gain of up to 9 seconds in finish time can be achieved when velocity fluctuations are absent. All but 1 rower in the men's single scull final of the World Championships in 1982 adapted the sliding rigger. The one rower that used a traditional rigger setup finished last in this final. In 1984, the sliding rigger was banned for competition by the FISA. Figure 1.2 shows that in '81 and '83 the winning times were much faster than in the previous years (the '82 finishing time is not known). However finishing times in the following years were just as fast or even faster, so other factors play a role as well. As a side-note, it is interesting to mention that many elite rowers that had been using the sliding rigger were glad that they were now banned. The sliding rigger made rowing 'too easy', meaning that strong, yet less technically skilled, athletes could all of a sudden compete at the highest level too (personal communication with one of the finalists)

Other sources of energy dissipation, such as friction in moving parts including deformation of boat and oars, are estimated to be negligibly small, and thus omitted in the power equation. The mechanical power equation for the system boat, rower and oars in still water can now be specified as follows;

$$P_{metabolical} \cdot e_{gross} + -k \cdot v_{boat}^3 + P_{blades} = dE_{kin}/dt \qquad \text{Equation 1.9}$$

Averaged for the steady state condition the power production equals the power dissipation. The dissipated mechanical power can be divided in terms related to average velocity ($-k \cdot \bar{v}_{boat}^3$) and terms unrelated to average velocity ($\bar{P}_{blade}$ and $\bar{P}_{\Delta v}$).
This becomes obvious when the average power equation for the steady state periodic rowing is written down:

$$\bar{P}_{metabolical} \cdot e_{gross} + -k \cdot \bar{v}_{boat}^3 + \bar{P}_{\Delta v} + \bar{P}_{blade} = 0 \qquad \text{Equation 1.10}$$

This fairly straightforward equation is central to every analysis made in this thesis. To illustrate its potential we will use this equation to analyze the 'confrontation' between the coat-and-badge race and the Olympic Final.

Coat and Badge vs. the Olympic Final
Let's first consider the power loss to drag; one obvious difference between the Coat and Badge race and the Olympic Final lies in the boats that were used. In the Olympic Final, boats were used that were optimized for minimum drag and probably all had the by FISA rules instated minimum weight of 14 kg*.
The watermen on the other hand had to row in very heavy boats; these boats were not primarily built for speed, but were designed to be sturdy and had to accompany at least one passenger. They had their oarlocks mounted on the gunwales instead of on outriggers, necessitating a much wider and thus much less streamlined boat. Moreover, they had to row against the current, where Tufte and his competition only had to face a slight headwind. Considering all this differences it is clear that at similar velocities relative to the shore, P_{drag} would be much higher for the boats used in the Coat and Badge race. Put otherwise, had Tufte rowed in an antique water taxi, he would have gone much slower. On the positive side for the watermen, because they used a fixed seat, velocity fluctuations (and the associated power loss) would be much lower for them. Nevertheless, this advantage would by no means compensate for the disadvantage of the much higher drag of the watertaxi.

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* FISA Rules of Racing; Rule 34, 2009

Now consider power losses at the blades; Tufte's oars were made of lightweight carbon fiber and fitted with large "big-blades", allowing Tufte to push off against a large water mass. The Watermen used heavy, wooden oars with small blades. It is very likely that Tufte had more efficient oars, and thus lost (relatively) less power at his blades.

Now let's turn to the power produced by the rower; since the watermen sat on a fixed seat, they had only their arms and trunk available to produce mechanical power. Modern racing shells are equipped with sliding seats, so that rowers can also use the muscles in their legs for propulsion; i.e. modern rowers have more muscle mass available to produce mechanical power. In any case, Tufte was able to produce (much) more mechanical power.

All in all, Tufte had much more power available to overcome water resistance; he produced more mechanical power and lost relatively less mechanical power at the blades. As there is no doubt that the advantage of the watermen in terms of velocity efficiency is far exceeded by the disadvantage of the watermen in terms of drag characteristics, it is now clear why Tufte could row that much faster.

The confrontation between today's Olympic champion and the 18th century waterman has an obvious winner. Yet, this comparison does illustrate rather nicely how the power equation can help understand the essential aspects of man and material and their effect on performance. From a historical perspective it is interesting how material developed between 1715 and now. The shape and weight of the boats have been virtually unchanged over the last century. In 1868, a company in Troy, New York produced racing shells made of paper(!)[25] with a claimed weight for a single scull of only 28 lbs (12.7 kg)[6], which is even under the now by FISA instated minimum boat weight. A first version of the sliding seat (using oil and grease to minimize friction!) was patented as early as 1874[7]. The adjustable outrigger, not very different from outriggers found today, was patented in 1883[8], but at that time riggers in different forms had already been around for many years.

Despite the fact that many important technical innovations occurred a long time ago, finishing times over 2000m rowing races (the official distance in rowing) are continuously improving[20]. Figure 1.2* shows the finishing times at the Rotsee course in Lucerne from 1955 until last year. The Rotsee is a very deep lake, surrounded by hills, so that weather and temperature influences on finishing times play a smaller role than usual. The Figure clearly shows a descending trend in finishing times.

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* With many thanks to Urs Kauffmann of Regattaverein Luzern, who was kind enough to provide us with the winning times.
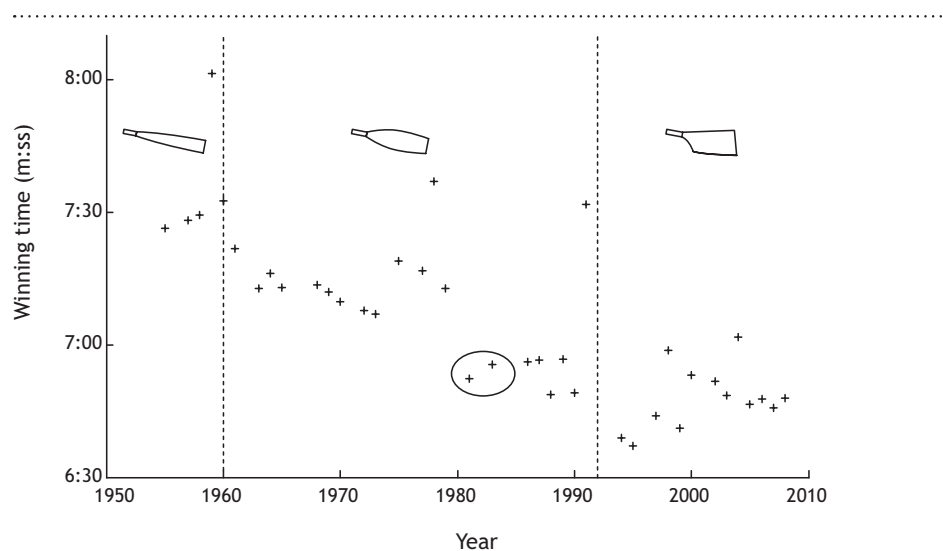
Figure 1.2: *Winning times of the men's single scull at the Rotsee Regatta in Lucerne. The Figure shows the evolution of blade shapes, with the introduction of the 'Macon' blade in 1960 and the introduction of the 'Big Blade' in 1992. The circled finish times (1981 through 1983) were realised with the use of a sliding rigger.*

Probably, the most influential change in recent years was the introduction of the 'hatchet' shape blade (big blades) Since their introduction in the early 90's, improvements in performance could be expected, since the use of big-blades results in a higher propelling efficiency[1]. Figure 1.2, showing the finish times at the Rotsee Regatta since 1955, shows a drop in finishing times after the introduction of the big-blades. However, as finish times in some of the following years are higher, this could be coincidental.

As modern equipment is not that different from the equipment used half a century ago, at least part of the improvement in finish times should be attributed to the rowers themselves. New and better training methods resulted in larger mechanical power production[20]. Better rowing technique has likely resulted in a more optimized trade-off between power production and power losses.

This thesis will point out that apart from material; also the skill of the rower is an important factor for performance. Any rowing coach will agree that rowing is not only a very physical, but also a very technical sport.

Thesis outline
This thesis focuses on modern competitive rowing. In every chapter, the power equation serves as the toolbox and is used to analyze aspects of either on-water or ergometer rowing. Chapter 2 describes the effect of the manipulation of stroke rate on the production and distribution of mechanical power. Chapters 3 and 4 focus on the 'production' side of the equation. Chapter 3 deals with the turnover from metabolical to mechanical energy and its suggested dependence on stroke rate. Chapter 4 explores how a simple adaptation to the boat might lead to a substantially higher power output. Chapters 5 and 6 discuss the two power loss terms, namely power lost to velocity fluctuations (Chapter 5) and power loss at the blades during push-off (Chapter 6).

Distribution of Energy in Rowing (Chapter 2)
Rowing performance is defined by the average boat speed. This is in turn defined by the amount of mechanical power that is 'available' to overcome drag at a constant velocity; i.e. mechanical power that is not lost at the blades or to velocity fluctuations. In Chapter 2 we investigated how the net mechanical power output of the rower, the fraction of this power contributing to the average velocity, and power losses quantified by propelling efficiency and velocity efficiency are affected by stroke rate.

Gross efficiency (Chapter 3)
A concern regarding to stroke rate in earlier work is that at increasing stroke rates, e_{gross} decreases[21]. This aspect of the power equation was not addressed in Chapter 2. In Chapter 3 we evaluate the claim that at higher stroke rates "more energy is needed to propel the rower's body back and forth"[5]. The aim of this chapter thus was to investigate if e_{gross} is affected by stroke rate. A second aim was to determine if the amount of negative mechanical power (i.e. mechanical power transferred from the environment to the rower) is an appropriate measure of internal power losses.

Increasing mechanical power (Chapter 4)
In general, constraining movement for a direction in which movement is undesirable is usually a good idea[23]. In endurance sports, this concept has been successfully applied in for instance cycling (clip-in pedals help cyclist to keep contact with the pedals) and running (spikes prevent slip of the shoe). In Chapter 4, the same concept is applied to rowing. It was tested if strapping the rower's pelvis to the sliding seat leads to improved performance during the start of ergometer rowing.

Energy losses to velocity fluctuations (Chapter 5)
Chapter 5 focuses on the power loss resulting from boat velocity fluctuations. The suggestion that technique is important for an optimal 'boat run' is addressed in this

chapter, using an adapted ergometer on slides. Here, the assumption is tested if, by superior movement execution, it is possible to minimize boat velocity fluctuations. The first aim of this study was to determine the relative contribution of $e_{velocity}$ to performance in relation to the relative contributions of O_2-max and e_{gross}. The second aim of this study was to investigate which kinematic and/or kinetic variables defining the rower's technique are related to differences in $e_{velocity}$.

Energy losses at the blades revisited (Chapter 6)

As mentioned earlier, the majority of mechanical energy is lost at the blades during the push-off against the water. To investigate those energy losses, it is crucial that reliable data about kinetics and kinematics of the oar blade can be obtained. In Chapter 6 we evaluated how the reconstructed kinematics and kinetics of the blade as well as power loss under race conditions are affected by assumptions regarding oar rigidity and blade force direction that are commonly adopted in literature.

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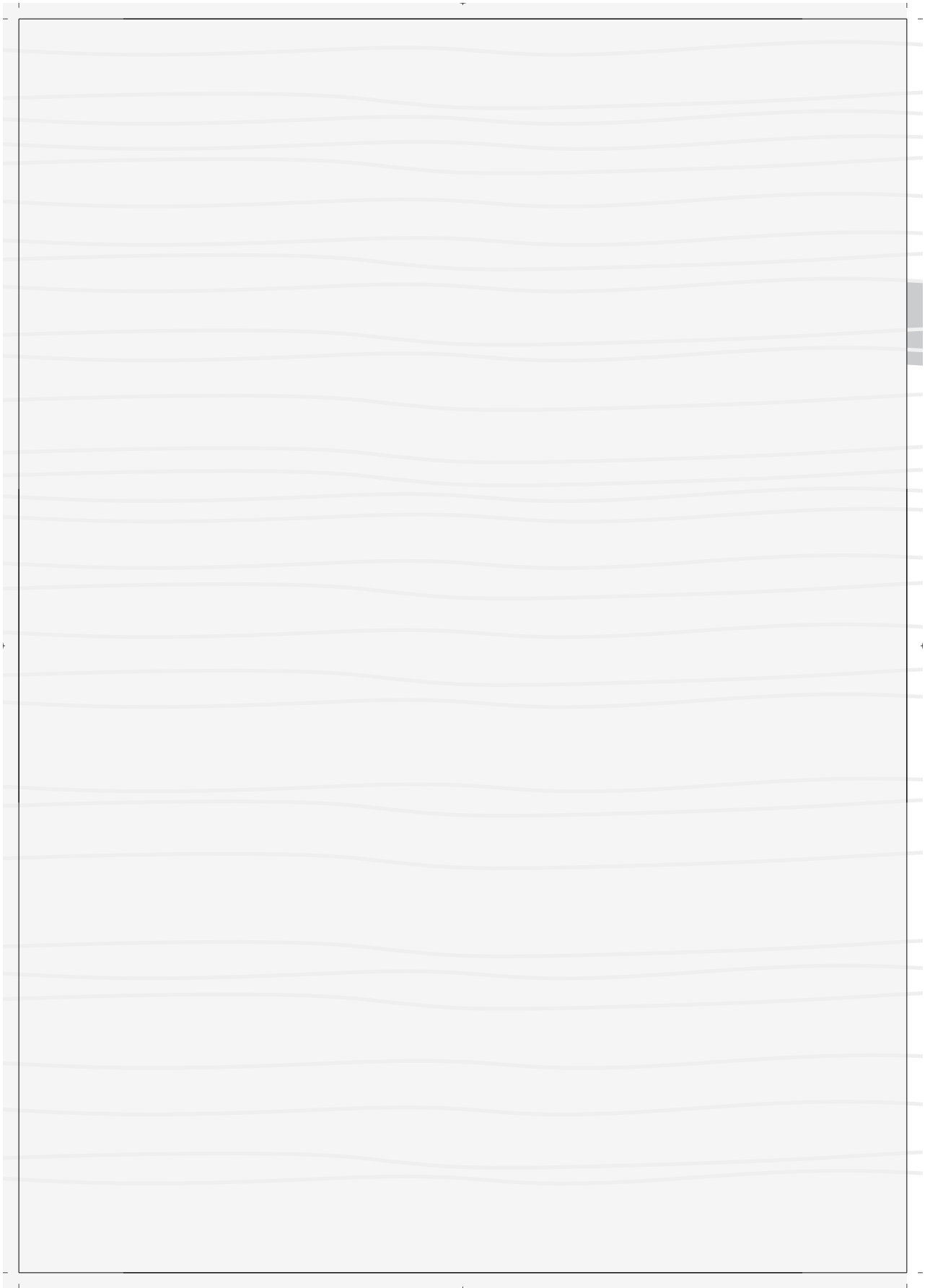
Chapter 2

Effect of stroke rate on the distribution of net mechanical power in rowing

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ABSTRACT

The aim of this study was to investigate the effect of manipulating stroke rate on the distribution of mechanical power in rowing. Two causes of inefficient mechanical energy expenditure were identified in rowing. The ratio between power not lost at the blades and generated mechanical power ($\bar{P}_{rower}$) and the ratio between power not lost to velocity fluctuations and $\bar{P}_{rower}$ were used to quantify efficiency ($e_{propelling}$ and $e_{velocity}$ respectively). Subsequently, the fraction of $\bar{P}_{rower}$ that contributes to the average velocity ($\bar{v}_{boat}$) was calculated (e_{net}). For 9 participants, stroke rate was manipulated between 20 and 36 strokes per minute to examine the effect on the power flow. Data was analysed using a repeated measures ANOVA. Results indicated that at higher stroke rates $\bar{P}_{rower}$, $\bar{v}_{boat}$, $e_{propelling}$ and e_{net} increase, whereas $e_{velocity}$ decreases (P<0.0001). The decrease of $e_{velocity}$ can be explained by a larger impulse exchange between rower and boat. The increase of $e_{propelling}$ can be explained because the work at the blades decreases, which in turn can be explained by a change in blade kinematics. The increase of e_{net} is caused because the increase of $e_{propelling}$ is higher than the decrease of $e_{velocity}$. This study shows the power equation to be an adequate conceptual model to analyze rowing performance.

INTRODUCTION

Rowing is a very demanding sport, physically as well as technically. As in most endurance sports, a high mean velocity is the performance goal. This not only requires the rower to develop a high power output, but also requires good technical skills, so that most of this power contributes to mean boat velocity.

Rowing regattas are usually held on a 2000 meter course. In a single scull it takes a male rower around 7 minutes to cover this distance. During a race average values for mechanical power output around 500 watt are not uncommon[6, 7].

The rowing cycle can be divided in a stroke phase and a recovery phase. During the stroke-phase, when the blades are in the water, the rower exerts a force on the oar handles and moves towards the bow. During the recovery, the blades are out of the water and the rower moves back towards the stern. Because the rower is about six times heavier than the boat, velocity changes of the rower have large effects on instantaneous boat velocity[5, 6, 18].

Rowing performance is affected by three factors[14]. Firstly, performance is affected by the power generated by the rower. Secondly, performance is affected by the power necessary to move the boat against drag forces. Possibilities of lowering the necessary power are limited however, since boat designs are constricted by FISA-regulations. Thirdly, rowing performance is affected by the efficiency of power utilization; this efficiency may be affected by technique or rigging of the boat.

The mechanical power equation has been argued to provide an adequate theoretical framework to study high-intensity periodic movements like rowing, cycling and skating[9]. This approach allows us to analyze how the net mechanical power delivered by the athlete's muscles and the power loss to the environment together determine the performance. When steady state rowing is concerned there will on average be no changes in the kinetic energy of the system and the fraction of the average delivered net mechanical power not contributing to average velocity can be considered "a loss". It is an important aspect of rowing to maximize the fraction of the net mechanical power of the rower that contributes to the average boat velocity. In steady state rowing two types of ineffective expenditure of mechanical power can be identified. First of all, a considerable amount of mechanical energy is spent on giving kinetic energy to water with the blades. The associated power loss is quantified in terms of the propelling efficiency, defined as the ratio of the power not lost to the movement of water and the net mechanical power generated by the rower[9]. For rowing, a propelling efficiency

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of 0.7 to 0.8 has been reported[1]. Second, power is lost because within the rowing cycle the rowing boat does not travel at a constant velocity. Because power lost due to drag is related to velocity cubed[18], fluctuations around the mean velocity have negative effects on the total average cost to overcome drag, as already argued by Sanderson and Martindale[14]. According to Sanderson and Martindale[14], the percentage of the net mechanical power used to overcome the extra resistance caused by velocity fluctuations, which will be quantified in terms of velocity efficiency ($e_{velocity}$) in this study, is in the order of 5-10%.

It should be kept in mind that we refer to the mechanical power delivered by the rower as the "net" mechanical power for good reasons: this term represents the sum of the positive and negative mechanical power delivered by all muscles involved[2]. In a periodic movement like rowing, the kinetic energy, although constant from cycle to cycle, fluctuates within a cycle. Any increase of the kinetic energy is induced by concentric muscle contractions. In as far as the subsequent decrease of velocity is caused by eccentric contractions of muscle fibres, the kinetic energy released is converted into heat (negative muscle power), meaning that it is "lost" and has to be regenerated in the next stroke cycle. Consequently, the net mechanical power as it appears in the mechanical power equation as used in this study is lower than the positive muscle power by an amount equalling the negative muscle power.

Altering the stroke rate is likely to affect the mechanical power flow in rowing. Stroke rate is an important aspect of rowing technique and is not constant during a 2000 meter race. Stroke rate is typically highest during the first and last 250 meters. First of all, the rower's average net mechanical power output over a single cycle is expected to increase with increasing stroke rate. We also expect stroke rate to influence power lost to velocity fluctuations. Accelerations of the rower in relation to the boat are expected to be higher at higher stroke rates, which will affect boat velocity because of larger impulse exchanges between rower and boat. Results of previous research on this subject are inconsistent. Celentano *et al*.[6] reported a decrease of fluctuations, whereas Kleshnev[10] and Sanderson and Martindale[14] reported an increase of fluctuations at higher stroke rates. Concerning the power loss at the blades, Kleshnev[10] reported a higher propelling efficiency at higher boat velocities. However, this finding appears to be inconsistent with the observation that more splashing and "foam" at the blades occur at higher stroke rates. One would expect this larger disturbance of water to lead to a greater power loss, thus a lower propelling efficiency. In this study, we investigated how the net mechanical power output of the rower, the fraction of this power contributing to the average velocity, and power losses quantified by propelling efficiency and velocity efficiency are affected by stroke rate.

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METHODS

Participants and protocol

Nine participants (6 male, 3 female) participated in this study. All participants were experienced rowers in the single scull. All participants signed an informed consent prior to the experiments. Subject statistics are displayed in Table 2.1. Participants were instructed to row at rates of 20, 24, 28, 32 and 36 strokes per minute. This range represents the range of stroke rates typical for training and competition. Participants rowed 5 trials at each prescribed stroke-rate, making a total of 25 trials. The trials were randomised. The participants were instructed to row as fast as possible for approximately 20 strokes, respecting the requested rating. Some of the participants were asked to also participate in several "resistance trials" (described below) following the testing. All trials were performed in the same month, under similar calm weather conditions with no apparent water current.

Equipment and data processing

A single scull (Euro Racing Boats, Australia) was equipped with the ROWSYS measuring and telemetry system, which was developed and built by the University of Sydney and the New South Wales Institute of Sports[15]. Forces on the pin were measured using three dimensional piezoelectric transducers (Kistler, Switzerland) mounted on each pin. Oar angles in the horizontal plane were measured using servo-potentiometers (Radiospares 173-580), which were mounted to both oars using a plastic rod. The oars (Croker S2 Slick, Australia) were allowed to move freely around all axes. Boat velocity was measured using a trailing turbine (Nielsen Kellermann) with embedded magnets, mounted underneath the hull of the boat. The location of the sliding seat in relation to the boat was measured using a cable and drum potentiometer (Aerospace technologies).

	Height (m)	Mass (kg)	Age (years)	Rowing exp. (years)	Pref. stoke rate in race (str·min^{-1})
Mean ± s	1.86 ± 0.09	77.80 ± 11.69	22.90 ± 2.96	5.83 ± 3.55	32.56 ± 1.13
Minimum	1.73	59	19	2	30
Maximum	1.97	97	26	12	34

Table 2.1: *Height, weight, age, years of rowing experience and the preferred stroke rate (in strokes per minute) during a 2000 m race were recorded.*

All data were sampled at 100 Hz. Raw data were transmitted to the shore in real-time using a wireless transmitter (PocketLAB, Digital effects) and stored in digital form.

Before further processing, all data were filtered with a cut-off frequency of 10 Hz, using a 3rd order Butterworth filter. All subsequent calculations were carried out using MatLab (The MathWorks, USA).

For all variables of interest, the average over an entire rowing cycle was calculated. For each of the 5 trials in each condition, 10 consistent rowing cycles were selected on the basis of visual inspection, so for each condition the average of 50 rowing cycles was calculated. From each trial, the first five strokes were discarded, as well as strokes showing disturbances (noise) in the data. Stroke consistency was checked by investigating force-time and velocity-time profiles. At the beginning of each stroke, boat velocity, as well as oar angle of both port and starboard oar were calculated. The differences of these values between each subsequent stroke were determined to provide an indication of periodicity. Statistical analysis was performed using a repeated measures ANOVA, using P = 0.05. Since in this design only the within-subject effects were investigated, there was no need to differentiate between male and female rowers. Following the repeated measures ANOVA, Student's t-tests were performed to evaluate differences between the conditions for all the dependent variables. Pearson's correlation coefficient between stroke rate and the dependent variables was calculated and tested for significance using P = 0.05.

Determination of the mechanical variables

All calculations were performed in two dimensions, a complete definition of the frame of reference used for the boat (x,y) and port-side oar (x',y') is given in Figure 2.1.
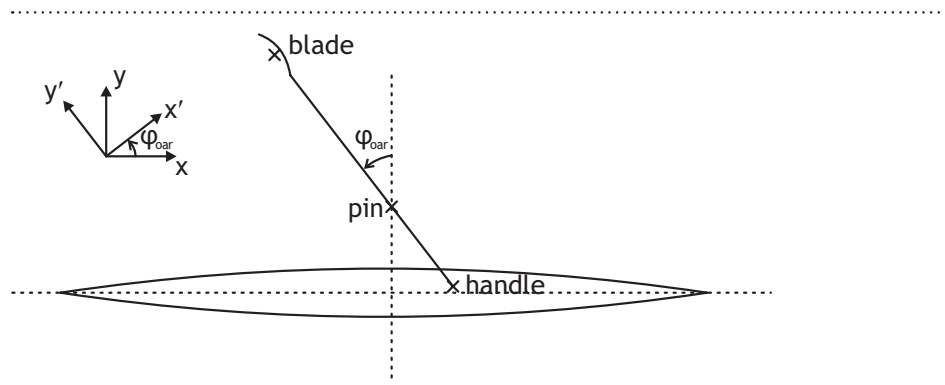
Figure 2.1: The shore-fixed frames of reference used in this study. The positive x direction is in the direction of boat motion; the orientation of the x'-y' system is defined by the orientation of the oar such that positive y' is in the direction of the vector from pin to handle. Oar angle (φ_{oar}) is defined positive in the direction of the release of the blades and zero when the oar is perpendicular to the boat. Points of application of handle, pin and blade forces (F_{hands}, F_{pin} and F_{blade} respectively) are denoted by handle, pin and blade.

Lateral and vertical displacements of the boat were assumed to be negligible. Although variables were determined for both oars separately, only the calculations for one oar are given. A full rowing cycle was assumed to be periodic. The stroke phase was defined to commence at minimum oar angle and to end at maximum oar angle. The recovery phase was defined to commence at maximum oar angle and end at minimum oar angle.

Oar angle (φ_{oar}) was zero when the oar was perpendicular to the shell, Stroke length (φ_{stroke}) and stroke duration (T_{stroke}) were defined as the change in φ_{oar} and time between catch and finish. The location of the centre of mass of the rower was assumed to be equal to the location of the sliding seat. Forces on the seat in x-direction were assumed to be negligible.

Forces on the blade were assumed to act only perpendicular to the blade[1] and to apply at the centre of the blade. Pin force perpendicular to the blade ($F_{pin}^{x'}$) was derived from directly measured pin forces in x and y-direction and oar angle. Neglecting oar mass and inertia, the forces perpendicular to the handle ($F_{hands}^{x'}$), assumed to act at 0.04 m. from the inboard end of the oar) and blade ($F_{blade}^{x'}$), can be derived using the equations of motion for the oar:

$$F_{hands}^{x'} + F_{pin}^{x'} + F_{blade}^{x'} = 0 \qquad \text{Equation 2.1a}$$

And:

$$-F_{hands}^{x'} \cdot (y'_{handle} - y'_{pin}) - F_{blade}^{x'} \cdot (y'_{blade} - y'_{pin}) = 0 \qquad \text{Equation 2.1b}$$

With y'_{handle}, y'_{pin} and y'_{blade} the y' coordinates of the points of application of the forces on the handle, pin and blade respectively in the x', y' frame of reference. With two equations that are linear in the two unknowns, this system can be solved for $F_{hands}^{x'}$ and $F_{blade}^{x'}$.

Oar angular velocity (ω_{oar}) was calculated by taking the 5-point numerical time derivative of φ_{oar}. The velocity in x'-direction of the blade ($\dot{x}'_{blade}$) in relation to the shore was calculated from the boat velocity signal ($\dot{x}_{boat}$) and ω_{oar} :

$$\dot{x}'_{blade} = \dot{x}'_{boat} - \omega \cdot (y'_{blade} - y'_{pin}) \qquad \text{Equation 2.2a}$$

With $\dot{x}'_{boat}$ the component of boat velocity in the x' direction:

$$\dot{x}'_{boat} = \dot{x}'_{boat} \cdot \cos(\varphi_{oar}) \qquad \text{Equation 2.2b}$$

In its general form, the power equation for a linkage of rigid bodies connected in hinge joints can be written as:

$$\Sigma \mathbf{F_e} \cdot \mathbf{v_e} + \Sigma \mathbf{M_e} \cdot \dot{\boldsymbol{\varphi}}_e + \Sigma \mathbf{M_j} \cdot \dot{\boldsymbol{\varphi}}_j = \Sigma \frac{dE_{kinetic}}{dt} \qquad \text{Equation 2.3}$$

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(e.g. [9, 17]). With the first term describing the power exchange with the environment due to external forces, the second term the power exchange with the environment due to external moments (negligible in the case of rowing) and the third term describing the power inflow from the joint torques (i.e. the net mechanical power production). The right-hand side of the equation describes the time derivitive of kinetic energy of all the segments.

Neglecting seat forces, the instantaneous net mechanical power equation applied to the rower can be written as:

$$P_{rower} + F^x_{handle} \cdot \dot{x}_{handle} + F^y_{handle} \cdot \dot{y}_{handle} + F^x_{stretcher} \cdot \dot{x}_{boat} = \sum \frac{dE_{kinetic}}{dt} \qquad \text{Equation 2.4a}$$

(e.g. [18]). Averaging this equation over one cycle during steady state rowing with period time T yields the following expression for the average net mechanical power delivered by the rower ($\bar{P}_{rower}$):

$$\bar{P}_{rower} = -\frac{1}{T} \int_{t_0}^{t_0+T} (F^x_{handle} \cdot \dot{x}_{handle} + F^y_{handle} \cdot \dot{y}_{handle}) \, dt$$

$$-\frac{1}{T} \int_{t_0}^{t_0+T} (F^x_{stretcher} \cdot \dot{x}_{boat}) \, dt \qquad \text{Equation 2.4b}$$

With $F^x_{stretcher}$ the force from the stretcher on the feet in x-direction, F^x_{handle} the force from the handle on the hands and $\dot{x}_{handle}$ and $\dot{y}_{handle}$ the velocity of the handle in respectively the x and y direction. As seen from this equation, $\bar{P}_{rower}$ is not affected by changes in the kinetic energy of the rower, because for any periodic movement, the time derivative of $E_{kinetic}$, averaged over one full cycle, equals zero.
Neglecting the horizontal seat force, it follows from the equation of motion of the rower that:

$$F^x_{stretcher} = m_{rower} \cdot \ddot{x}_{rower} - F^x_{handle} \qquad \text{Equation 2.4c}$$

With m_{rower} the mass of the rower and $\ddot{x}_{rower}$ the acceleration of the rower in x-direction (approximated by the acceleration of the sliding seat). Substituting equation 2.4c into equation 2.4b yields:

$$\bar{P}_{rower} = -\frac{1}{T} \int_{t_0}^{t_0+T} (F^x_{handle} \cdot (\dot{x}_{handle} - \dot{x}_{handle}) + F^y_{handle} \cdot \dot{y}_{handle}) \, dt +$$

$$-\frac{1}{T} \int_{t_0}^{t_0+T} (m_{rower} \cdot \ddot{x}_{rower} \cdot \dot{x}_{boat}) \, dt \qquad \text{Equation 2.4d}$$

This can be rewritten into:

$$\bar{P}_{rower} = -\frac{1}{T} \int_{t_0}^{t_0+T} (F^{x'}_{handle} \cdot (y'_{handle} - y'_{pin}) \cdot \omega_{oar})\, dt +$$
$$-\frac{1}{T} \int_{t_0}^{t_0+T} (m_{rower} \cdot \ddot{x}_{rower} \cdot \dot{x}_{boat}) \qquad\qquad \text{Equation 2.4e}$$

With F^x_{hands} equalling minus F^x_{handle} as defined in equation 2.1a. The average power lost at the blades ($\bar{P}_{blade}$) was calculated by taking the average over a rowing cycle of the dot product of $\dot{x}'_{blade}$ and F^x_{blade} for both oars:

$$\bar{P}_{blade} = -\frac{1}{T} \int_{t_0}^{t_0+T} (F^{x'}_{blade} \cdot \dot{x}'_{blade})\, dt \qquad\qquad \text{Equation 2.5}$$

In line with previous research (e.g. [5, 14]), instantaneous drag power (P_{drag}) was assumed to be proportional to frontal area and C_d-value (both assumed to be constant throughout the rowing cycle), to density of water and to velocity to the power n. Lumping the parameters, P_{drag} can then be calculated as:

$$P_{drag} = -k \cdot \dot{x}_{boat}{}^n \qquad\qquad \text{Equation 2.6}$$

Constants k and n were determined from trials where participants were asked to build up speed and to subsequently keep the blades from the water as long as possible while sitting still. During these "resistance trials" the drag force is the only horizontal force acting on the system and the acceleration of the total centre of mass is equal to the boat acceleration. This means that the equation of motion for the system boat, rower and oars can be written as:

$$m_{total} \cdot \ddot{x}_{boat} = -k \cdot \dot{x}_{boat}{}^{n-1} \qquad\qquad \text{Equation 2.7a}$$

This is a first order non-linear ordinary differential equation, which has the following solution:

$$\ddot{x}_{boat}(t) = \left(\left(-\frac{k}{m_{total}} \cdot t + C\right) \cdot (2-n)\right)^{\frac{1}{2-n}}$$

With:

$$c = \frac{\dot{x}_0{}^{2-n}}{2-n} \qquad\qquad \text{Equation 2.7b}$$

Where $\dot{x}_{boat}(t)$ is the boat velocity as a function of time (t), $\dot{x}_0$ is the initial velocity at t = 0 and m_{total} is the total mass of the system. Constant k can be scaled to the total

mass since the boat frontal area, and thus k, is expected to increase linearly with increasing mass. By fitting this model to the experimental data using the least squares method, values for k and n were obtained. $\overline{P}_{drag}$ was calculated as the average over a full rowing cycle of P_{drag}.

Determination of the efficiency terms
To calculate the efficiency terms described below, the assumption was made that rowing is perfectly periodic, hence the average time derivative of all kinetic energy terms equals zero. Consequently, the average sum of all power terms should equal zero:

$$\overline{P}_{rower} + \overline{P}_{blade} + \overline{P}_{drag} = 0 \qquad \text{Equation 2.8}$$

Propelling efficiency ($e_{propelling}$), describing the fraction of $\overline{P}_{rower}$ not lost at the blades, was calculated as:

$$e_{propelling} = 1 - \frac{\overline{P}_{blade}}{\overline{P}_{rower}} \qquad \text{Equation 2.9a}$$

This can also be written as:

$$e_{propelling} = 1 - \frac{W_{blade,\ cycle}}{W_{rower,\ cycle}} \qquad \text{Equation 2.9b}$$

$W_{blade,cycle}$ represents the performed work at the blades and $W_{rower,cycle}$ the performed net mechanical work by the rower during one complete rowing cycle.

To quantify the power loss caused by fluctuations in velocity, we introduce the term velocity efficiency ($e_{velocity}$). The difference between actual drag and hypothetical drag if the boat speed would be constant was calculated. Hypothetical drag at constant boat velocity was calculated using equation 2.6, but with average velocity of the rowing cycle ($\overline{v}_{boat}$) as input. The fraction of $\overline{P}_{rower}$ that was not lost to velocity fluctuations, $e_{velocity}$, was calculated as follows:

$$e_{velocity} = 1 - \frac{\overline{P}_{drag} - k \cdot \overline{v}_{boat}^{n}}{\overline{P}_{rower}} \qquad \text{Equation 2.10}$$

The fraction of $\overline{P}_{rower}$ that contributes to the average velocity was expressed as net efficiency (e_{net}), which was calculated as:

$$e_{net} = \frac{\overline{P}_{rower} - (1-e_{propelling}) \cdot \overline{P}_{rower} - (1-e_{velocity}) \cdot \overline{P}_{rower}}{\overline{P}_{rower}} \qquad \text{Equation 2.11}$$

$$= e_{propelling} + e_{velocity} - 1$$

RESULTS

Drag

The constants k and n in equations 2.6, 2.7a and 2.7b were experimentally determined at 0.054 times the mass of the subject, boat and oars for k and 2.7 for n. Figure 2.2 shows the relationship between the actual and the predicted velocity during the resistance trials. The correlation between actual and predicted velocity was significant at 0.99 (P < 0.05). Although due to the nature of the measurements, most data points are collected below the range of shell velocity during the other experiments, the data shows there is no need to expect different drag behaviour at higher velocities.
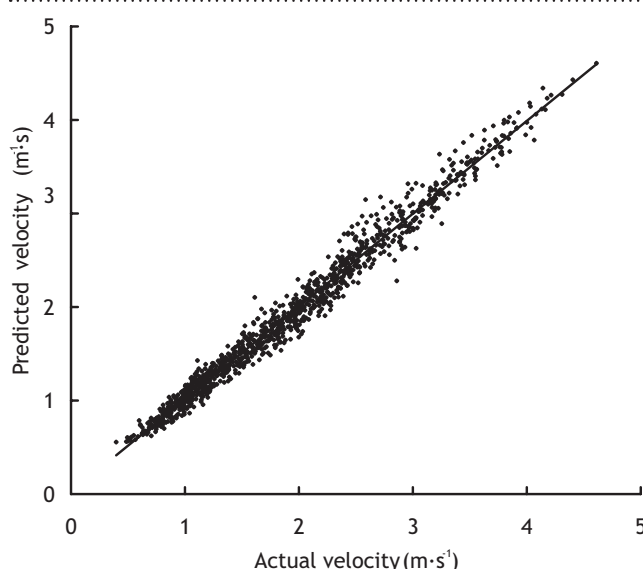
Figure 2.2: *Relationship between the predicted velocity and the actual velocity during the "resistance trials". Note that data are taken from several subjects.*

Accuracy of the calculated powers and indication of periodicity

In steady state rowing, $\overline{P}_{rower}$ should equal the absolute sum of $\overline{P}_{blade}$ and $\overline{P}_{drag}$ (equation 2.8). A comparison of the calculated values for the power terms provides an indication of the accuracy of the calculation of the separate terms. In this study the sum of $\overline{P}_{blade}$ and $\overline{P}_{drag}$ had an average absolute deviation of 7% of $\overline{P}_{rower}$ (26.3 W) for all trials.

The mean absolute difference between φ_{oar} of the port and starboard side oar and $\dot{x}_{boat}$ at the beginning of the stroke between each subsequent stroke was 1.16 (s = 4.40)

degrees, 1.14 (s = 4.92) degrees and 0.13 (s = 0.14) m·s⁻¹ respectively. This indicates that the behaviour was sufficiently close to being periodic, as intended.

Effect of stroke rate on $\overline{P}_{rower}$, $e_{propelling}$, $e_{velocity}$ and e_{net}

The repeated measures ANOVA demonstrated a significant main effect of stroke rate for $\overline{v}_{boat}$ ($P < 0.0001$), $\overline{P}_{rower}$ ($P < 0.0001$), $e_{propelling}$ ($P < 0.0001$), $e_{velocity}$ ($P < 0.0001$) and e_{net} ($P < 0.0001$). $\overline{v}_{boat}$, $\overline{P}_{rower}$ and $e_{propelling}$ all increased monotonically as stroke rate increased while $e_{velocity}$ decreased with increasing stroke rate. The correlation coefficients of stroke rate and $\overline{v}_{boat}$, $\overline{P}_{rower}$, $e_{propelling}$, $e_{velocity}$ and e_{net} averaged over participants equalled 0.96, 0.98, 0.82, -0.72 and 0.73 respectively, indicating a linear relationship between stroke rate and these dependent variables ($P < 0.05$ for all comparisons).

In Table 2.2a the average values and standard deviations for $\overline{v}_{boat}$, $\overline{P}_{rower}$, $e_{propelling}$, $e_{velocity}$ and e_{net} at the 5 different stroke rates are presented. Figure 2.3a provides a graphical representation of the average values for $e_{propelling}$, $e_{velocity}$ and e_{net}.
The increase of $\overline{P}_{rower}$ was mainly due to the increasing stroke rate as $W_{rower,cycle}$ did not differ significantly between stroke rates per subject. $e_{propelling}$ increased at increasing stroke rate despite an increase in $\overline{P}_{blade}$, because $\overline{P}_{rower}$ increased more than $\overline{P}_{blade}$. Velocity efficiency decreased at increasing stroke rate because $\overline{P}_{rower}$ increased less than the power lost due to velocity fluctuations. e_{net} increased at increasing stroke rate because the increase of $e_{propelling}$ is higher than the decrease of $e_{velocity}$. In Figure 2.3b a graphical representation of the average values for $\overline{P}_{rower}$, $\overline{P}_{drag}$ and $\overline{P}_{blade}$ is presented. The values for T_{stroke}, φ_{stroke}, $W_{rower,stroke}$ and $W_{blade,stroke}$ are presented in Table 2.2b.
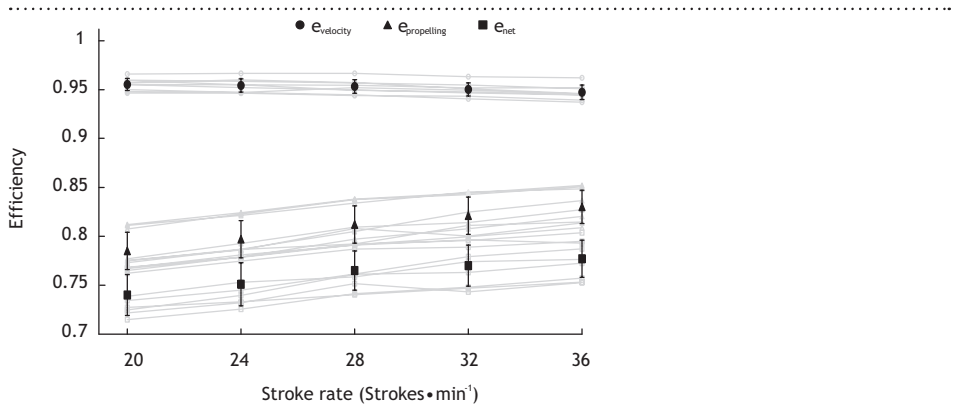

Figure 2.3a: Values and the inter subject standard deviations of epropelling, evelocity and enet as a function of stroke rate. Average values are indicated by filled symbols. Open symbols indicate individual values. Note that the standard deviations concern inter subject variability and do not influence the ANOVA.

Figure 2.3b: Values and the inter subject standard deviations of $\bar{P}_{rower}$, $\bar{P}_{drag}$ and $\bar{P}_{blade}$ as a function of stroke rate. Average values are indicated by filled symbols. Open symbols indicate individual values. Note that the standard deviations concern inter subject variability and do not influence the ANOVA.
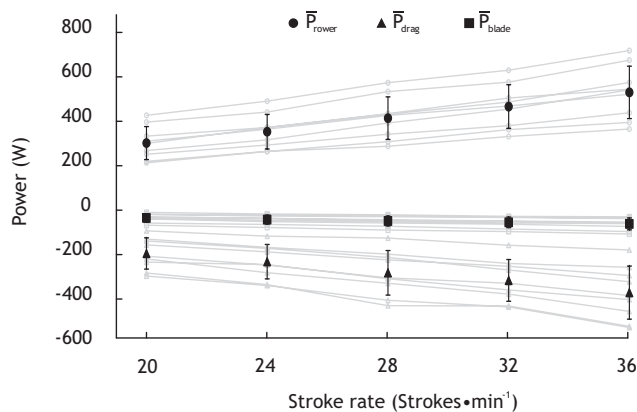
Stroke rate	$\bar{v}_{boat}$ (m·s^{-1})	$\bar{P}$rower (W)	$e_{propelling}$	$e_{velocity}$	e_{net}
20	3.84 ± 0.32	277 ± 74.0	0.785 ± 0.019	0.955 ± 0.0062	0.740 ± 0.021
24	4.07 ± 0.29	328 ± 77.6	0.797 ± 0.019	0.954 ± 0.0068	0.751 ± 0.022
28	4.33 ± 0.37	389 ± 95.8	0.812 ± 0.019	0.953 ± 0.0070	0.765 ± 0.020
32	4.52 ± 0.30	441 ± 98.1	0.821 ± 0.019	0.950 ± 0.0067	0.770 ± 0.021
36	4.76 ± 0.76	505 ± 118	0.830 ± 0.017	0.947 ± 0.0074	0.777 ± 0.019

Table 2.2a: Average values and standard deviations of average velocity, the rower's average power, propelling efficiency, velocity efficiency and total efficiency at the five different stroke rates. Note that the standard deviations concern inter subject variability and do not influence the ANOVA.

Stroke rate	T_{stroke} (s)	φ_{stroke} (^{0})	$W_{rower,stroke}$	$W_{blade,stroke}$
20	1.12 ± 0.059	105.4 ± 5.83	799.1 ± 211	173.4 ± 54.4
24	1.06 ± 0.044	104.5 ± 5.33	799.5 ± 194	163.6 ± 49.7
28	1.00 ± 0.044	103.4 ± 5.72	809.0 ± 195	153.1 ± 45.8
32	0.94 ± 0.039	102.3 ± 5.32	813.9 ± 187	147.3 ± 45.5
36	0.89 ± 0.037	100.1 ± 5.46	827.6 ± 188	141.8 ± 42.5

Table 2.2b: Average values and standard deviations of stroke time, stroke length, work of the rower per stroke and work at the blades per stroke. Note that the standard deviations concern inter subject variability and do not influence the ANOVA.

DISCUSSION

The values for $e_{propelling}$ and $e_{velocity}$ found in this study are in the same range as values obtained from earlier experiments. Although using different methods of calculation, Kleshnev[10] reported values of 0.785 for $e_{propelling}$ and 0.938 for $e_{velocity}$ (in his study called blade and boat efficiency respectively). Kleshnev concluded that the largest improvements in performance could be expected in increasing $e_{propelling}$, because the amount of power that is lost to blade slip is considerably higher than the amount of power lost to boat speed fluctuations. However, it is currently unclear in which way the net efficiency can be improved by the rower. Overall, rowing appears to get more efficient at higher stroke rates.

The results clearly demonstrate that at higher stroke rates the rower is able to generate a higher net mechanical power output, resulting in a higher average velocity. This is in accordance with earlier results[13]. However, it must be noted that it is unlikely that rowers are able to maintain the $\overline{P}_{rower}$ found at the highest stroke rates during a 2000 meter race, if only because the preferred racing stroke rate reported by the participants was considerably lower than 36 strokes·min^{-1}.

Velocity efficiency is reduced when the stroke rate increases. This is most likely caused by the fact that at higher stroke rates there is more impulse exchange between the rower and the boat, since the accelerations of the rower relative to the boat must be higher when stroke length remains constant (see Table 2.2b). This is in accordance with Loschner and Smith[12], who previously reported the relationship between movement of the rower (represented by seat movement) and boat acceleration. Higher accelerations of the rower will result in larger fluctuations of the velocity of the rowing boat, which in turn will result to a higher relative power loss.

Although average $e_{velocity}$ differs less than 1% between the lowest and the highest stroke rate, the differences are significant between all stroke rates. However small, these differences are important. This is illustrated when the outcome on a 2000 meter race is predicted. With all other variables remaining constant, a rower with an $e_{propelling}$ of 0.8 and an $e_{velocity}$ of 0.950 finishes the 2000 meter race 5 meters ahead (almost a boat length in a single scull) of an otherwise identical rower with an $e_{velocity}$ of 0.945, as can be calculated from equations 2.6 and 2.8 through 2.10.

As mentioned in the introduction, analysis of our data in the context of the mechanical power equation does not allow separation of the rower's net mechanical power output into positive and negative muscle contributions. Internal dissipation of mechanical

energy (negative muscle power) is associated with deceleration of the body (reduction of the kinetic energy) through eccentric muscle contractions. At higher stroke rates, the fluctuations in kinetic energy are larger, suggesting that the internal dissipation of mechanical energy increases with stroke rate. An indirect way to investigate the magnitude of the negative muscle power is by considering metabolic energy expenditure. As both the dissipation of mechanical energy and the subsequent regeneration thereof involve metabolic energy expenditure, gross mechanical efficiency might be expected to deteriorate with increasing stroke rate if negative muscle power is substantial. From this it follows that minimization of negative muscle power could be an important aspect of intermuscular coordination in rowing. As no data are known to us on the relation between stroke rate and gross mechanical efficiency or the amount of internal dissipation of mechanical energy in rowing, this is an area for future research.

The calculation of drag forces is based on relaxation measurements during which the rower does not move relative to the boat and during which the boat was monotonically decelerating. Determining drag forces during passive motion in water is common practice in this type of research (e.g.[18]). This is open for future research however, since during actual rowing the orientation and immersion depth of the boat vary[16] and the boat acceleration is nonzero during a rowing cycle. These variations must be expected to affect the drag forces. Lazauskus[11] has proposed a more extensive model for calculating drag. However, actual measurements of drag during rowing are also necessary to obtain reliable values.

Intuitively, the positive correlation between stroke rate and $e_{propelling}$ is unexpected, because at higher stroke rates more splashing and foam at the blades are typically observed, which could indicate a greater $\bar{P}_{blade}$. In fact, both $\bar{P}_{rower}$ and $\bar{P}_{blade}$ increase when the stroke rate increases. However, the relative increase in $\bar{P}_{blade}$ is smaller, causing an increase of $e_{propelling}$, as also found by Kleshnev[10]. During the recovery almost no mechanical work is done by the rower (data not shown in this study) and by definition no work is done by the blades. Thus it can be stated that with $W_{rower,cycle}$ not varying between stroke rates (see table 2.2b), the relatively small increase in $\bar{P}_{blade}$ in relation to the increase in $\bar{P}_{rower}$ is caused by a decrease in $W_{blade,stroke}$ (equation 2.9b).

Figure 2.4 illustrates the path of the blade through the water at stroke rate 20 and 36. Although at both stroke rates the distance between blade insertion and retraction is about the same, at stroke rate 20 the blade moves over a considerably larger distance in the direction opposite to the direction of movement during the middle part of the stroke. In this phase of the stroke the greatest amount of work at the blades is performed, since the blade is almost perpendicular to its path and a large mass of

water is being moved. This may explain why at higher stroke rates, when the blade moves less in the opposite direction, less work is performed at the blades.

The exact mechanisms of the way $\overline{P}_{blade}$ is generated remain unclear. From investigation of calculated blade kinematics it appears that lift forces contribute to the propulsion. This has also been mentioned by several other authors[1, 4]. Figure 2.4 clearly shows that the displacement of the blade in propulsive direction is mainly in the direction of movement. Because the direction of drag forces is opposite the direction of movement, lift forces on the blade are necessary to create a propulsive force on the boat during the stroke phase. This poses blade developers with a challenge, since, for optimal functionality lift forces should be maximal during the first part of the stroke whilst drag forces should be maximal during the middle part[8].

The flow of water around the blade will be very turbulent, causing the hydrodynamics around the blade to be complex[3]. The best way to obtain the kinetics of the blade would be to measure the forces directly. Future research on blade hydrodynamics, as well as the development of equipment allowing measurement of the force distribution over the blade, might provide answers to what actually happens around the blades.
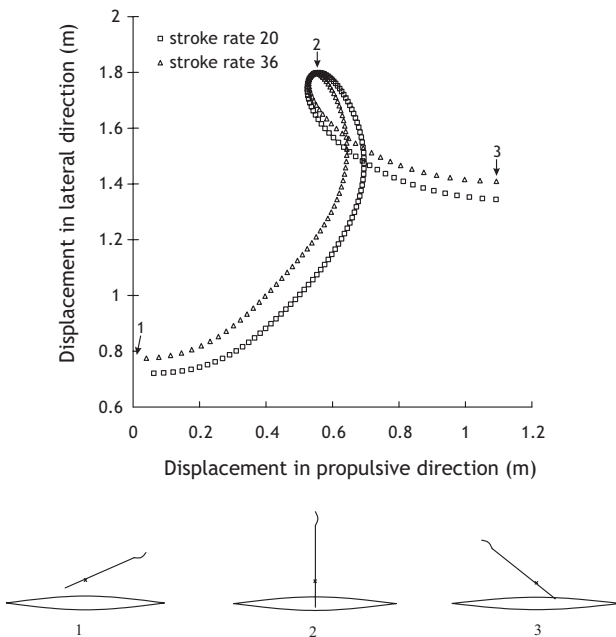
Figure 2.4: Example of the trajectory of the blade through the water during the stroke phase at stroke rates 20 and 36. The entry of the blade is plotted at the left hand side of the graph. The curves are obtained from a 10 stroke average of a typical subject. The time interval between data points is 0.01 seconds. 1, 2 and 3 indicate the oar orientation at the beginning, middle and end of the stroke

CONCLUSION

This study has indicated the effect of stroke rate on the power flow in short-duration maximum-effort rowing. As the average net mechanical power output generated at the highest stroke rates investigated is unlikely to be sustainable over a 2000 meter race, future research should address the possible changes in power flow during a longer period of exertion.

We have shown that the power equation is an adequate conceptual model to analyze rowing performance. Results indicate that stroke rate not only affects the net mechanical power output of the rower, but also affects the power loss at the blades and the power loss associated with velocity fluctuations. When similar results become available regarding the effect of other technique-related factors, it may become possible to understand the optimal technique as the optimal compromise between generation of power by the rower and power loss to terms not contributing to average velocity.

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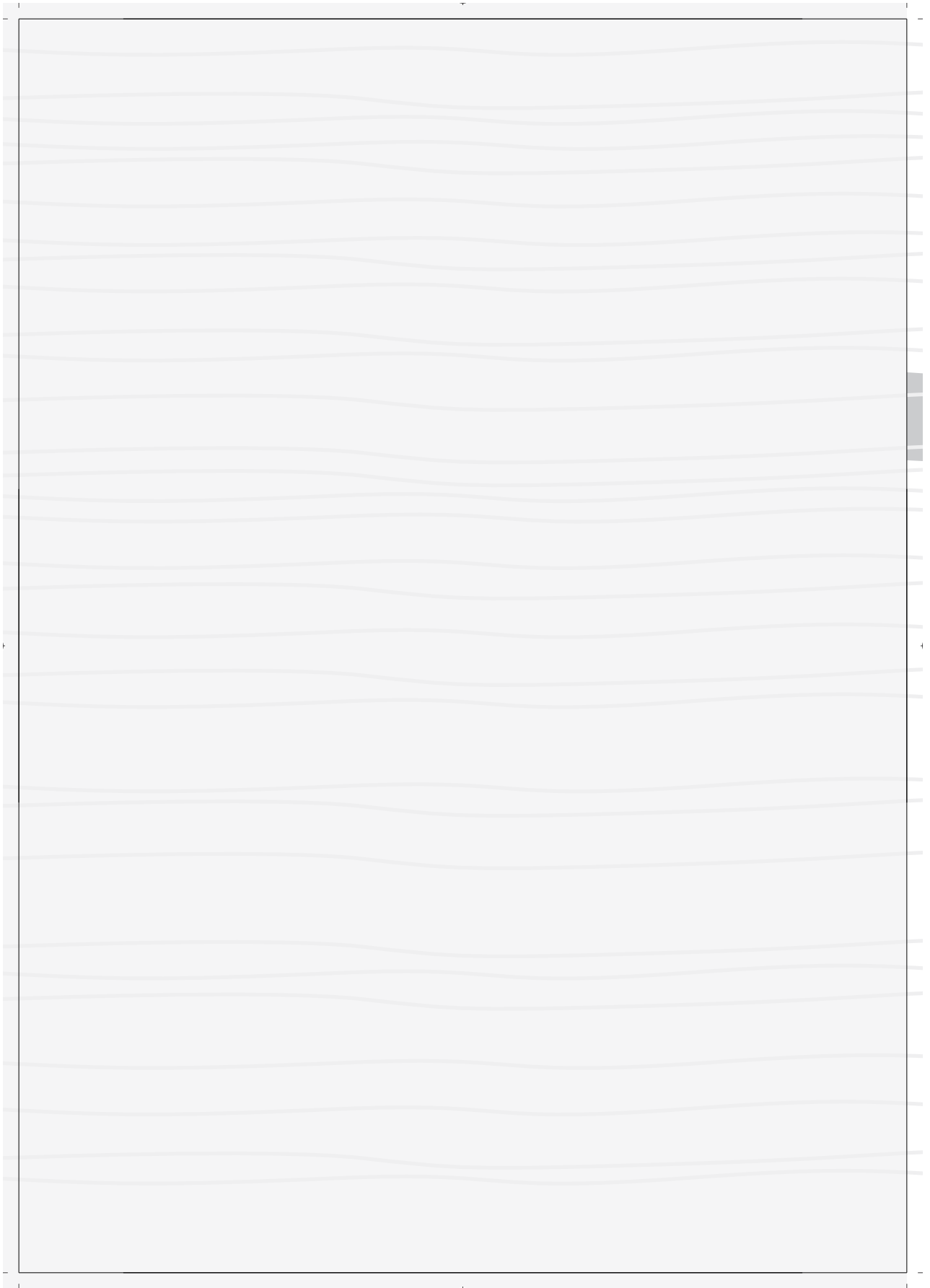
Chapter 3

Gross efficiency during rowing is not affected by stroke rate

Hofmijster MJ, Soest AJ van, Koning JJ de.

ABSTRACT

It has been suggested that the optimal stroke rate in rowing is partly determined by stroke rate dependence of internal power losses. This should be reflected in a stroke rate dependency of gross efficiency (e_{gross}). The purpose of this study was to investigate if e_{gross} is affected by stroke rate. A second aim was to determine whether internal power losses can be estimated by the negative power output during the stroke cycle ($\bar{P}_{negative}$), which was defined as the total amount of negative work divided by cycle duration.

Seventeen well-trained female rowers participated in this study. They rowed three trials on a modified rowing ergometer on slides at a submaximal intensity (RER one or close to one). Stroke rates were 28, 34 and 40 strokes·min^{-1}. The trials were held in a random order. Power transfer to the flywheel was kept constant while egross was determined during each trial.

Gross efficiency was identical during all three stroke rates and was 0.20 on average. This finding suggests that in rowing internal power losses are not influenced by stroke rate. Furthermore, although $\bar{P}_{negative}$ increased at increasing stroke rate (P<0.001), no relationship was found with e_{gross}. This suggests that $\bar{P}_{negative}$ is not a reliable measure to estimate internal power losses.

This study shows that within the range of stroke rates applied in competitive rowing, internal power losses appear unrelated to rowing cycle frequency.

INTRODUCTION

Competitive rowing is a very demanding endurance sport. During a 2000m rowing regatta, requiring 6-7 minutes, rowers achieve an average mechanical power output that often exceeds 500 Watts[4]. Depending on the boat type, races are rowed at a pace of around 30 to 40 strokes per minute[14]. Each rowing cycle consists of a stroke phase, during which the blades are in the water, and a recovery phase. Virtually all positive mechanical work is done during the stroke phase. For a given setup of boat and oars, the positive mechanical work per stroke phase depends on technique but is relatively constant[9]. As a consequence, the most effective way to increase the average mechanical power output is to increase the stroke rate. However, it has also been suggested that "... the energy spent to move the rower's body back and forth is higher at higher stroke rates"[5]. In line with this suggestion, several authors have argued that these internal power losses are an important aspect of rowing[7, 20, 23]. In part, this suggestion is based on the observation that during unloaded rowing the metabolic energy cost increases at increasing stroke rate[20]. If internal power losses indeed depend on stroke rate, this would suggest that this dependency affects the optimal stroke rate, as smaller internal power losses could lead to a higher mechanical power output at a given metabolic cost.

Currently, it is not viable to directly measure internal power losses. As an alternative to direct measurement of internal power losses, we compared mechanical power output with the rate of metabolic energy consumption in order to measure gross mechanical efficiency (e_{gross}) in this study. We imposed a fixed mechanical power output, to be achieved at different stroke rates. Any increase of internal power loss that is related to stroke rate should then lead to an increase of the rate of metabolic energy consumption. Everything else being equal, e_{gross}, defined as the ratio between average mechanical power output and average metabolic power production ($\bar{P}_{metabolic}$), should decrease if internal power losses increase with increases in stroke rate. For an exact description of the definition and the derivation of internal power losses, the interested reader is referred to the appendix.

In the light of the above, it should be mentioned that contraction velocities of the muscles active during the stroke phase may depend on stroke rate. As efficiency of contracting muscle depends on shortening velocity[22], substantial differences in shortening velocity may affect e_{gross} to the extent that potential effects of internal losses are masked. Therefore, an indication of shortening velocities of the active muscle groups will be derived at all stroke rates considered. In addition to the determination of e_{gross}, we investigated if an indication that power loss in muscle tendon complexes (MTC's) increases with stroke rate can be derived from the mechanical power output. To that end we determined the phase in which the net instantaneous mechanical power output of the rower (P_{rower}) is negative. We divided the associated negative mechanical work by stroke cycle duration to obtain a variable that we will refer to as $\bar{P}_{negative}$. This variable was considered at different stroke rates; on the reasoning that the average power absorption by all MTC's combined must at least equal $\bar{P}_{negative}$. It should be noted that this quantity does not necessarily reflect power losses, as it is possible that (part of) the power absorbed by MTC's is stored in elastic structures rather than converted to heat.

To summarize, it has been suggested that the optimal stroke rate in rowing is partly determined by stroke-rate-dependence of internal power losses. Such power losses should be reflected in a stroke-rate-dependence of e_{gross}. Thus, the aim of this study is to investigate if e_{gross} is affected by stroke rate. A second aim is to determine if $\bar{P}_{negative}$ is an appropriate measure of internal power losses.

METHODS

Participants

Seventeen well trained female competitive rowers participated in this study. Body mass, age and years of rowing experience are shown in Table 3.1. All participants provided written informed consent. The experiments were approved by the local ethic committee.

	Body Mass (kg)	Age (years)	Experience (years)
Mean ± SD	73.2 ± 6.6	22.5 ± 2.6	3.3 ± 2.41
Minimum	64.3	19	1
Maximum	90.0	26	10

Table 3.1: participant characteristics

Experimental setup and instrumentation

The experiments took place on a rowing ergometer (Concept 2, USA). With a standard rowing ergometer, power is transferred to a flywheel which has fans, so that it is air braked. Air resistance can be manipulated by changing the size of the air inlet, which effectively changes the aerodynamic constant. In the remainder of the text we will refer to the power transferred to the flywheel as $P_{flywheel}$. To more closely resemble on water rowing, the ergometer was mounted on wheels ("slides", Concept 2 USA), allowing it to move back and forth.

In this study, movement of the ergometer was resisted by a servomotor that was programmed to act as a linear damper. In this way the velocity fluctuations that are present in on-water rowing were simulated, including the associated power loss. For an extensive description of the simulated power losses, the reader is referred to an earlier study from our laboratory[10]. A schematic representation of the setup is shown in Figure 3.1.

Forces on the foot stretcher ($F_{stretcher}$) and on the seat (F_{seat}) were recorded by three six-degree force transducers, one mounted under each foot (AMTI, USA) and one mounted under the seat. Forces at the handle (F_{handle}) were measured using a linear force transducer mounted between the chain and handle. Kinematics of body segments, the ergometer and the handle were measured using active infrared markers and cameras (Optotrak, Northern Digital, Canada). To record segment kinematics, markers were

placed at the left side of the body, on the lateral malleolus, the lateral epicondyle of the knee, the greater trochanter, the acromion, the lateral epicondyle of the elbow and the ulnar styloid. Preliminary testing revealed that the marker at the acromion was obscured from view in several occasions. Therefore, a marker was placed on the line between elbow and acromion marker, allowing us to reconstruct the acromion marker position if necessary. Markers where also placed on the flywheel, the handle force transducer, the foot stretcher and the seat. Figure 3.1 also shows the positions of the markers. Force signals were sampled at 200 Hz. Due to equipment limitations, position markers were sampled at 100 Hz. Position samples were converted to 200 Hz using spline interpolation. Velocity data were obtained by taking the five point derivative of the position signals. To estimate $\overline{P}_{metabolic}$, oxygen consumption was registered breath-by-breath using open circuit spirometry (Oxycon, Jaeger ind., Germany).
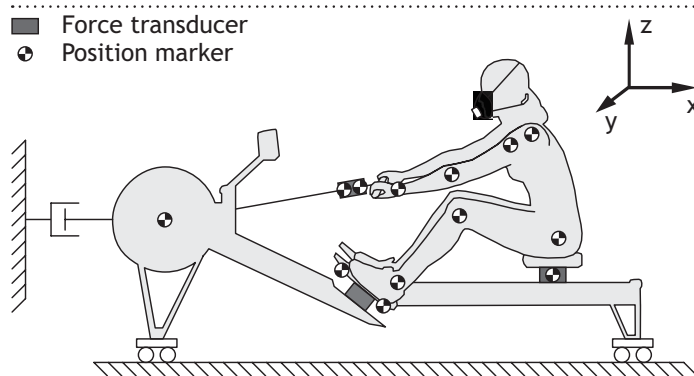
Figure 3.1: *Schematic representation of the experimental setup. The ergometer was put on wheels and movement was resisted by a servomotor and belt, which acted as a linear damper. Force transducers under the foot stretcher and seat and between the handle and chain are drawn in the Figure, as well as the position markers. Oxygen uptake was measured via a mask.*

Protocol

Two experiments were conducted. In the first experiment, participants were asked to perform a 2000m time trial. All participants were familiar with this exercise. Maximum oxygen uptake ($\dot{V}O_{2\text{-max}}$) was established as the highest 30 second average reached during the time trial. Average power transferred to the flywheel on our modified ergometer ($\overline{P}_{2000m}$) was determined for each participant.

The second experiment was conducted between 2 days and 4 weeks after the 2000m time trial. Participants rowed one trial at 28, one at 34 and one at 40 strokes per minute.

Participants received feedback about the power dissipated in the flywheel by means of a monitor (Concept 2, USA) and were instructed to keep their power transfer to the flywheel at 70% of $\bar{P}_{2000m}$. Initial testing revealed that when power transfer to the flywheel was 70% of $\bar{P}_{2000m}$, RER approached 1.0. For all trials, the flywheel was set at the lowest resistance setting, in which case the aerodynamic constant is approximately $1 \cdot 10^{-4}$ kg·m^{-1}. This was done to allow the rowers to row at a high stroke rate at the relatively low power output of 70% of $\bar{P}_{2000m}$. The trials lasted 3 minutes each and were performed in random order. During the trials, respiratory gas exchange was monitored to ensure RER $\leq$ 1, so e_{gross} could be reliably calculated. Participants were verbally corrected by the experiment leader when deviating from the intended stroke rate or power output. Participants that showed an average RER greater than 1.0 were excluded from the study.

Power

All variables were determined in the time period from 90 seconds to 150 seconds into the trial. In this period, oxygen uptake can be expected to have reached constant value (for a typical example, see Figure 3.2). All power terms were calculated instantaneously and averaged over a number of complete stroke cycles within the 60 second time period, with the total number of stroke cycles depending on the stroke rate. Instantaneous mechanical output was calculated according to:

$$P_{rower} = -(\mathbf{F}_{handle} \cdot \mathbf{v}_{handle} + \mathbf{F}_{stretcher} \cdot \mathbf{v}_{stretcher} + \mathbf{F}_{seat} \cdot \mathbf{v}_{seat}) + dE_{pot}/dt + dE_{kin}/dt \qquad \text{Equation 3.1}$$

In this equation $\mathbf{F}_{handle}$ and $\mathbf{v}_{handle}$ represent the force and velocity vectors of the handle, $\mathbf{F}_{stretcher}$ and $\mathbf{v}_{stretcher}$ represent the force and velocity vectors of the foot stretcher and $\mathbf{F}_{seat}$ and $\mathbf{v}_{seat}$ the force and velocity vectors of the seat. Changes in potential energy are described by dE_{pot}/dt. In rowing, dE_{pot}/dt is negligible, as there are only small translations of the centre of mass in the vertical direction.

The kinetic energy content of the rower (E_{kin}) was calculated as the sum of the kinetic energy of all the body segments. Calculated in this way, E_{kin} includes both the translational and rotational energy of all body segments. To obtain dE_{kin}/dt, the five point derivative of E_{kin} was taken. In steady state rowing, e_{gross} can be calculated according to $e_{gross} = \bar{P}_{rower}/\bar{P}_{metabolic}$, with $\bar{P}_{rower}$ the average mechanical power output and $\bar{P}_{metabolic}$ the average metabolic power generation. Metabolic power was calculated using the relationship between $\bar{P}_{metabolic}$, $\dot{V}O$ and RER value, as described by Garby and Astrup[8].

Instantaneous power losses due to velocity fluctuations ($P_{\Delta v}$) equal all mechanical power dissipation by the external damper[10], and were calculated according to:

$$P_{\Delta v} = F^x_{ergometer} \cdot v^x_{ergometer}$$
Equation 3.2

In which $F^x_{ergometer}$ is the resultant ergometer force and $v^x_{ergometer}$ is the ergometer velocity. The superscript 'x' indicates movement or force along the x-axis (Figure 3.1). In turn, $F^x_{ergometer}$ can be calculated according to:

$$F^x_{ergometer} = m_{ergometer} \cdot a^x_{ergometer} - (F^{x'}_{handle} + F^{x'}_{stretcher})$$
Equation 3.3

With $m_{ergometer}$ and $a^x_{ergometer}$ representing the ergometer mass and acceleration. In line with previous work in our laboratory, power losses due to velocity fluctuations were quantified in terms of velocity efficiency, or $e_{velocity}$: $e_{velocity} = 1 - \overline{P}_{\Delta v} / \overline{P}_{rower}$ (9, 10).

In a steady state, $\overline{P}_{rower}$ equals the sum of $\overline{P}_{flywheel}$, which could be seen as 'useful power', and $\overline{P}_{\Delta v}$, which could be seen as 'wasted power'. Power transfer to the flywheel can be calculated according to:

$$\overline{P}_{flywheel} = F_{handle} \cdot (v_{ergometer} - v_{handle})$$
Equation 3.4

See also[10].

Preliminary testing showed that the values for $\overline{P}_{flywheel}$ given by the ergometer monitor corresponded to a satisfactory degree with $\overline{P}_{flywheel}$ as calculated according to equation 3.4. To obtain an indication of internally absorbed mechanical power, the average amount of negative power ($\overline{P}_{negative}$) was calculated for each complete rowing cycle by dividing the total amount of negative work found within the rowing cycle by that cycle's duration. The average amount of positive power ($\overline{P}_{positive}$) was also determined for each stroke cycle by dividing the total amount of positive work within that stroke cycle by the cycle time. When added, $\overline{P}_{negative}$ and $\overline{P}_{positive}$ equal the total net mechanical power output of the complete rowing cycle.

Movement execution
For the selected time period, the average stroke length (SL) was determined each rowing cycle as the difference between maximum and minimum distance of the handle to the flywheel. Average stroke time (ST) and recovery time (RT) were also recorded for each rowing cycle. Stroke time was defined as the time it took the rower to move the handle from the position closest to the flywheel (catch position) to the position furthest away from the flywheel (finish position). Recovery time was defined as the time

it took the rower to get the handle from the finish position back to the catch position. The average ratio between ST and RT (S/R) was also determined.

To provide an indication of the contraction velocities of the hip and knee extensors in the phase in which these muscles were strongly activated, the average knee-angle and hip-angle velocities ($\dot{\varphi}_{knee}$ and $\dot{\varphi}_{hip}$ respectively) were calculated during the stroke phase at times when F_{handle} was greater than 200 N.

Statistics

Repeated measures ANOVA was performed to investigate differences in e_{gross}, as well as differences in $\overline{P}_{rower}$, $\overline{P}_{flywheel}$, $\dot{V}O_2$, RER, evelocity, $\overline{P}_{negative}$, SL, ST, RT, S/R and $\dot{\varphi}_{knee}$ and $\dot{\varphi}_{hip}$ between the three stroke-rates. When a main effect was found, post-hoc statistics were performed and results were compared using the least significant difference (LSD) method. Differences were accepted as significant at $p<0.05$. Pearson's r was calculated between e_{gross} and $\overline{P}_{negative}$, $\dot{\varphi}_{knee}$ and $\dot{\varphi}_{hip}$. Correlations were accepted as significant at $p<0.05$.

RESULTS

Experiment 1:

Average 2000m time was 452 ± 16 s (minimum 430 s, maximum 485 s). Average $\dot{V}O_{2\text{-max}}$ was 3.60 ± 0.36 l·min^{-1} (minimum 2.61 l·min^{-1}, maximum 4.32 l·min^{-1}). Average power over 2000m ($\overline{P}_{2000m}$) was 264 ± 30 W (minimum 201 W, maximum 312 W).

Experiment 2:

All participants reached steady state values for $\dot{V}O_2$ and $\overline{P}_{rower}$ before 90 seconds after the start of each trial, ensuring reliable determination of e_{gross}. Figure 3.2 shows a typical example of $\dot{V}O_2$ of one of the participants.
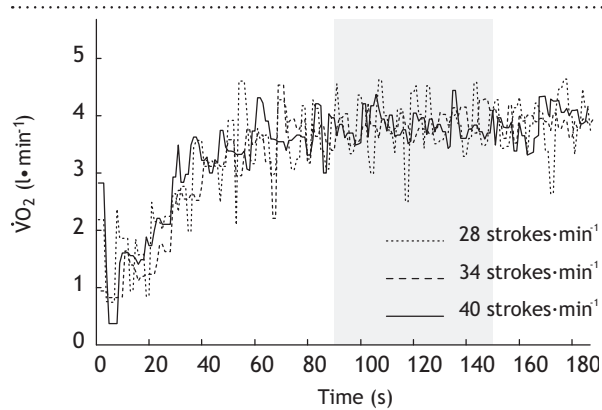
Figure 3.2: *Typical example of oxygen uptake during the 3 minute trials of rowing at 70% of $\overline{P}_{2000m}$. The dotted line represents oxygen uptake at stroke rate 28, the dashed line represents oxygen uptake at stroke rate 34, the solid line represents oxygen uptake at stroke rate 40. The shaded area represents the period for which analysis was done. All participants included in the study reached steady state values well before 90 seconds after the start of the trial.*

Gross efficiency was 0.20 in each of the three conditions (Table 3.2). No differences in egross were observed between the three stroke rates. This finding suggests that in rowing the internal power losses are not influenced by stroke rate. Figure 3.3 shows egross plotted against $\overline{P}_{rower}$. The figure shows that there was no systematic relationship between $\overline{P}_{rower}$ and egross within the range of $\overline{P}_{rower}$ values observed. The figure also illustrates that there is no effect of stroke rate on egross within participants. A main effect for stroke rate on $\overline{P}_{negative}$ was observed (P<0.001) showing a significantly larger value of $\overline{P}_{negative}$ at increasing stroke rate (Table 3.2). Negative power was 14.0 ± 2.41 W at stroke rate = 28, 20.0 ± 3.72 W at stroke rate = 34 and 29.9 ± 7.42 W at stroke rate = 40. In the introduction we postulated that an increase in energy absorption could indicate an increase in internally dissipated mechanical power. However e$_{gross}$ was insensitive for changes in $\overline{P}_{negative}$, as changes in $\overline{P}_{negative}$ were not reflected in e$_{gross}$. No significant correlation between e$_{gross}$ and $\overline{P}_{negative}$ was found (r= 0.174). These findings indicate that energy absorption by the rower's body is not necessarily an internal loss. Figure 3.4 shows a typical example of the net mechanical power production during the rowing cycle. The figure clearly shows that during the recovery phase, negative mechanical work is performed.
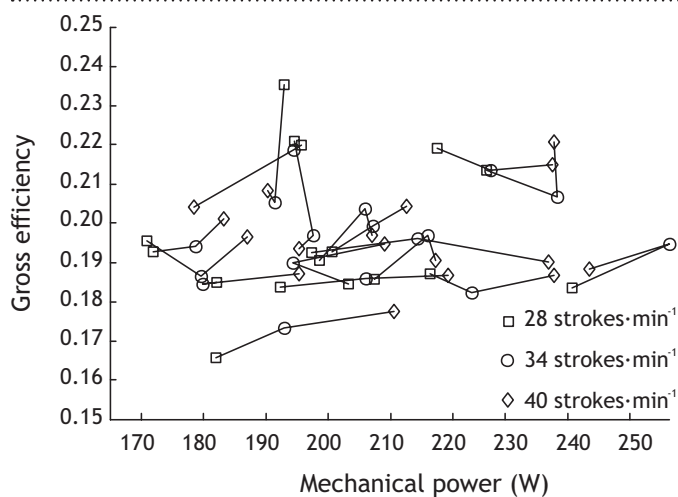
Figure 3.3: *Mechanical power production versus gross efficiency. Squares represent stroke rate 28, Circles represent stroke rate 34, diamonds represent stroke rate 40. Results of the same participant are connected by a line. The figure shows that in the range of observed $\bar{P}_{rower}$, there is no relationship between $\bar{P}_{rower}$ and e_{gross}. The Figure also shows that stroke rate has no effect on e_{gross}.*
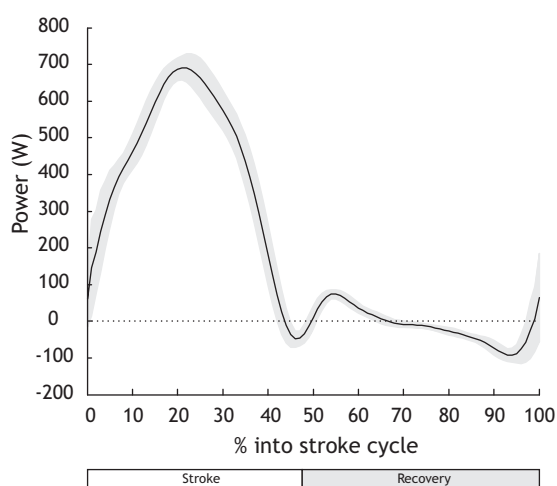
Figure 3.4: *Mechanical power averaged over a one minute period of a typical participant rowing at 34 strokes·min^{-1}. The gray area indicates the standard deviation. The Figure shows that for a large section of the recovery phase, P_{rower} has a negative value.*

Power transfer to the flywheel was identical in all 3 conditions at an average value of 183 W. This was expected, as participants received constant feedback about this variable and were instructed to keep $\bar{P}_{flywheel}$ at a certain value. However, $\bar{P}_{rower}$ differed significantly between all three conditions ($P<0.001$). Net mechanical power production was 199.3 ± 18.1, 205.8 ± 21.0 and 211.2 ± 20.8 W at respectively 28, 34 and 40 strokes·min^{-1}. A main effect was also found for ($P<0.05$). Oxygen uptake increased at increasing stroke rate and was 3.00 ± 0.36, 3.08 ± 0.32 and 3.11 ± 0.36 l·min^{-1} at respectively 28, 34 and 40 strokes·min^{-1}. Post hoc statistics revealed that $\dot{V}O_2$ at 28 strokes·min^{-1} and $\dot{V}O_2$ at 40 strokes·min^{-1} were significantly different. The increase in $\bar{P}_{rower}$ at increasing stroke rate, coupled to the increase in $\dot{V}O_2$ was caused by an increase in power absorption by the external damper, in turn resulting in a significant decrease of $e_{velocity}$ (Table 3.2). This effect of stroke rate on $e_{velocity}$ is consistent with our earlier results during on-water rowing[9]. Since e_{gross} is the ratio between mechanical power and metabolic power, e_{gross} did not differ between conditions, as both $\bar{P}_{rower}$ and $\dot{V}O_2$ changed by similar amounts. All things considered, in our experiment rowing at higher stroke rates at a constant power transfer to the flywheel was less efficient. This was caused by an increase in power lost due to velocity fluctuations, and not, as previously suggested, by an increase in internal power losses.

No differences were found in $\dot{\varphi}_{knee}$ between the 3 conditions, suggesting similar muscle contraction velocities of the knee extensors at all stroke rates during the stroke phase. A main effect was found for $\dot{\varphi}_{hip}$ ($P<0.01$). Hip joint angular velocity was 2.91 ± 0.24 rad·s^{-1} at stroke rate 40, which was significantly higher compared to stroke rate 28 ($P<0.01$, 2.76 ± 0.20 rad·s^{-1}) and 36 ($P<0.001$, 2.81 ± 0.23 rad·s^{-1}), suggesting slightly higher contraction velocities of the hip extensors at the highest stroke rate during the active part of the stroke phase. Figures 3.5a and 3.5b show a typical example of $\dot{\varphi}_{knee}$ and $\dot{\varphi}_{hip}$ at the three different stroke rates. These results illustrate that differences in angular velocities between the three conditions are either very small or do not exist at all.

No significant correlations were observed between e_{gross} and $\bar{P}_{negative}$, $\dot{\varphi}_{knee}$ or $\dot{\varphi}_{hip}$ (respective r values were 0.174, -0.174 and -0.150). This result suggests that at the observed conditions $\bar{P}_{negative}$, $\dot{\varphi}_{knee}$ or $\dot{\varphi}_{hip}$ are not related to e_{gross}, or that the observed differences were not large enough to influence e_{gross}.
Stroke length significantly decreased at increasing stroke rates, from 1.41 ± 0.077m at 28 strokes·min^{-1} to 1.25 ± 0.107m at 40 strokes·min^{-1} ($P< 0.001$). Stroke time and RT decreased at increasing stroke rate ($P < 0.001$). Recovery time decreased to a greater extent than ST, which was reflected in a significant increase in S/R. Stroke to recovery ratio increased from 0.76 ± 0.058 at 28 strokes·min^{-1} to 1.14 ± 0.138 at 40 strokes·min^{-1}

(P < 0.001). Rowers thus adapted their technique at increasing stroke rate by shortening the stroke length and decreasing the time spend in the recovery phase (Table 3.2).
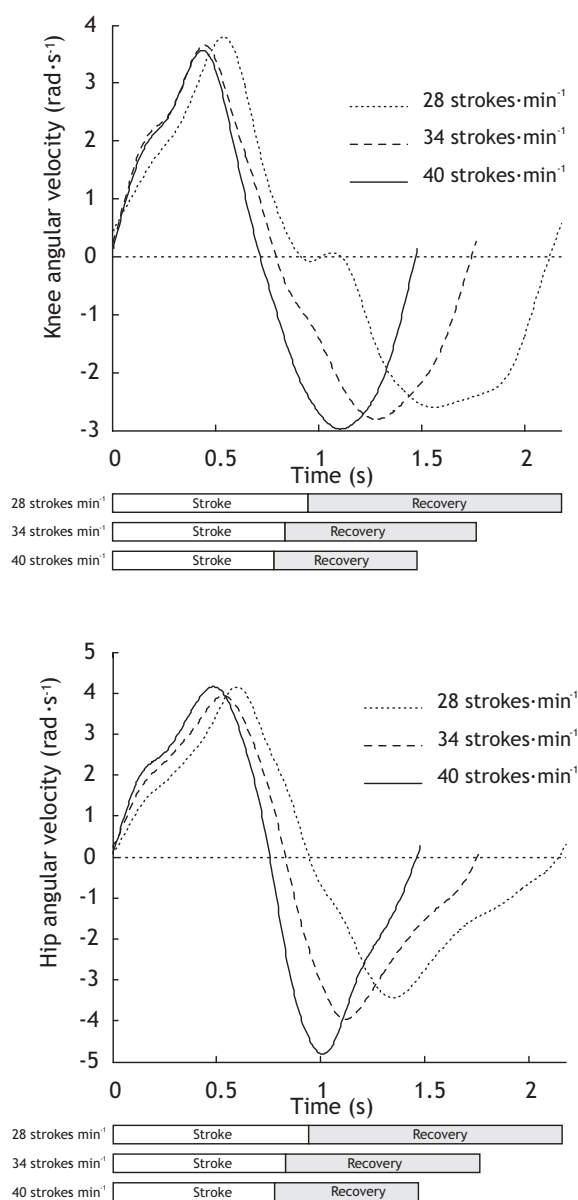
Figure 3.5: *Typical examples of joint angular velocity during one stroke cycle. Figure A (top) shows knee angular velocity, Figure B (bottom) shows hip angular velocity. The dotted line represents joint angular velocity at stroke rate 28, the dashed line represents joint angular velocity at stroke rate 34, the solid line represents joint angular velocity at stroke rate 40. Both Figures show that, especially during the stroke phase, differences in joint angular velocity between conditions are small.*

	A: 28 strokes·min^{-1}	B: 34 strokes·min^{-1}	C: 40 strokes·min^{-1}
e_{gross}	0.197 ± 0.018	0.196 ± 0.012	0.197 ± 0.011
$\dot{V}O_2$ (l·min^{-1})^{AC}	3.00 ± 0.36	3.08 ± 0.32	3.11 ± 0.36
$\overline{P}_{rower}$ (W)^{AB,AC}	199.3 ± 18.1	205.8 ± 21.0	211.2 ± 20.8
$\overline{P}_{flywheel}$ (W)	181.5 ± 17.0	182.6 ± 19.3	185.0 ± 17.9
RER^{AB,BC,AC}	0.88 ± 0.039	0.91 ± 0.027	0.96 ± 0.034
$e_{velocity}$^{AB,AC}	0.92 ± 0.021	0.90 ± 0.020	0.89 ± 0.030
$\overline{P}_{negative}$ (W)^{AB,BC,AC}	14.0 ± 2.41	20.0 ± 3.72	29.9 ± 7.42
$\dot{\varphi}_{knee}$ (rad·s^{-1})	2.69 ± 0.18	2.73 ± 0.20	2.75 ± 0.27
$\dot{\varphi}_{hip}$ (rad·s^{-1})^{BC,AC}	2.76 ± 0.20	2.81 ± 0.23	2.92 ± 0.24
SL (m)^{AB,BC,AC}	1.41 ± 0.077	1.34 ± 0.071	1.25 ± 0.107
ST (s)^{AB,BC,AC}	0.92 ± 0.054	0.87 ± 0.048	0.81 ± 0.058
RT (s)^{AB,BC,AC}	1.22 ± 0.062	0.91 ± 0.039	0.72 ± 0.040
S:R^{AB,BC,AC}	0.76 ± 0.058	0.96 ± 0.095	1.14 ± 0.138

Table 3.2: *Summary of the results (Differences significant at P < 0.05, AB: Significant difference between conditions A and B, BC: Significant difference between conditions B and C, AC: Significant difference between conditions A and C.*

DISCUSSION

In this study we investigated whether gross efficiency is affected by stroke rate. Our results show that in rowing on our modified rowing ergometer there is no relationship between stroke rate and e_{gross}. We also investigated if the average amount of negative power within the rowing cycle ($\overline{P}_{negative}$), defined as the total amount of negative work divided by rowing cycle duration, is an appropriate measure for internal power losses. Although significant differences of $\overline{P}_{negative}$ between conditions were found, there was no correlation between $\overline{P}_{negative}$ and e_{gross}. This suggests that $\overline{P}_{negative}$ is not a good measure to estimate internal power losses. On the whole it appears that within the range of stroke rates applied in competitive rowing, internal power losses are unrelated to rowing cycle frequency. Although $\overline{P}_{negative}$ is higher at higher stroke rates, e_{gross} appears to be insensitive to any changes in $\overline{P}_{negative}$.

The values found for e_{gross} (~0.20) are close to the optimum of individual muscles (~0.25)[22]. This finding suggests that on the whole, internal power losses are likely to be small. It was previously reported that metabolic energy expenditure depends on stroke-rate during unloaded rowing[21]. These results have limited relevance to the actual situation in rowing, since, in the former case, there is no mechanical power exchange with the environment. In the unloaded situation, there is thus no energy transfer from kinetic energy to mechanical energy. This means that for each stroke cycle, the total amount of positive work equals the total amount of negative work, or in other words, that all of the generated (positive) work has to be either stored or dissipated within the MTC's. Thus, internal losses will be higher in the unloaded situation compared to actual (ergometer) rowing.

The amount of $\overline{P}_{negative}$ represents the minimum amount of power that is absorbed by the rower's MTC's during each stroke cycle. Compared to the total net mechanical power production, $\overline{P}_{negative}$ is relatively small. The difference between the smallest average value of $\overline{P}_{negative}$ found at stroke rate 28 (14.0 W) and the largest average value of $\overline{P}_{negative}$ found at stroke rate 40 (29.9 W) was 15.9 W. As the cycle duration at stroke rate 40 is 1.5 seconds, the difference in $\overline{P}_{negative}$ found between those two conditions indicates energy absorption by the rower's body to be roughly 24 J more during each rowing cycle at 40 strokes·min^{-1}. However, our data do not allow us to separate this power into power that is dissipated and power that is conserved in elastic structures such as tendons. To our knowledge, there are no studies that investigate the in vivo energy storage in MTC's during rowing. However, it is known that energy storage in elastic structures occurs in various tasks such as walking[13], counter movement jumping[15] and one legged hopping[17]. The amounts of energy stored in elastic structures in these

studies have the same magnitude as the amount of energy we found to be absorbed during each stroke cycle. It is feasible that energy storage occurs also in rowing, as the contraction conditions in rowing include an increasing force during the stretching of the MTC's, which would allow elastic storage. From this, we can hypothesize that the insensitivity of e_{gross} to $\overline{P}_{negative}$ is not only due to the fact that it is a relatively small term, but probably also due to the fact that a part is stored elastically.

As stated in the introduction, mechanical work per stroke is determined by setup and technique. In this study, the ergometer setup (i.e. the resistance setting) was kept at a constant value. In order to keep transfer to the flywheel constant at different stroke rates, mechanical work per stroke had to decrease at increasing stroke rate. Our results confirm that this was indeed the case. The results show that rowers adapted their technique at higher stroke rates, by shortening the stroke length and increasing the stroke to recovery ratio.

Mechanical efficiency of individual muscles depends on muscle contraction[22]. Although we did not measure contraction velocities directly, an indication was given by reporting joint angular velocities in the active part of the stroke phase, which were referred to as $\dot{\phi}_{knee}$ and $\dot{\phi}_{hip}$. No main effect was found for $\dot{\phi}_{knee}$ between stroke rates. For $\dot{\phi}_{hip}$ a main effect was observed. Post hoc analyses revealed that $\dot{\phi}_{hip}$ at 40 strokes·min^{-1} differed significantly from the other 2 stroke rates. However, the magnitude of these differences was small. These results suggest that in rowing contraction velocities in the active phase are relatively invariant over a broad range of stroke rates. This finding is clearly different from cycling, where contraction velocities are directly related to cadence[19]. In cycling this strong dependence of shortening velocities in cadence results in a systematic relation between cadence and gross efficiency[18]. In our view, the lack of such a correlation between joint angular velocities and e_{gross} in rowing is likely to be the result of contraction velocities at all stroke rates being close to the optimum of the velocity – efficiency relationship.

The results show a decrease of $e_{velocity}$ at increasing stroke rates. While $\overline{P}_{flywheel}$ remained constant in the 3 conditions, more power was dissipated by the external damper. In other words, the amount of power by which $\overline{P}_{rower}$ increased at increasing stroke rate was completely dissipated by the external damper. This is reflected in a significant decrease in $e_{velocity}$ at increasing stroke rate. The effect of stroke rate on $e_{velocity}$ is in accordance with earlier results, obtained during on-water rowing[9]. Ideally, $\overline{P}_{rower}$ instead of $\overline{P}_{flywheel}$ had been kept constant at all stroke rates. However, as the only available direct feedback of power in the experiment was feedback on $\overline{P}_{flywheel}$, this was impossible to accomplish.

Although this study was carried out on an adapted rowing ergometer, we have no reason to expect that the insensitivity of e_{gross} for stroke rate will be any different in on-water rowing. The kinematics of ergometer rowing closely resemble those of on-water rowing[16]. The similarity was further enhanced by putting the ergometer on wheels[3, 6], thereby reducing the amplitude of velocity changes of the rower's centre of mass. If there would be any effect of stroke rate on e_{gross}, one could speculate it would be more pronounced on the ergometer than during on-water rowing, since the ratio of weights of rower to 'boat' is smaller in our set-up than in an actual boat. This implies that, on the ergometer, the fluctuations in rower velocity will be slightly higher compared to those in the boat. Nevertheless, it is worthwhile to study the relationship between stroke rate and e_{gross} in on-water rowing.

In conclusion, the results of this study show that e_{gross} is not influenced by stroke rate, which suggests that internal power losses are also not influenced by stroke rate. Negative power as evaluated in this study is affected by stroke rate, albeit that the effect is small. However, part of the absorbed energy is expected to be stored in elastic structures rather than dissipated. All in all, we have found no support for the suggestion that a noticeable amount of metabolic power is spent on motion of the rower relative to the boat. Our results suggest that choice of stroke rate cannot be explained by gross efficiency.

ACKNOWLEDGEMENTS

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Appendix: Internal energy dissipation

A valuable tool for analysis of high-intensity periodic tasks such as rowing is the mechanical power equation[12]. In its instantaneous form, the mechanical power equation for the rower can be expressed as follows:

$$\Sigma P_{MTC} + \Sigma P_{ext} = dE_{kin}/dt \qquad \text{Equation A3.1}$$

P_{MTC} refers to mechanical power generated by a muscle-tendon complex (MTC):

$$\Sigma P_{MTC} = \Sigma -F_{muscle} \cdot v_{o-i} \qquad \text{Equation A3.2}$$

In which F_{muscle} refers to the force of any muscle, which by definition is always positive, and v_{o-i} refers to the origin-insertion velocity of the corresponding MTC. Origin-insertion velocity is defined as the first derivative to time of origin insertion length, such that a shortening muscle has $v_{o-i}<0$ and a lengthening muscle has $v_{o-i}>0$. The total sum of power generated by all MTC's, ΣP_{MTC}, equals the instantaneous net mechanical power output (P_{rower}).

P_{ext} refers to mechanical power exchange with the environment:

$$\Sigma P_{ext} = \Sigma F_{ext} \cdot v_{p.o.a.} \qquad \text{Equation A3.3}$$

In which F_{ext} refers to the vector of any external force and $v_{p.o.a.}$ is the velocity vector of its point of application. Note that in this formulation the energetic aspects of the force of gravity are incorporated in terms of the power of this force rather than in terms of the time derivative of the gravitational potential energy. Finally, dE_{kin}/dt refers to the time derivative of the total kinetic energy of the rower's body.

The term in this power equation that would appear to be related to the aforementioned 'energy to move the body back and forth' (see Introduction) is dE_{kin}/dt. At higher stroke rates, dE_{kin}/dt reaches more extreme values and the kinetic energy content of the rower has larger fluctuations. However, in steady-state rowing, the average value of dE_{kin}/dt equals zero at any stroke rate by definition, as there is no net acceleration or deceleration of the rower. In strict mechanical terms there is thus no energy loss that is associated per se with moving the body back and forth periodically.

With $v_{o-i}<0$ (muscle shortens), an MTC will generate mechanical power ($P_{MTC}>0$), whereas with $v_{o-i}>0$ (muscle lengthens), an MTC will absorb mechanical power ($P_{MTC}<0$) and with $v_{o-i}=0$ an MTC will have $P_{MTC}=0$. From equation A3.2 it follows that P_{rower} will always be

smaller than the positive mechanical power generated by all shortening MTC's together. As MTC's are not perfectly elastic, it is inevitable that a part of the mechanical power absorbed by all lengthening MTC's combined is converted into heat. We will refer to this term as the instantaneous internal mechanical power loss. In our view, it is this term that captures any energy expenditure related to moving the body back and forth.

It is currently not viable to measure mechanical behavior at the level of individual MTC's. As an alternative, it is common practice to calculate P_{rower} from the remaining terms in equation A3.1. A direct implication of this procedure is that it does not allow quantification of the instantaneous internal mechanical power loss. This implication has led to several proposals regarding methods with which internal mechanical power loss can be estimated on the basis of mechanical variables. For example, it has been suggested to estimate internal power loss from the fluctuations in kinetic energy and stroke phase and recovery phase durations[19]. A serious drawback of this proposal is that results are dependent on the chosen frame of reference, while there is no such thing as the 'correct' frame of reference; analysis of on-water rowing when using an earth-bound frame of reference will yield substantially higher values for dE_{kin}/dt than when a moving frame of reference is adopted. As an alternative, it has been suggested to use the absolute values of joint powers obtained from an inverse dynamical analysis as an indication of internal power loss[1, 2]. These and similar proposals have been dismissed by other authors, however, on the ground that they lack theoretical basis[11].

Chapter 4

Strapping rowers to their sliding seat improves performance during the start of ergometer rowing

ABSTRACT

Rowers are seated on a seat that slides relative to the boat/ergometer. If a rower lifts him/herself from this sliding seat at any time, then the sliding seat will move away from under the rower and the rowing action is disrupted. From a mechanical perspective, it is clear that the necessity for the rower to remain in contact with the sliding seat at all times imposes position-dependent constraints on the forces exerted at the oar handle and the footstretcher. Here we investigate if the mechanical power output during rowing, which is tightly related to these forces, might be improved if the contact with the sliding seat would be of no concern to the rower. More in particular, we investigate if elimination of these constraints by strapping the rower to the sliding seat leads to an increase in performance during the start on a standard rowing ergometer. Eleven well-trained female rowers performed 5-stroke starts in normal and strapped conditions. Handle force, vertical seat force, footstretcher force and handle kinematics were recorded, from which mechanical power and work output were calculated. Most of the relevant mechanical variables differed significantly between the normal and strapped conditions. Most importantly, mechanical power output (averaged over the 5-stroke start) in the strapped condition was 12% higher than in the normal condition. It is concluded that strapping a rower's pelvis to the sliding seat allows more vigorous execution of the stroke phases, resulting in a substantial improvement in performance during the start of ergometer rowing.

INTRODUCTION

In the vast majority of sporting activities, the athlete is in physical contact with the mechanical environment, be it the earth or a mechanical device. There are several cases where it is desired that no slip or loss of contact occurs between the athlete and the mechanical environment. For example, a track and field athlete does not want slip to occur between the foot of the stance leg and the ground; a cyclist does not want the feet to slip off the pedals at any time; a rower does not want to lose contact with the sliding seat at any time. In each of these examples, the forces that the athlete can exert on the environment are constrained by the requirement to prevent slip, unless technical measures are taken. Ideally, such technical measures ensure that no slip or loss of contact occurs, without constraining the athlete's coordination or impeding performance in any respect. Regarding the first two examples mentioned such technical measures have indeed been implemented: stance foot slip in the track and field athlete is prevented by using spikes; contact loss between the cyclist's foot and the pedal is prevented by using toe clips or so-called clip-in pedals. In this study, we will consider the third example, i.e. the requirement for a rower to maintain contact with the sliding seat at all times.

In competitive rowing, the rower's toes are connected to the footstretcher, which in turn is rigidly connected to the hull. In order to achieve a high average boat velocity, the rower has to exert high forces on the handles of the oar(s) and, consequently, on the footstretcher, during the stroke phase. Rowers sit on a seat that can slide in fore-aft direction relative to the boat, allowing the use of leg extension in the stroke phase. If a rower inadvertently lifts him/herself from this sliding seat at any time, then the sliding seat will move away from under the rower; contact between rower and sliding seat is unlikely to be re-established when the rower subsequently lowers his/her buttocks, and the rowing action is quasi-permanently disrupted. Consequently, rowers want to maintain contact with their sliding seat at all times. The frictional force in fore-aft direction that causes the seat to move in concert with the rower's pelvis only exists when a normal force between the pelvis and the seat is present. Thus, contact loss is bound to occur when this normal force becomes zero. Mechanical analysis of the free body 'rower', as shown schematically in Figure 4.1, indicates that the vertical force of the seat on the pelvis is directly related to the force acting from the handle on the hands and the force acting from the footstretcher on the feet. Thus, the necessity to retain contact with the sliding seat imposes an upper limit on the forces acting at the hands and feet, and thus on performance.
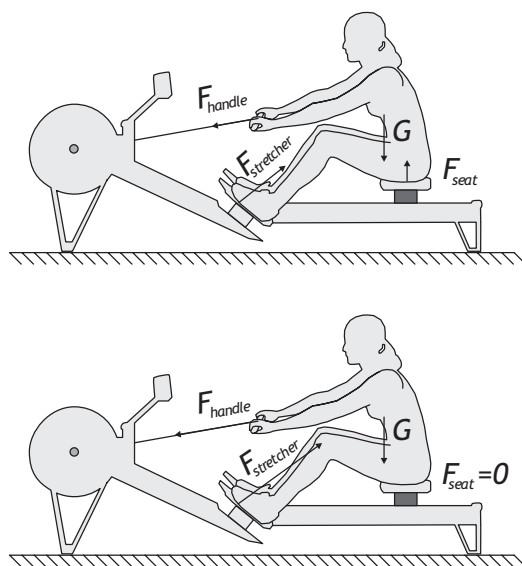
Figure 4.1. *Illustration of the relation between handle, footstretcher and seat force, for a given body position that is analyzed quasi-statically. G represents the force of gravity. In the analysis it is assumed that the horizontal seat force is negligible. Given a value for handle force magnitude, the force and torque equilibrium conditions (three conditions in total) allow calculation of horizontal and vertical footstretcher force and vertical seat force (three unknowns). Top panel: $|F_{handle}| = |G|$, resulting in a vertical seat force of $0.4 \cdot |G|$; bottom panel: $F_{handle} = 1.8 \cdot G$, resulting in a seat force of zero.*

The actual value of the upper limit on handle and footstretcher force depends on several factors, including the position of the footstretcher, the position of the rower's centre of mass and the acceleration of the rower. It has been suggested, albeit on different grounds, that it may be advantageous to position the point of contact on the footstretcher as high as possible[1]. From our perspective, this would indeed make sense because it would reduce the torque of the handle force relative to this point of contact. In fact, rowers optimize the location of this contact point on an individual basis. Unfortunately, the possibilities for this type of adaptation are limited due to geometric and anthropometric constraints.

A straightforward way to investigate if the necessity to retain contact with the sliding seat at all times indeed constrains performance during high-intensity rowing is to measure the vertical seat force. While such measurements are not easily performed during on-water rowing, they are feasible when using a rowing ergometer. Rowing ergometers are routinely used by competitive rowers for training purposes and rower

kinematics has been reported to be similar during on-water rowing and ergometer rowing[2]. In a recent pilot experiment, we measured the vertical seat force during ergometer rowing in an Olympic-level rower (see Figure 4.2). It was found that the vertical seat force reaches values that are very close to zero, which at least suggests that the necessity to retain contact with the sliding seat may indeed constrain the handle and/or footstretcher forces and may thus have a detrimental effect on performance.
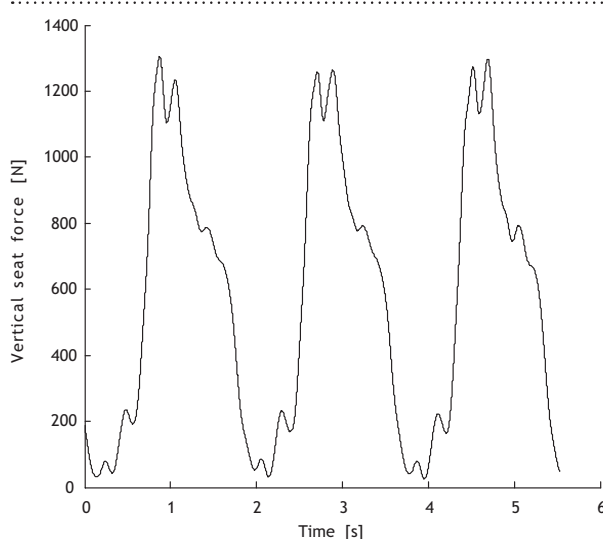
Figure 4.2. *Vertical seat force for three consecutive strokes of an Olympic-level Dutch rower during high-intensity ergometer rowing. It is seen that the minimum value of the vertical seat force is only marginally larger than zero.*

Inspired by the technical solutions for the first two examples described above, it is clear that strapping the rower's pelvis to the sliding seat will allow the rower to pull at the handle as hard as (s)he can. It is thus predicted that strapping the rower to the sliding seat will allow the rower to improve performance. Experimental evaluation of this prediction during on-water rowing requires that safety issues are adequately dealt with and furthermore requires that the sliding seat and rail mechanism are redesigned (see Discussion); in our view, addressing these problems should be postponed until it is established that strapping the rower's pelvis to the sliding seat indeed has the potential to improve performance. Consequently, the experimental evaluation reported in this study is limited to ergometer rowing. Furthermore, it is not clear if, during steady state rowing, central physiological processes allow any increase in mechanical power

output; consequently, the current experiment is concerned with a starting task in which central physiological processes do not constrain the mechanical power output. In sum, it is investigated in this study if strapping the rower's pelvis to the sliding seat leads to improved performance during the start of ergometer rowing.

METHODS

Outline of the study.
Each participant performed four maximum-effort starts on a standard Concept2c rowing ergometer (Concept2, Morrisville VT, USA). On this ergometer the seat slides on a rail constructed in such a way that the seat cannot be lifted from the rail and that the frictional force between rail and seat is low for both pushing and pulling forces on the seat. Two starts were made in the normal condition and two in the strapped condition, in which the pelvis of the subject was tightly strapped to the sliding seat. Handle position, handle force, and seat force were measured.

Participants.
Eleven well-trained female rowers participated in this study. Their level of experience varied from having one year of experience in competitive rowing at club level to being a member of the Dutch national team. All participants trained regularly on a Concept2c rowing ergometer. Body mass, age and years of rowing experience are reported in Table 4.1. The experiment was approved by the Ethics Committee of the Faculty of Human Movement Sciences (VU University Amsterdam), and participants provided written informed consent.

	Age [years]	Body mass [kg]	Rowing experience [years]
Mean ± SD	23 ± 3	75 ± 6	2.9 ± 2.2
Range	19-26	68-90	1-10

Table 4.1. Mean, standard deviation (SD) and range for selected subject characteristics.

Protocol.
Participants performed a 10 minute warm up, in which they familiarized themselves with the experimental setup and with the strap mechanism. Subsequently, participants were instructed to perform two maximum-effort starts under normal circumstances (condition N), and two maximum-effort starts while being strapped to the sliding seat (condition S). Ordering of the starts was NSSN in one half of the subjects and SNNS in

the other half, in an attempt to exclude order effects. Each of the starts consisted of 5 strokes. No constraints were imposed on the initial body configuration. Care was taken that the initial flywheel angular velocity was zero. The subject was instructed to initiate the start at a self-chosen moment in time. Ample time for recovery was allowed between the starts.

Apparatus and instrumentation.

The Concept2c ergometer uses an air-braked resistance mechanism in the form of a flywheel with fans. The flywheel is accelerated during the stroke phase by pulling on a handle, which is attached to a chain that revolves around a cog. The cog is mounted on a freewheel, causing flywheel rotation to be decoupled from handle motion during the recovery phase. During this phase, the handle is pulled back towards the flywheel by an elastic band that is in series with the chain. In the standard Concept2c ergometer as used in this study, the ergometer cage as well as the footstretcher do not move relative to the ground. In the strapped condition, the rowers wore a waist belt that was tightly fastened. Two vertical straps were used to connect this belt to hooks on left and right sides of the sliding seat. Seat force and footstretcher force were measured using 6 degree-of-freedom force transducers mounted under the seat and under the footstretchers (AMTI, Watertown MA, USA). Handle force, that can only act in line with the chain, was measured using a one degree-of-freedom force transducer (AST, Dresden, Germany) mounted between the handle and the chain. Forces were sampled at 200 Hz. Kinematics of the handle and the flywheel axis were measured using an Optotrak 3020 system (Northern Digital, Waterloo, Canada), using a sample frequency of 100 Hz. Velocity data were obtained by taking the five-point derivative of position data.

Data analysis.

The instant in time at which each of the five stroke phases were initiated (the 'catch') and completed (the 'finish') were determined on the basis of a threshold in the handle force (see Figure 4.3 for an example of the instants of catch and finish as detected). The scalar handle 'position' d_{handle} was calculated as the Euclidian distance between the midpoint of the handle and the flywheel axis. Scalar handle velocity v_{handle} was calculated by taking the five-point time derivative of d_{handle}. The scalar variable F_{seat} refers to the vertical component of the force exerted by the seat on the rower, where a positive value indicates an upward force. Similarly, the scalar variable F_{handle} refers to the force exerted by the handle on the rower along the line from flywheel axis to handle, where a force in the direction of the flywheel axis is defined to be positive. The scalar variable $F_{stretcher}$ refers to the horizontal component of the force exerted by the left and right footstretchers together on the feet of the rower, where a positive value indicates that the footstretchers push against the feet. P_{ergo}, the instantaneous

mechanical power transferred by the rower to the ergometer, was calculated from these variables as $P_{ergo} = v_{handle} \cdot F_{handle}$. In order to carry out this calculation, kinematic data were resampled at 200 Hz using cubic spline interpolation. Mechanical work done by the rower on the ergometer W_{ergo} was calculated by taking the numerical integral over time of P_{ergo}, either over a stroke phase or over the full start. Each of the scalar variables reported is the average value over the two starts for the condition considered.

Statistical analysis.

To investigate if variables differed between the normal and strapped conditions, paired Student's t-tests were performed, using a significance level of p=0.01.
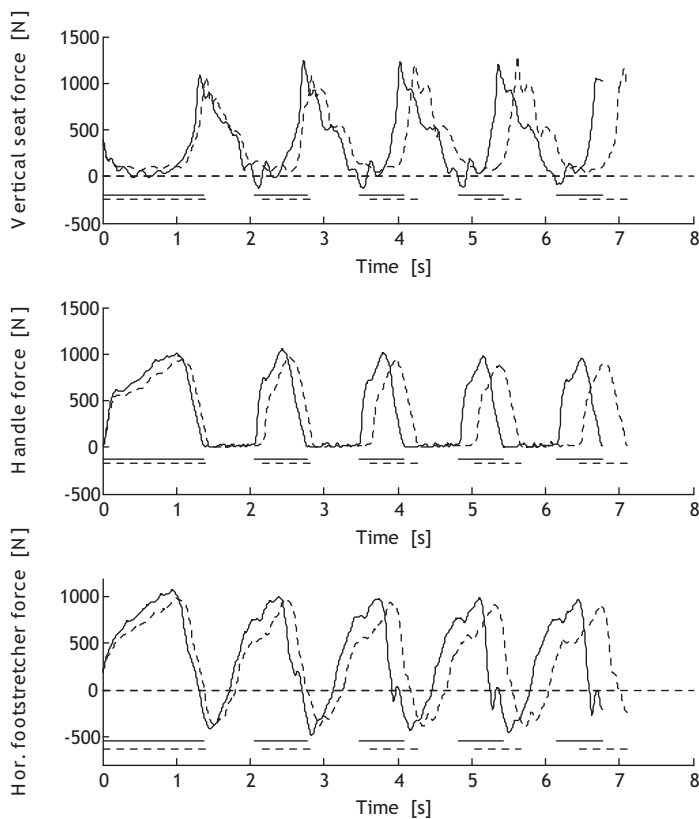
Figure 4.3. *Typical example of the vertical seat force (top panel), handle force (middle panel), and horizontal footstretcher force (bottom panel) as a function of time for the normal (dashed lines) and strapped (solid lines) trials with highest average handle power. The bars at the bottom of each panel delimit the stroke phases. It is seen that minimal vertical seat force is lower, that maximal handle force is higher, and that horizontal footstretcher force around the catch is higher in the strapped condition.*

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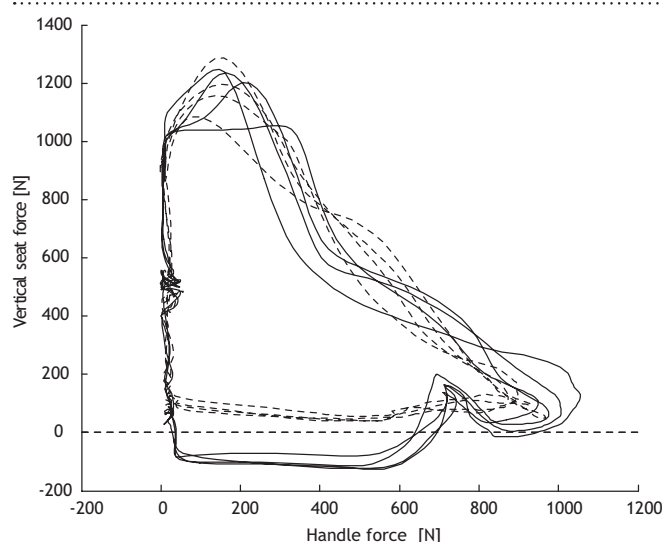
Figure 4.4. *Typical example of vertical seat force versus handle force for strokes 2-5 for the normal (dashed lines) and strapped (solid lines) trials with highest average handle power. In these force loops, time progresses in counterclockwise direction. Data correspond to those used in Fig. 4.3. It is seen that handle and vertical seat force are tightly related and that the vertical seat force is negative during part of each cycle in the strapped condition.*

RESULTS

Vertical seat force as a function of time for a typical subject is presented in Figure 4.3. The minimum value of the seat force was negative in the strapped condition, which is mechanically impossible in the normal condition. This is more clearly seen in Figure 4.4, where F_{seat} is plotted against F_{handle} for strokes 2-5. In the normal condition F_{seat} was positive throughout, as expected; in the strapped condition the minimum seat force was negative during part of the cycle, indicating that the rower was indeed using the strap to pull on the seat. Closer examination of Figure 4.4 reveals that, in the strapped condition, the seat force already became negative around the catch, i.e. when handle force was still low. This suggests that, around the catch, the strap was not used to allow a higher handle force but was rather used to allow a higher value of $F_{stretcher}$, i.e. to allow more vigorous acceleration of the rower's centre of mass. This suggestion is supported by the typical example shown in Figure 4.3 (bottom panel), where it is indeed seen that, around the catch, $F_{stretcher}$ is substantially higher in the strapped condition for all strokes except stroke 1. Somewhat further into the stroke

phase, the lower vertical seat force in the strapped condition is accompanied by a higher maximal handle force, as can be seen from both Figure 4.3 and Figure 4.4. As expected, the higher handle force resulted in a substantially higher P_{ergo} (the mechanical power delivered by the rower to the ergometer) and, consequently, a substantially higher W_{ergo} over the five strokes considered (see Figure 4.5).
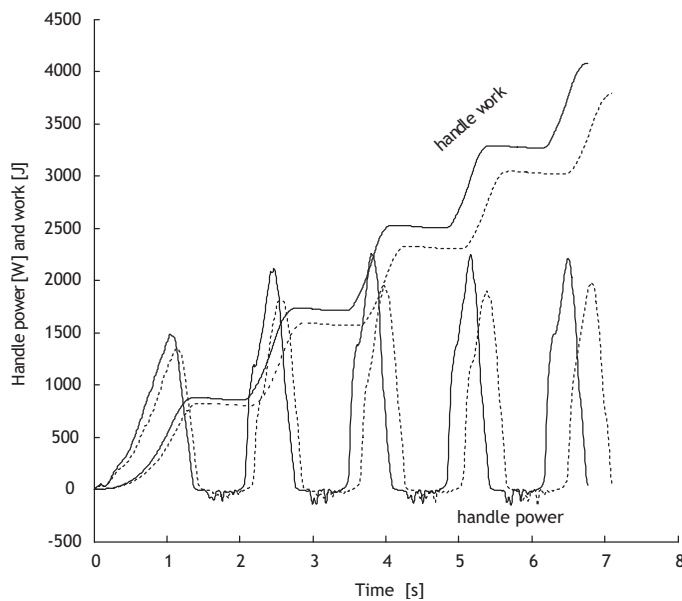
Figure 4.5. *Typical example of the instantaneous mechanical power done on the handle as a function of time, and its time integral, i.e. the cumulative mechanical work done on the handle, for the normal (dashed lines) and strapped (solid lines) trials with highest average handle power. Data correspond to those used in Fig. 4.3. It is seen that maximal power during the stroke phases and total work over the first five cycles are higher in the strapped condition.*

	Normal	Strapped	Δ	Rel. Δ (%)	Sign.
ΔT [s]	6.67 ± 0.40	6.43 ± 0.30	−0.23 ± 0.33	−3.3 ± 5.0	0.049
Wergo [J]	3237 ± 400	3486 ± 424	+248 ± 144	+7.8 ± 4.7	<0.001
Mean(Pergo) [W]	485 ± 45	541 ± 53	+56 ± 29	+11.6 ± 6.3	<0.001

Table 4.2. *Total time ΔT, total work W_{ergo} and mean mechanical power P_{ergo} from the catch of stroke 1 to the finish of stroke 5 (5 stroke phases and 4 recovery phases). Values represent mean ± SD (between subjects). Δ represents the difference between strapped and normal conditions. Note that the repeated-measures statistical analysis resulting in the significance values as given is only concerned with the distribution of Δ.*

In terms of performance up to the finish of the fifth stroke, the effect of strapping the rower to the sliding seat was remarkably large (see Table 4.2): the average mechanical power delivered by the rower to the ergometer was almost 12% higher. As the time to complete these first 5 strokes was only slightly shorter in the strapped condition (see Table 4.2), the total work done by the rower on the ergometer over these first 5 strokes was also substantially higher in the strapped condition. The observed increase in average mechanical power output in the strapped condition results in an improvement in virtual boat displacement of approximately 1.0 meter at 5 seconds after the start. This value is calculated from our data, using the algorithm used in the Concept2 computer (personal communication from technical staff of Concept2, Morrisville VT, USA).

When the effects of the strap on individual strokes were analyzed, it was found that the minimum of F_{seat} was negative during each of the strokes in the strapped condition, and differed significantly from the minimum of F_{seat} in the normal condition (see Table 4.3). As expected, this difference in F_{seat} was accompanied by a significant difference in the maximum of F_{handle}, which was significant for all strokes except the fifth stroke. Again as expected, $F_{stretcher}$@catch (the horizontal component of the combined footstretcher forces, at the catch) was substantially higher in the strapped condition for all strokes except the first stroke. Stroke length Δd_{handle} was slightly longer in strokes 3-5, but this difference was significant only in the third stroke; in our view this indicates that the kinematic pattern was not drastically different between conditions. The combination of higher handle force and higher handle velocity led to substantially higher P_{ergo} (averaged over each individual stroke phase); this difference ranged from 8.0% to 10.7%. Similarly, W_{ergo} was significantly higher for each of the stroke phases except the first one (Table 4.3), the difference ranging from 4.9% (for the first stroke) to 8.7%. Note that, due to the small amount of negative work during the recovery phase (data not shown), the total work as reported in Table 4.2 is slightly less than the total work for the five strokes combined that follows from Table 4.3. Finally, the duration of stroke and recovery phases are reported in Table 4.4. No significant differences were found between conditions, even if all stroke and recovery phases were slightly shorter in the strapped condition.

Stroke number		1	2	3	4	5
Δd_{handle} [m]	Normal	1.19	1.15	1.18	1.20	1.25
	Strapped	1.18	1.15	1.21	1.24	1.29
	Rel. diff (%)	−1.5	+1.0	**+2.9***	+3.2	+2.9
$Max(v_{handle})$ [m·s⁻¹]	Normal	1.57	1.92	2.08	2.15	2.20
	Strapped	1.61	1.98	2.16	2.24	2.27
	Rel. diff (%)	+2.3	**+3.2***	**+3.8***	**+4.0***	**+3.6***
$Max(F_{handle})$ [N]	Normal	889	885	866	850	853
	Strapped	953	960	920	899	896
	Rel. diff (%)	**+7.2***	**+8.7***	**+6.4***	**+6.0***	+5.1
$Min(F_{seat})$ [N]	Normal	71	59	63	61	49
	Strapped	8	−27	−42	−39	−39
	Diff (N)	**-63***	**-86***	**-105***	**-101***	**-88***
$F_{stretcher}$@catch [N]	Normal	163	684	684	686	679
	Strapped	139	844	870	864	846
	Rel. diff (%)	-11.5	**+24.1***	**+27.9***	**+26.6***	**+25.6***
W_{ergo} [J]	Normal	748	639	633	633	655
	Strapped	785	689	688	687	708
	Rel. diff (%)	+4.7	**+8.2***	**+9.1***	**+8.8***	**+8.2***
$Mean(P_{ergo})$ [W]	Normal	534	959	1030	1054	1073
	Strapped	577	1061	1132	1156	1173
	Rel. diff (%)	**+8.0***	**+11.1***	**+10.1***	**+9.8***	**+9.3***

Table 4.3. Key mechanical characteristics per stroke. See main text for definitions. All relative differences were obtained by averaging the individual relative differences. Due to the sign change in min(F_{seat}), the relative difference in this variable is not very meaningful and therefore the unscaled difference is reported instead. Significant effects are in boldface and are denoted by an asterisk ($p<0.01$).

Cycle number		1	2	3	4	5
Stroke duration [s]	Normal	1.40	0.67	0.61	0.60	0.61
	Strapped	1.36	0.65	0.61	0.59	0.60
	Rel. diff (%)	−2.9	−2.5	−0.9	−0.9	−1.1
Recovery duration [s]	Normal	0.67	0.67	0.70	0.73	
	Strapped	0.62	0.64	0.67	0.70	
	Rel. diff (%)	−6.3	−5.1	−4.0	−4.9	

Table 4.4. Stroke and recovery durations. Recovery duration refers to the recovery phase following the respective stroke phase. As subjects were asked to perform 5 maximal strokes (not 5 maximal cycles), recovery duration cannot be reported for cycle 5. All relative differences were obtained by averaging the individual relative differences. No significant differences were observed between the normal and strapped conditions.

Summarizing, it was found that strapping the rower to the sliding seat allowed the rowers to execute more vigorous strokes, resulting in a substantial improvement in performance over the starting phase considered.

DISCUSSION

Our prediction that strapping the rower to the sliding seat may result in improved performance clearly holds true during the start of ergometer rowing as considered in this study. From a theoretical perspective, the results of this study confirm the concept outlined in the introduction: performance can only increase when the desired type of physical contact between actor and environment (here: continuous contact between buttocks and sliding seat) is enforced through technical means (here: a strap).

The magnitude of the observed improvement in mechanical power output induced by the strap is such that it seems worthwhile to investigate the potential advantage of the strap during on-water rowing. As a first step, it should be established if the effect at the start observed in this study can be reproduced during on-water rowing. To this aim, a strap mechanism that conforms to strict safety regulations should be designed for use during on-water rowing. Furthermore, the sliding seat and rail mechanism currently used in on-water rowing should be slightly redesigned, so that low-friction sliding is possible both during compression of and during traction on the sliding seat. As a second step, it might be investigated if a similar advantage exists during the all-out sprint that typically occurs just before the finish of a race. As the positive effect of the strap is definitely not limited to the first one or two cycles (see Table 4.3), one

might expect that the strap will entail a similar advantage during such a final sprint, where, as during the start, mechanical rather than central physiological processes are performance-limiting.

The results of this study do not shed light on the question if the strap provides an advantage during steady state high-intensity rowing. It may well be that during steady state rowing, central or peripheral metabolic processes rather than mechanical considerations are performance-limiting. In that case the strap would not be beneficial during steady state rowing, but, if well-designed, would not be detrimental to performance either. On the other hand, it has been suggested that the maximum level of performance that can be maintained does not depend on limitations in any single subsystem, but is regulated centrally on the basis of integration of signals from various sources[3]. In that case, it would seem plausible that there is room for improvement in the functioning of each of the subsystems involved. If this suggestion is to be taken seriously, then any future attempt to determine if strapping rowers to their sliding seats may be advantageous during steady state rowing would have to include a prolonged period during which the subjects train under strapped conditions, thus imposing additional stress on the relevant subsystems.

Even if the benefits of the strap will turn out to be limited to the start phase, it may be worthwhile to introduce a strap (in whatever form) in competitive rowing, as any advantage at the start is considered to be very important by rowers; fast starting results in the tactical and psychological advantage of being able to see all opponents. Given the magnitude of the strap-induced improvement in mechanical power output observed in this study, we indeed expect this advantage to be non-negligible.

ACKNOWLEDGEMENTS

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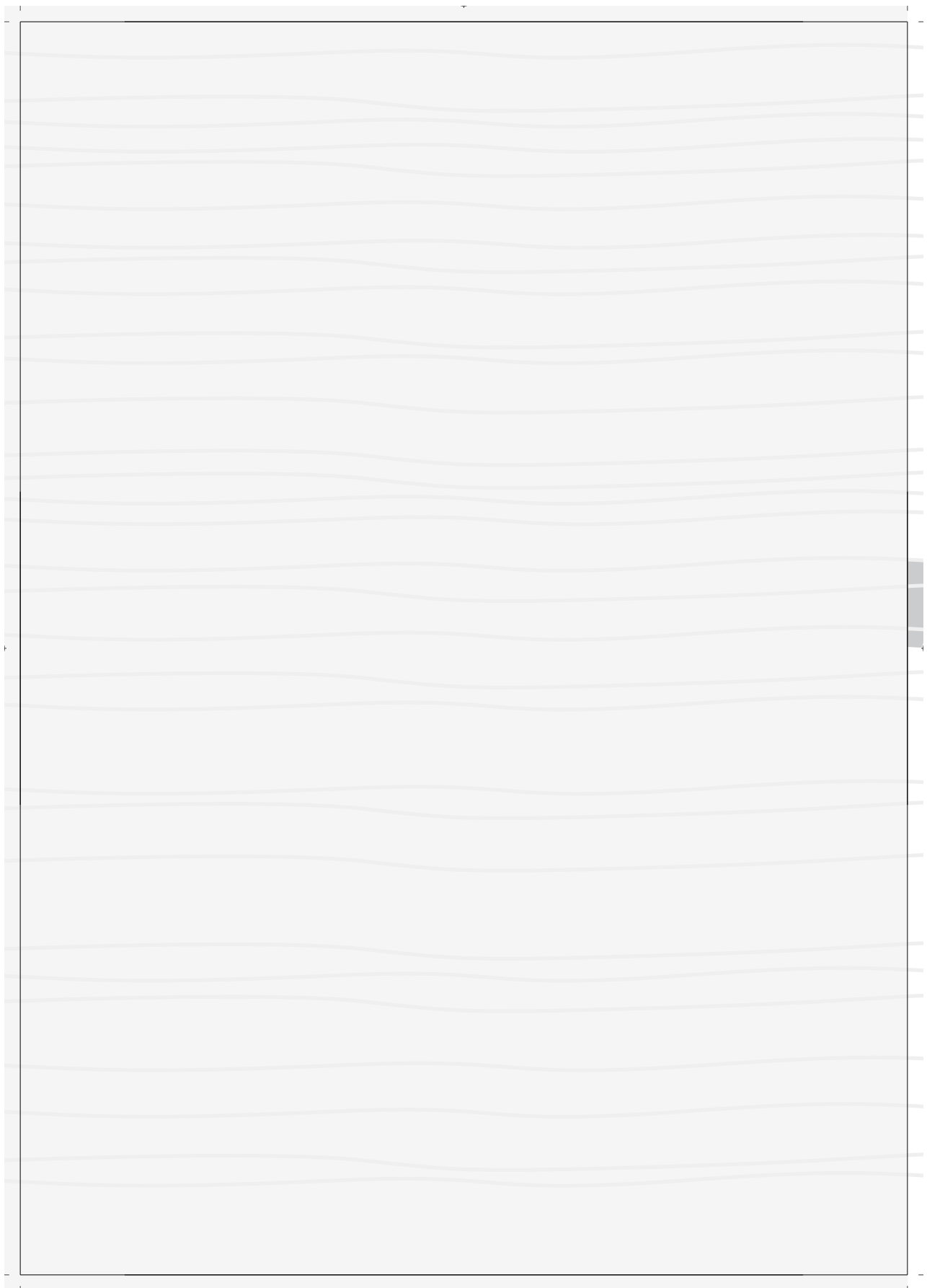
Chapter 5

Rowing skill affects power loss on a modified rowing ergometer

ABSTRACT

In rowing, the athlete has to maximize power output and minimize energy losses to processes unrelated to average shell velocity. The contribution of velocity efficiency ($e_{velocity}$; the fraction of mechanical power not lost to velocity fluctuations) to rowing performance in relation to the contributions of $\dot{V}O_{2\text{-}max}$ and gross efficiency (e_{gross}) were investigated. Relationships between $e_{velocity}$ and movement execution were determined.

Twenty-two well-trained female rowers participated in two testing sessions. In the first session they performed a 2000 m time trial on a modified rowing ergometer that allowed for power losses due to velocity fluctuations. $\dot{V}O_{2\text{-}max}$, $e_{velocity}$ and the amount of rower induced impulse fluctuations (RIIF) due to horizontal handle and foot stretcher forces were determined in a steady state part of the time trial. RIIF was used as a measure of movement execution. In the second session, e_{gross} was determined at submaximal intensity.

As expected, $\dot{V}O_{2\text{-}max}$ accounted for the major part of explained variance in 2000 m time (53%, $p<0.001$). Velocity efficiency accounted for a further 14%, e_{gross} for 11% ($p<0.05$). Negative correlations were found between $e_{velocity}$ and RIIF values of several discreet intervals within a stroke cycle. The results suggest that optimal timing of forces applied to the ergometer will help minimizing power loss to velocity fluctuations.

This study indicates that a relationship exists between performance and $e_{velocity}$. Furthermore, $e_{velocity}$ appears to be related to movement execution, in particular the timing of handle and foot stretcher forces.

INTRODUCTION

It is generally recognized that skill or technique is an important aspect in the sport of rowing [2, 15, 22, 24]. From a biomechanical point of view, a rower has to expend his or her energy in such a way that it results in the highest possible average shell velocity for the duration of a 2000 m race (the official Olympic distance). In other words, the athlete has to maximize power output and minimize energy loss to processes unrelated to average shell velocity. Van Ingen Schenau and Cavanagh[10] have shown the power equation to be an adequate conceptual model to analyze performance in cyclic sport activities. For steady state rowing the power equation can be written as:

$\overline{P}_{metabolic} \cdot e_{gross} = \overline{P}_{rower} = -(\overline{P}_{drag,cv} + \overline{P}_{\Delta v} + \overline{P}_{blade})$. In this equation, $\overline{P}_{metabolic}$ is the average total (metabolic) power production, e_{gross} the average gross efficiency and $\overline{P}_{rower}$ the resulting mechanical power output. Gross efficiency typically lies between 0.15-0.20 in rowing [6, 15, 17, 20, 21]. $\overline{P}_{drag,cv}$ and $\overline{P}_{\Delta v}$ together describe power loss due to shell resistance. $\overline{P}_{drag,cv}$ describes the power loss that would occur if shell velocity would be constant at the average value observed. $\overline{P}_{\Delta v}$ describes the additional power loss that results from shell velocity fluctuations[19]. This term is indeed a power loss term, as it is unrelated to average velocity. $\overline{P}_{blade}$ describes the power loss due to the fact that water is moved by the blades during the push off. Throughout the text, when power terms are referred to, it is implied that the power terms are averaged over a number of complete stroke cycles in steady state rowing. In general, about 75% of $\overline{P}_{rower}$ is transferred to $\overline{P}_{drag,cv}$[9] whereas 5% is transferred to $\overline{P}_{\Delta v}$[9, 19] and about 20% is transferred to $\overline{P}_{blade}$[1, 9, 30]. For given drag conditions, maximization of shell velocity is equivalent to maximization of $\overline{P}_{drag,cv}$ and minimization of $\overline{P}_{\Delta v}$ and $\overline{P}_{blade}$. In a previous study, we have shown that losses of mechanical power are dependent on stroke rate[9].

Relative power loss terms can be quantified by propelling efficiency ($e_{propelling}$) and velocity efficiency ($e_{velocity}$)[9]. Propelling efficiency can be calculated as:

$e_{propelling} = 1 - |\overline{P}_{blade}| / |\overline{P}_{rower}|$; a propelling efficiency of zero would indicate that all power produced by the rower is dissipated at the blades; similarly, a propelling efficiency of 1 would indicate that no power is dissipated at the blades. Velocity efficiency can be calculated as $e_{velocity} = 1 - |\overline{P}_{\Delta v}| / |\overline{P}_{rower}|$ [9]. A velocity efficiency of zero would indicate that all power produced by the rower is dissipated by fluctuations of shell velocity, and a velocity efficiency of 1 would indicate that no power is dissipated due to velocity fluctuations, i.e. that velocity is constant.

Good rowing technique would allow on the one hand for a maximum mechanical power output and on the other hand for a maximum contribution of mechanical power to average velocity.

The importance of understanding the effect of force profiles on boat velocity has been stressed[16]. Indeed, force profiles of oar or handle force[11, 23, 28], stretcher force [12] or both[14, 22] have been reported. However, to our knowledge a mechanical relation with performance has not yet been made. Insight into the relationship between movement execution, force production and performance is important, as it points out whether rowing efficiency can be improved and how that can be done.

The shape and consistency of force profiles can discriminate between skill level in rowing[23, 25]. In crew rowing, consistency between force profiles between individual rowers appears to be important[8, 28], although an offset in the timing of achieving peak force between the bow and stroke rower is beneficial when rowing in a pair[8, 22, 30]. None of these studies however established a direct relationship between the measured force profiles and boat velocity and thus none of these studies were able to quantify stroke effectiveness.

In this study we investigated how the execution of the rowing stroke is related to one of the causes of inefficient propulsion, namely the power losses due to fluctuations in shell velocity. The study was performed using a rowing ergometer, which allowed us to eliminate effects of weather or water current and eliminate any interactions with $e_{propelling}$. The ergometer is a popular training device among rowers, especially during the winter season. On the ergometer there is no power lost at the blades, thus $e_{propelling}$ is one by definition. On a standard rowing ergometer, the ergometer is fixed to the earth and consequently $e_{velocity}$ is also one; thus, all of the rower's power output goes into an air-braked flywheel, simulating P_{drag}. With a standard ergometer, the power dissipated by the air friction on the flywheel is measured and subsequently converted into a virtual boat speed by a small computer, using the cubic relationship between power and velocity. In recent years, it has become clear that introduction of velocity fluctuations improves the resemblance of ergometer rowing to on-water rowing[3, 5]; these velocity fluctuations are introduced by putting the ergometer on wheels, allowing the ergometer to move back and forth. The velocity of an ergometer on wheels mimics the shell velocity relative to average shell velocity during on-water rowing. However, while putting the ergometer on wheels introduces velocity fluctuations, the mechanical power loss due to these fluctuations is negligible, as the frictional forces resisting the movement of the ergometer are close to zero. In order to introduce a realistic power loss term related to these velocity fluctuations, in this study the ergometer on wheels was coupled to a motor that dissipates power in a way that is similar to the power loss due to velocity fluctuations in on-water rowing, as will be detailed below.

The power equation of steady state rowing on our modified ergometer can be written

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as $\overline{P}_{rower} = \overline{P}_{metabolic} \cdot e_{gross} = -(\overline{P}_{flywheel} + \overline{P}_{\Delta v})$, with $\overline{P}_{flywheel}$ the average mechanical power dissipated in the flywheel and $\overline{P}_{\Delta v}$ the power loss to velocity fluctuations, dissipated by the motor. The power equation makes it clear that optimal performance, i.e. when $\overline{P}_{flywheel}$ has a maximum value, is achieved when $\overline{P}_{metabolic}$ and e_{gross} have maximum values and $\overline{P}_{\Delta v}$ has a minimum value. $\overline{P}_{\Delta v}$ increases with decreasing $e_{velocity}$, therefore $e_{velocity}$ should have maximal value for optimal performance.

Maximum oxygen uptake is a very important determinant of (indoor) rowing performance [4,18,20]. The aerobic contribution of the metabolism to power output has been reported to be 67 to 86% during a race[15], therefore $\dot{V}O_{2\text{-max}}$ and $\overline{P}_{metabolic}$ are closely related in rowing. While being aware of the importance of $\dot{V}O_{2\text{-max}}$, we were interested in the relative contribution of $e_{velocity}$ to performance. Although the magnitude of $e_{velocity}$ is clear, it is unclear if there is a relationship between $e_{velocity}$ and performance level when comparing individual well-trained rowers. Such a relationship would suggest that rowers with a sub-optimal $e_{velocity}$ may improve their performance by changing their technique in such a way that $e_{velocity}$ is increased. Velocity efficiency, $\dot{V}O_{2\text{-max}}$ and e_{gross} are representative for the terms in the power equation described above and are therefore expected to explain the major part of variance in performance. Thus, the first aim of this study was to determine the relative contribution of $e_{velocity}$ to performance in relation to the relative contributions of $\dot{V}O_{2\text{-max}}$ and e_{gross}. The second aim of this study was to investigate which kinematic and/or kinetic variables defining the rower's technique are related to differences in $e_{velocity}$.

METHODS

Outline of the study
Two experiments were conducted in this study. During the first experiment, the participants had to perform a 2000 meter time trial (2K-MAX) on our modified rowing ergometer (see below). During the time trial, power production and power losses were continuously recorded. Kinetic and kinematical variables of the rower were recorded to describe movement execution. Gross efficiency could not be adequately measured during the 2K-MAX trial, as it is generally overestimated when it is determined during maximal exertion, due to the contribution of anaerobic metabolic processes. Therefore, a second experiment was conducted, which followed the first experiment. In this experiment, participants were asked to row at 70% of the power output of the 2K-MAX trial, at which intensity the exercise was expected to be completely aerobic. As it was anticipated that e_{gross} might depend on stroke rate, e_{gross} was determined at different stroke rates (28, 34 and 40 strokes·min^{-1}).

In the analysis of the 2K-MAX trials, e_{gross} was assumed to be equal to the e_{gross} determined in the second experiment at the stroke rate closest to the self chosen stroke rate of the 2K-MAX trial. Stroke to recovery ratios were determined for both the selected strokes in the 2K-MAX trial as the selected strokes in the second experiment, at the stroke rate closest to the self chosen stroke rate at the 2K-MAX trial. The study was approved by the local ethic committee.

Participants

In this study, 22 female rowers participated. Their level of experience varied from having one year of experience in competitive rowing at club level to being a member of the Dutch national team. Body mass, age and years of rowing experience are shown in Table 5.1. Participants were asked to take part in the two experiments, with a minimum of 48 hours and a maximum of two weeks between experiments. All participants provided written informed consent. For both experiments, participants were asked to refrain from any food or caffeine from 2 hours before the trial. Participants were also asked not to do any heavy exercise from 24 hours before the trial.

	Body Mass (kg)	Age (years)	Experience (years)
Mean ± SD	74.0 ± 6.6	22.4 ± 2.3	2.9 ± 2.2
Minimum	64.3	19	1
Maximum	90.0	26	10

Table 5.1: participant characteristics

Ergometer

The ergometer we used in our study (Concept II, USA) uses an air braked resistance mechanism in the form of a flywheel with fans. The flywheel is accelerated each stroke by pulling on a handle, attached to a chain which revolves around a cog. The cog is mounted on a freewheel, so during the recovery phase the flywheel is decoupled from the handle, which is pulled back towards the flywheel by an elastic band. We put the ergometer on wheels (Slides, Concept 2 USA). As a result the ergometer (and, coupled to that, the foot stretcher) moves back and forth, simulating the fluctuations in shell velocity in on-water rowing.

To introduce power losses due to velocity fluctuations on our ergometer, movement of the ergometer was resisted by a servomotor, which was connected to the moving ergometer using a belt transmission. During preliminary experiments, friction in the

Experiment II:

After a 10 minute warm-up period on our modified ergometer participants had to row one trial at 28, one at 34 and one at 40 strokes per minute. Each trial lasted 3 minutes. The order of the trials was random. During all trials, oxygen uptake was measured. Participants were instructed to row at a velocity corresponding to approximately 70% of the power output during the 2K-MAX trial. During the trials the RER value was monitored to ensure RER < 1, so exercise would be completely aerobic and e_{gross} could be calculated. Between trials, there was a 5 minute resting period. Participants received feedback about velocity and stroke rate. They were corrected when deviating from the intended stroke rate and velocity.

Instrumentation

Stretcher force was determined by two 6 degree-of-freedom force transducers, one mounted under each foot (AMTI, USA). Seat force was measured using one 6 degree-of-freedom force transducer mounted under the seat (AMTI, USA). Handle force can only act in line with the chain and was measured using a one degree-of-freedom force transducer (AST, Germany) mounted between the handle and the chain. All kinematic variables were obtained using the Optotrak measurement system (Northern Digital, Canada) which uses active infrared markers to capture 3D position data. Position markers were placed on the flywheel axis (1 marker), the handle force transducer (2 markers), the foot stretcher (2 markers) and the seat (1 marker). To record segment kinematics, markers were placed at the left side of the body, at the lateral malleolus, the lateral epicondyle of the knee, the greater trochanter, the acromion, the lateral epicondyle of the elbow and the ulnar styloid. Preliminary testing revealed that the marker at the acromion was obscured from view in several occasions. Therefore, a marker was placed on the line between elbow and shoulder marker, allowing us to reconstruct the acromion marker position if necessary. See Figure 5.1 for a schematic representation of the locations of force transducers and optotrak markers. Velocity data were obtained by taking the five-point derivative of position data. Oxygen uptake ($\dot{V}O_2$) was measured using breath-by-breath analyzing equipment (Oxycon Alpha, Jaeger, Germany).

All kinetic variables were recorded at 200 Hz. Due to equipment limitations kinematic data were sampled at 100 Hz and converted to 200 Hz samples using cubic spline interpolation after collection.
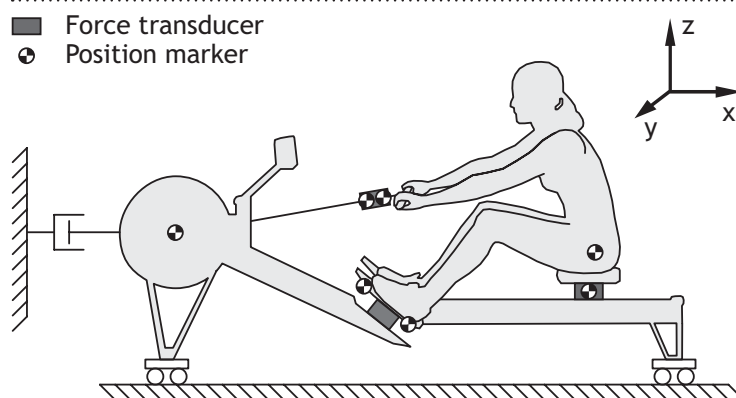
Figure 5.1. *Schematic representation of the experimental setup. The ergometer was put on wheels and movement was resisted by a servomotor and belt, which acted as a linear damper. Force transducers under the foot stretcher and seat and between the handle and chain are drawn in the figure, as well as the position markers.*

DETERMINATION OF VARIABLES

Velocity efficiency:

Data were analyzed for a 20 stroke cycle period in the fifth minute of the time trial, in which steady state rowing was assumed. The steady state assumption was verified by visual inspection of the stroke to stroke power production. The beginning of each stroke cycle was defined as the moment in time the handle started to move away from the flywheel. In rowing, this moment is called the "catch". The end of the stroke phase and the start of the recovery phase was defined as the moment in time the handle started to move towards the flywheel. This moment is called the "finish".

A frame of reference was chosen such that the positive x-axis was parallel to the horizontal seat rail and pointing from the flywheel to the back of the ergometer, the positive y-axis was pointing to the left when facing the ergometer from the back, and the positive z-axis was pointing upwards (Figure 5.1). Velocity efficiency on our modified ergometer can be calculated from a complete rowing cycle according to; $e_{velocity} = |\bar{P}_{flywheel}| / |\bar{P}_{rower}|$.

Instantaneous mechanical power (P_{rower}) can be determined from measured forces on the handle, foot stretcher and seat, and position data using the power equation for the rower;

$$P_{rower} = -v_{handle} \cdot F_{handle} - v_{stretcher} \cdot F_{stretcher} - v_{seat} \cdot F_{seat} + dE/dt \qquad \text{Equation 5.1}$$

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With v_{handle}, $v_{stretcher}$ and v_{seat} the velocity vectors of handle, foot stretcher and seat, F_{handle}, $F_{stretcher}$ and F_{seat} the vectors of handle, foot stretcher and seat force and dE/dt the time derivative of kinetic and gravitational potential energy of the rower. In this study, we were interested in the average power output during steady state rowing. When it is assumed that rowing was in steady state, there is no change in kinetic and potential energy of the rower over any full rowing cycle, so the dE/dt term averages zero. Body velocity, and thus the instantaneous value of dE/dt, fluctuates within each stroke cycle. It is possible that these fluctuations lead to higher metabolic energy expenditure. Such an increase in metabolic energy expenditure at the same average mechanical power output will be reflected in the value for e_{gross} (see also [9]).

The instantaneous power transferred to the flywheel and the rubber band that retracts the chain into the cage during recovery ($P_{flywheel}$) can be calculated according to:

$$P_{flywheel} = -F_{handle} \cdot (v_{handle} - v_{ergometer}) \hspace{3cm} \text{Equation 5.2}$$

With $v_{ergometer}$ the vector of ergometer velocity. The average value of power transferred to the flywheel ($\overline{P}_{flywheel}$) was calculated by taking the average of $P_{flywheel}$ over a full rowing cycle. Velocity efficiency was determined as the average of $e_{velocity}$ calculated for 20 consecutive rowing cycles in the fifth minute of the 2K-MAX trial.

When in steady state and averaged over a number of complete stroke cycles, the sum of $\overline{P}_{rower}$, $\overline{P}_{flywheel}$ and $\overline{P}_{\Delta v}$ equals zero. Throughout the remainder of the text, when power terms are discussed, it is implied that these terms are calculated in steady state and averaged over a number of complete stroke cycles, which were 20 strokes in the 2K-MAX trial and 28 to 40 strokes in the sub-maximal trials.

$\dot{V}O_{2\text{-}max}$ and e_{gross}:

$\dot{V}O_{2\text{-}max}$ was determined as the highest 30 seconds average of oxygen uptake during the 2K-MAX trial. Gross efficiency was the only term obtained during the second experiment and was calculated according to $e_{gross} = \overline{P}_{rower}/\overline{P}_{metabolic}$. Metabolic power was calculated using the relationship between RER value, $\dot{V}O_2$ and metabolic power as described by Garby and Astrup[7]. Preliminary testing showed that a steady state $\dot{V}O_2$ was reached after a maximum of 90 seconds. To calculate e_{gross} at each of the 3 different stroke rates, both $\overline{P}_{rower}$ and $\overline{P}_{metabolic}$ were averaged over a number of complete stroke cycles in the time period between 90 seconds to 150 seconds into each three minute sub-maximal trial (an expected 28 strokes at stroke rate 28, 34 strokes at stroke rate 34 and 40 strokes at stroke rate 40). For each trial, the $\dot{V}O_2$-time profile was visually inspected to ensure steady state had been reached during the selected time window.

Movement execution variables:

Movement execution was evaluated in both kinetic and kinematic terms. Stroke length for an individual stroke (l_{stroke}) was determined as the difference between maximum and minimum distance of the handle to the flywheel within the stroke cycle. Centre of mass movement of the rower in relation to the ergometer was estimated from the movement of the centres of mass of the individual body segments. The difference between maximum and minimum distance of the centre of mass to the flywheel within a stroke cycle was recorded (dxCOM). Body segment centres of mass were determined according to Winter[29]. Left-right symmetry was assumed.

Coordination and timing between hand and foot forces were expected to be related to power losses due to velocity fluctuations, since these forces completely determine the movement of our modified ergometer. The quality of force coordination and timing was quantified in terms of the impulse given to the ergometer by the rower. The impulse equation of the ergometer in the x-direction is given by:

$$m_{ergometer} \cdot \Delta \dot{x}_{ergometer} + \int F_{x,servo}dt = -\int (F_{x,handle} + F_{x,stretcher} + F_{x,seat})dt \qquad \text{Equation 5.3}$$

In steady state rowing with period time T, the velocity at $t=t_0$ is equal to the velocity at $t=t_0+T$. Therefore, the impulse change over a complete rowing cycle equals zero. Based on the impulse equation for the ergometer (Equation 5.3), we defined a variable intended to capture the quality of the rower's coordination of the important forces. We will refer to the contribution of the rower to the within-cycle fluctuations in ergometer velocity as rower induced impulse fluctuations (RIIF), which was calculated as follows:

$$RIIF = \int |(F_{x,handle} + F_{x,stretcher} + F_{x,seat})|dt \qquad \text{Equation 5.4}$$

RIIF was determined for each of the selected stroke cycles as well as for well defined parts within each stroke cycle to be able to investigate the relative importance of the different phases in the rowing cycle. RIIF was calculated for the entire rowing cycle ($RIIF_{cycle}$), the stroke phase ($RIIF_{stroke}$), the recovery phase ($RIIF_{recover}$), the last 250 ms before the catch ($RIIF_{catch,before}$) the first 250 ms after the catch ($RIIF_{catch,after}$), the last 250 ms before the finish ($RIIF_{finish,before}$), the first 250 ms after the finish ($RIIF_{finish,after}$) and 250 ms in the exact middle in time of the stroke phase ($RIIF_{mid-stroke}$). All variables described above were calculated for 20 consecutive strokes in the fifth minute of the 2K-MAX trial, in steady state rowing and averaged over these 20 strokes.

Statistical analysis

To investigate whether a relationship exists between performance level and $e_{velocity}$, a stepwise multiple regression analysis was performed with $\dot{V}O_{2\text{-max}}$, e_{gross} and $e_{velocity}$ as independent variables and time over 2000 meter as the dependent variable. A relationship between $e_{velocity}$ and performance was assumed to exist when adding $e_{velocity}$ to the regression equation would lead to an significant improvement of the prediction of time over 2000m ($p < 0.05$).

To investigate the relationship between $e_{velocity}$ and movement execution, Pearson's r was calculated between $e_{velocity}$, all RIIF terms, l_{stroke} and dxCOM. Correlation was significant at $p < 0.05$.

RESULTS

General results

Table 5.2 lists average, minimum and maximum values for 2K-MAX time, stroke rate, P_{rower}, $\dot{V}O_{2\text{-max}}$, $e_{velocity}$ and e_{gross}. It took the rowers on average 452 seconds to cover the 2000 virtual meters on the 2K-MAX trial. They performed an average of 12.8±4.7 seconds (2.7%) slower than their time achieved at the national indoor rowing championships (NKIR), held a month after the tests, which is close to the expected deficit of 10 seconds as described in the methods section. Correlation between 2K-MAX times and NKIR times was very high (Pearson's r=0.96, p<0.001). $\overline{P}_{rower}$ during the 2K-MAX trial was on average 264±30 W, which was an average of 3.4±9.8W (1.3%) lower than the estimated power expenditure during the NKIR championships. This difference was not significant, as expected. These results indicate that the effort during the 2K-MAX trials was similar to race effort and that times achieved on our modified ergometer were representative for performance in competitive rowing. Mean $e_{velocity}$ during the 2K-MAX trials was 0.90±0.02, meaning that on average 10% of net mechanical power was lost to velocity fluctuations, which is at the high end of the intended range (see methods).

	2K-MAX time (s)	stroke rate (str·min^{-1})	$\overline{P}_{rower}$ (W)	$\dot{V}O_{2\text{-max}}$	$e_{velocity}$	e_{gross}
Mean ± SD	452 ± 16	33.2 ± 2.3	264 ± 30	3.60 ± 0.36	0.90 ± 0.02	0.19 ± 0.01
Minimum	430	28.8	201	2.61	0.86	0.16
Maximum	485	36.6	312	4.32	0.94	0.21

Table 5.2: general results

Mean e_{gross} during the 2K-MAX trial, which was estimated from the sub-maximal performance in our second experiment, was 0.19±0.01. Gross efficiency did not differ significantly between the three sub-maximal trials. In the sub-maximal trials, the stroke rate closest to the self chosen rate in the 2K-MAX trial did not differ significantly from the 2K-MAX trial (33.3 strokes/min for the 2K-MAX trial, 32.6 strokes/min for the sub-maximal trial). Drive to recovery ratios did not differ significantly between those two cases (1:0.93 for the 2K-MAX trial, 1:0.93 for the sub-maximal trial), providing an indication that movement execution between the sub-maximal trial and the 2K-MAX trial was similar.

Evaluation of steady state rowing

For all participants, the 20 strokes selected in the 2K-MAX experiment for the analysis of $e_{velocity}$ and RIIF were assumed to be in steady state rowing. The steady state assumption was checked by investigation of total power production. Within each participant, the power-time profiles showed little or no deviation between strokes. Figure 5.2 shows an example of a typical participant. $\bar{P}_{flywheel}$ during the 20 selected strokes was strongly correlated to 2K-MAX time ($r=-0.97$, $p<0.01$), indicating that the selected section of the trial was a good indicator for time trial performance. Mean, standard deviation and extreme values of stroke to stroke power for the 20 selected strokes for each individual rower are listed in Table 5.3. During the second experiment, $\dot{V}O_2$ had reached steady state value within 90 seconds for each of the trials. A typical example of a $\dot{V}O_2$-time profile is given in Figure 5.3.
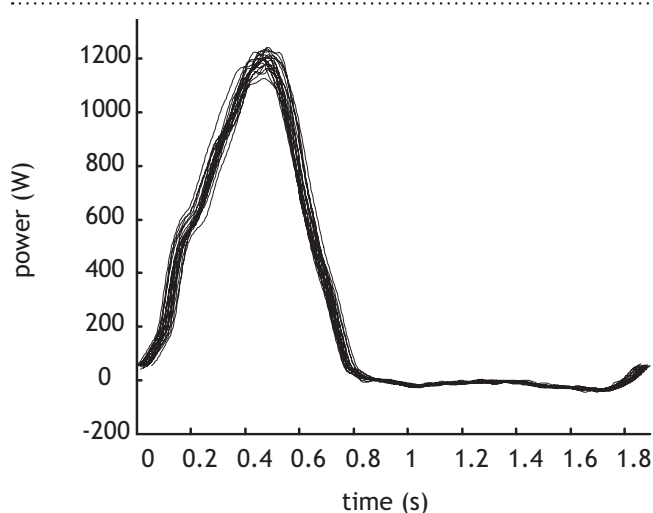

Figure 5.2. Typical example of P_flywheel for 20 consecutive strokes of a single participant.

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Participant	$\overline{P}_{rower} \pm$ SD (W)	minimum $\overline{P}_{rower}$ (W)	maximum $\overline{P}_{rower}$ (W)
A	233.8 ± 8.20	217.0	247.4
B	222.0 ± 6.54	211.8	235.9
C	236.1 ± 4.20	228.5	242.2
D	235.1 ± 4.76	228.2	246.6
E	264.2 ± 6.22	253.5	274.8
F	278.4 ± 9.62	257.6	294.9
G	255.9 ± 6.03	243.4	263.9
H	261.9 ± 6.04	245.9	269.8
I	226.0 ± 8.04	203.0	237.8
J	199.8 ± 9.30	175.9	210.6
K	298.3 ± 8.67	284.0	315.3
L	296.4 ± 8.47	276.5	308.7
M	258.1 ± 9.48	242.3	275.4
N	311.8 ± 6.21	298.8	325.9
O	270.6 ± 8.20	254.5	288.5
P	296.4 ± 7.30	281.2	307.9
Q	248.6 ± 18.6	212.3	275.5
R	259.3 ± 12.0	236.9	282.7
S	310.8 ± 17.9	257.3	331.7
T	284.7 ± 12.4	260.1	313.7
U	286.6 ± 11.2	259.9	302.0
V	267.4 ± 5.74	255.2	277.9

Table 5.3: Mean, standard deviation, minimum and maximum value of cycle to cycle average power over the 20 selected stroke-cycles of each individual participant. The average range equalled 33.9 W.
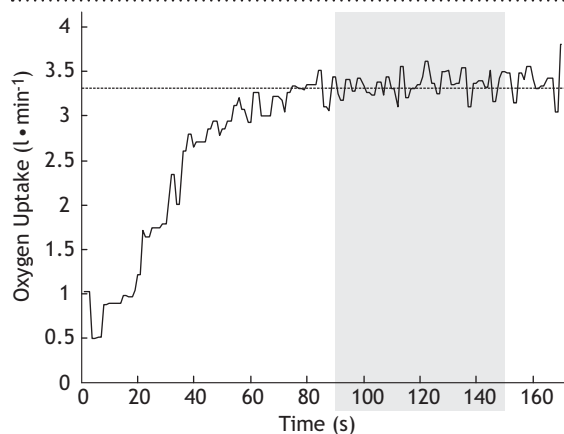

Figure 5.3. Typical example of O2 development during a sub-maximal trial at 34 strokes·min⁻¹. Oxygen uptake reached a plateau within 90 seconds.

Velocity efficiency and performance level

To establish whether a relationship exists between skill level and $e_{velocity}$, $\dot{V}O_{2\text{-max}}$, $e_{velocity}$ and e_{gross} were entered in a stepwise multiple regression analysis. No significant correlation existed between the selected variables. Table 5.4 lists the results. As expected, $\dot{V}O_{2\text{-max}}$ accounted for the major part for the variance in 2000m time, namely 53% (p<0.001). Entering $e_{velocity}$ and e_{gross} into the analysis led to a further improvement of the explained variance of 2000m time by 14% and 11% respectively (p<0.05). The results indicate that within a group of well-trained rowers, a relationship exists between performance level and $e_{velocity}$.

	B	SE B	ß	R^2
Step 1				
Constant	571.47	26.90		
$\dot{V}O_{2\text{-max}}$	-32.26	7.22	-.73***	.53
Step 2				
Constant	920.03	130.87		
$\dot{V}O_{2\text{-max}}$	-43.34	7.44	-.97***	.53
$e_{velocity}$	-339.52	125.47	-.45*	.14
Step 3				
Constant	999.05	114.26		
$\dot{V}O_{2\text{-max}}$	-43.87	6.30	-.99***	.53
$e_{velocity}$	-333.50	106.14	-.45**	.14
e_{gross}	-428.96	153.91	-.33*	.11

* p<0.05; ** p<0.01, *** p<0.001

Table 5.4: Multiple regression table, showing unstandardized coefficients (B) and their standard error (SE B) as well as the standardized coefficient (ß) for each of the regression steps. Total explained variance (R^2) of the regression model was .78, evelocity accounted for an increase in R^2 of .14.

Movement execution and evelocity

A typical example of $F_{x,handle}$, $F_{x,stretcher}$ and $F_{x,seat}$ is given in Figure 5.4. The figure shows $F_{x,seat}$ is negligibly small. Seat force is therefore not shown in the other figures, although it was measured and used in the calculations. Relationships between $e_{velocity}$ and movement execution variables were investigated in terms of correlations. An example of the determination of the RIIF terms is given in Figure 5.5. Correlation between $e_{velocity}$ and $RIIF_{cycle}$ was found to be strong at -0.782 (p<0.01). Significant negative correlations were also found between $e_{velocity}$ and $RIIF_{recover}$, $RIIF_{catch,after}$ and $RIIF_{catch,before}$ (p<0.01). Correlations are shown in Table 5.5. The negative sign of these correlations indicates that $e_{velocity}$ is reduced when RIIF increases. This is as expected, since higher RIIF results

in larger ergometer velocity fluctuations, which in turn results in larger power loss due to F_{servo}. The relationship between relative timing of foot stretcher and handle forces and $e_{velocity}$ was found to be strong around the catch, which is the phase where force changes are most prominent (correlation coefficients between $e_{velocity}$ and $RIIF_{catch,before}$ and $RIIF_{catch,after}$ were -0.608 and -0.850 respectively) and during the recovery phase (correlation coefficient -0.819). Typical examples of force timing of the least efficient participant and the best performing participant in our study are shown in Figure 5.6. Table 5.6 lists average values of the RIIF parameters, as well as average intra-individual standard deviation and intra-individual range for the 20 selected strokes Altogether, the coordination of handle and foot stretcher forces appears to be clearly related to $e_{velocity}$ in a group of well trained rowers.

	evelocity
$RIIF_{cycle}$	-.782*
$RIIF_{stroke}$	-.530
$RIIF_{recover}$	-.819*
$RIIF_{catch,after}$	-.850*
$RIIF_{mid-stroke}$	.187
$RIIF_{finish,before}$	.154
$RIIF_{finish,after}$	-.506
$RIIF_{catch,before}$	-.608*
dxCOM	-.313
I_{stroke}	-.366

correlation significant at p<0.01

Table 5.5: *Correlations between evelocity and movement execution variables. Significant correlations were found between evelocity and RIIFcycle, RIIFrecover, RIIFcatch,after and RIIFcatch,before. These results indicate that the coordination of in particular handle and footstretcher forces is related to* $e_{velocity}$.

	mean (Ns)	mean of within participant standard deviation (Ns)	mean of within subject participant range (maximum – minimum) (Ns)
RIIF$_{cycle}$	134	4.33	16.8
RIIF$_{stroke}$	67.4	2.98	11.0
RIIF$_{recover}$	67.1	3.13	12.1
RIIF$_{catch,after}$	42.4	1.43	5.21
RIIF$_{mid-stroke}$	9.30	1.22	4.72
RIIF$_{finish,before}$	8.95	1.14	4.26
RIIF$_{finish,after}$	13.3	1.28	4.80
RIIF$_{catch,before}$	33.5	2.55	9.29

Table 5.6: *Mean, mean within participant standard deviation and mean within participant range of the RIIF parameters.*
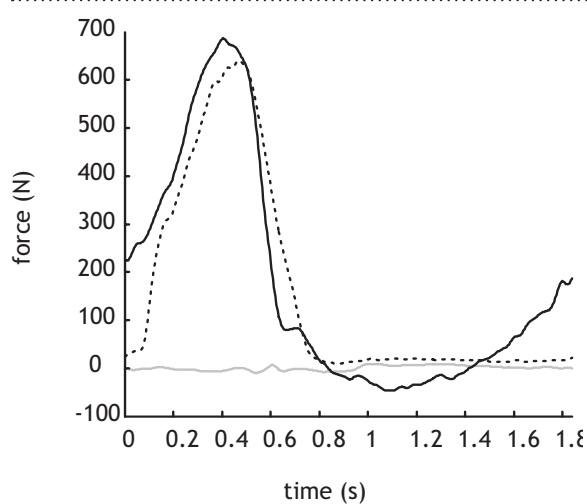

Figure 5.4. *Typical example of a single stroke cycle, showing handle force (dashed line, multiplied by -1 for better comparison), seat force (solid grey line) and stretcher force (solid black line) in the x-direction. The figure shows that seat force in x-direction is very low. Seat force is therefore not separately shown in the other figures.*
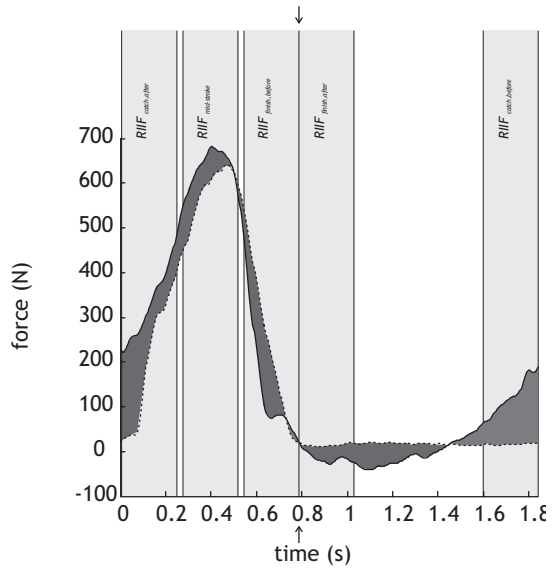
Figure 5.5. *Force-time profiles of handle force (dashed line, multiplied by -1 for better comparison) and the sum of stretcher force and seat force (solid line) in x-direction of a typical stroke cycle. The catch is at t = 0, the small arrows indicate the finish. The area between both curves represents RIIF$_{cycle}$, the area between both curves from catch to finish represent RIIF$_{stroke}$, and the area between both curves from finish to the next catch represent RIIFrecover. The shaded columns indicate RIIF$_{catch,after}$, RIIF$_{mid-stroke}$, RIIF$_{finish,before}$, RIIF$_{finish,after}$ and RIIF$_{catch,before}$.*
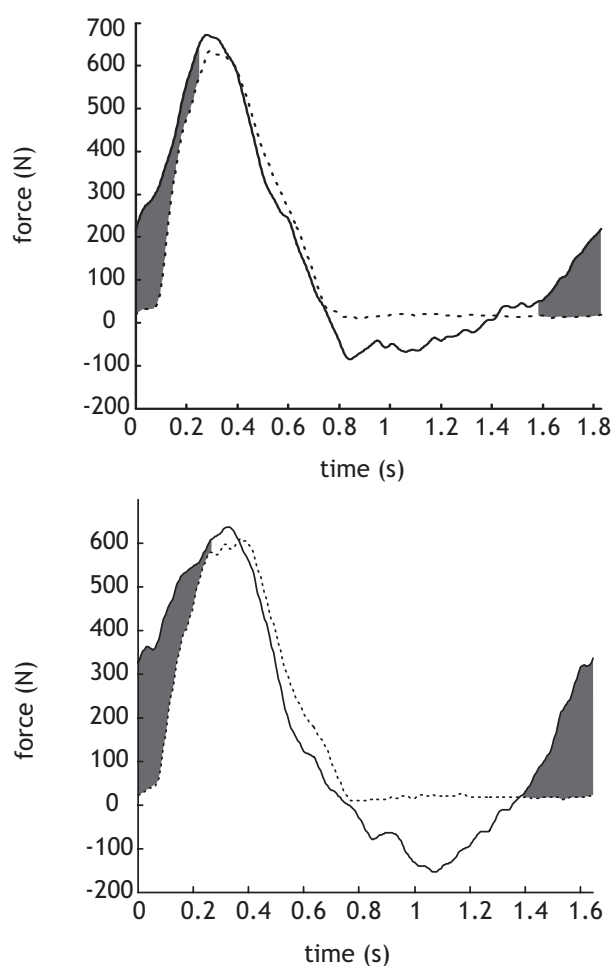
Figure 5.6. *Force-time profiles of handle force (dashed line, multiplied by -1 for better comparison) and the sum of stretcher force and seat force (solid line) in x-direction. Rower N, represented in the top figure had the highest score for average P_{rower} (312 W), but also the lowest score for $e_{velocity}$ (0.84), resulting in a time of 437 seconds at the 2K-MAX trial. Rower P, represented in the bottom figure had the best overall score at the 2K-MAX trial of 430 seconds, with an average power output of 296 W and an $e_{velocity}$ of 0.91. Rower induced impulse fluctuations before the catch ($RIIF_{catch,before}$) and after the catch ($RIIF_{catch,after}$) are indicated by the shaded areas. For rower N this area is 1.5 times as large compared to that of rower P. The Figures illustrate the relationship between coordination of handle and footstretcher forces, $e_{velocity}$ and performance.*

DISCUSSION

This study shows that within a group of well-trained rowers, a relationship exists between $e_{velocity}$ and performance as well as a relationship between $e_{velocity}$ and movement execution, when rowing on our modified rowing ergometer. Negative correlations were found between $e_{velocity}$ and variables describing the timing and coordination of handle and foot stretcher forces in different phases of the stroke cycle, meaning that low rower induced impulse fluctuations will lead to low losses to velocity fluctuations. The correlations were high around the catch, which indicate the importance of this part of the stroke. Correlation was also high between $e_{velocity}$ and $RIIF_{recover}$, which is understandable as any negative impulse given to the ergometer at the catch is coupled by a positive impulse during the recovery phase. In steady state rowing the total impulse change of the ergometer in one complete rowing cycle averages to zero. Because movement execution on a rowing ergometer is similar to that in a rowing boat[13] and our experimental setup was such that the power losses to velocity fluctuations approximate those in on-water rowing, it is possible that our results also apply to on-water rowing.

As expected this study reconfirms that maximum oxygen uptake is the single best predictor for performance in rowing (see also[4, 18, 20]). However, as pointed out in a review by Baudouin and Hawkins (2004), subtle biomechanical factors might play a crucial role in performance[2]. This study shows that the timing of forces at the handle and foot stretcher is one of those factors.

Several studies have stressed the importance of creating the ability to provide feedback of force-time or force-length profiles[11, 16, 19] and emphasis is put on the need to find the optimum force curve. However, most studies have only investigated either the force on the oar or the force on the foot stretcher. Because past research has pointed out that every individual produces a unique force pattern, but can be equally successful in competition[11, 12], the usefulness of the search for the optimum force pattern can be questioned. Instead of analyzing just one of the applied forces, the coordination of forces should be considered, as an improved coordination of these forces will likely lie within the ability of the rower[22]. This study shows that a relationship exists between coordination of hand and feet forces and power losses to velocity fluctuations.

Theoretically, it is possible to row on our modified ergometer setup with an $e_{velocity}$ of 1. This would be the case when the ergometer would not move. This can only be achieved when the rower's centre of mass does not accelerate during the stroke cycle, which is the case when F_{handle} equals $-F_{stretcher}$ during the entire stroke cycle. The fact

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that no significant correlation exists between dxCOM and $e_{velocity}$ indicates that this is not a strategy that rowers are likely to adopt. The movement pattern needed to keep the centre of mass stationary will exclude optimal use of virtually all large muscle groups of the legs and trunk. Power output would thus be low. It is therefore likely that the execution of the best rowing stroke will be a compromise between maximizing mechanical power output and maximizing velocity efficiency.

Typical examples of the differences between force coordination of a rower with low $e_{velocity}$ (rower N, $e_{velocity}$ averaged over 20 strokes = 0.86) and a rower with high $e_{velocity}$ (rower P, $e_{velocity}$ averaged over 20 strokes = 0.91) are shown in Figure 5.6. Rower P was the best overall performer, whereas rower N had the highest average power output (312 W). The area between the curves of F_{handle} and $F_{stretcher}$ 250 ms before and after the catch; representing RIIF, is much smaller with rower P; the sum of $RIIF_{catch,before}$ and $RIIF_{catch,after}$ was 68 Ns for rower P, as opposed to 91 Ns for rower N. Averaged over 20 cycles, her virtual velocity was 4.59 m·s^{-1}, a little faster than the average velocity of rower N at 4.57 m·s^{-1}. Knowing that during steady state rowing on our modified ergometer $e_{velocity} = 1 - |\bar{P}_{\Delta v}| / |\bar{P}_{rower}|$ and $\bar{P}_{rower} = -(\bar{P}_{flywheel} + \bar{P}_{\Delta v})$, and the relationship between $P_{flywheel}$ and virtual velocity ($v_{virtual}$), defined by the manufacturer is $\bar{P}_{flywheel} = 2.8 \cdot v_{virtual}^3$ (personal communication with the manufacturer), it is possible to calculate performance benefits from an improvement of $e_{velocity}$. Would rower N be able to achieve an $e_{velocity}$ equal to that of rower P, while maintaining the same power output, she would improve her average velocity by 0.1 m·s^{-1}. In terms of finish times, rower N would improve her 2000 m time by 9 seconds, which would make her the best overall performer.

Rowers who want to improve performance by improving $e_{velocity}$ should particularly focus on the catch. Velocity efficiency is highest when the differences between handle and foot forces are small around the catch. During the recovery-phase, peak velocity of the center of mass should therefore be kept to a minimum, as the force applied to the foot stretcher to change the movement direction of the center of mass will brake the boat velocity.

During the first part of the stroke phase, the arms and trunk are passive. The pushing force on the foot stretcher is generated by the leg muscles and transferred to the handles via the hips through the trunk and arms. It is important that the connection from hips to handle is stiff, as any slack in this connection will lead to a high acceleration of the center of mass accompanied by a low force on the handle, and thus to a high discrepancy between handle and foot forces. The latter is a common technical error in novice rowers and is called "shooting the slide", which happens as at the beginning

of the stroke the seat moves backwards without any movement of the handles. This mistake will most likely lead to high RIIF and low values for $e_{velocity}$.

Some aspects of rowing were not addressed in this study. The interaction with water at the hull and at the blades were not simulated. Hull drag can be minimized by minimizing boat yaw, pitch and roll movements during the stroke cycle[24, 27] and is thus partially dependent on movement execution. Another important aspect of rowing is the power loss of the blades. It is known that blade design can positively affect $e_{propelling}$[1]. Although it is now known that $e_{propelling}$ decreases with increasing velocity caused by an increase in stroke rate[9], it is not known to what extent $e_{propelling}$ depends on the rower's technique. Research in swimming for instance has shown competitive swimmers have a higher $e_{propelling}$ compared to triathletes, because of a better swimming technique[26]. To fully understand the relationship between movement execution and performance in rowing, future research should also focus on these on-water aspects of rowing.

The dynamics of on-water rowing differ from those of rowing on our modified ergometer due to the fact that on the ergometer $\overline{P}_{drag}$ and $\overline{P}_{\Delta v}$ are completely decoupled. As a result, the ergometer acceleration during the recovery will be zero when the net force of the rower on the modified ergometer is zero. This is different from the recovery during on-water rowing, where the boat will decelerate due to shell drag. Thus, the movement pattern that is optimal with respect to velocity fluctuations differs between rowing on our modified ergometer and on-water rowing. As the contribution of the drag force on the hull to the acceleration of the hull is modest, the difference between the optimal movement patterns for ergometer rowing and on-water rowing is expected to be modest as well. Nevertheless, this is an area for further research.

It is likely that $e_{velocity}$ will be an important factor for on-water rowing performance as well. During on-water rowing, the relative importance of the catch will be more pronounced, as the timing of the blade entry in the water likely will contribute to $e_{velocity}$. If the blades enter the water too soon, they will act as brakes and the boat deceleration will be high. If the blades enter the water too late, the initial pushing force on the stretcher will not be accompanied be a force on the handle and this will have the same effect as with the shooting the slide mistake. Although the catch phase appears to be even more critical in on-water rowing, the same mechanisms do apply once the blades are in the water. Consequently, conclusions drawn from this study can likely be generalized to on-water rowing.

CONCLUSION

In well-trained rowers, a positive relationship was found between $e_{velocity}$ and 2 km performance on a modified rowing ergometer. Furthermore, $e_{velocity}$ was found to be related to movement execution. It is suggested that velocity efficiency can be improved by keeping the speed of the rower's center of mass in the recovery phase to a minimum and by ensuring there is a stiff connection from hips to hands to transfer stretcher force during the first part of the drive phase.

ACKNOWLEDGEMENTS

Chapter 5

Rowing skill affects power loss on a modified rowing ergometer

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Appendix, Energy dissipation due to intra-stroke cycle velocity fluctuations

Water resistance is the dominant resisting force in rowing. Due to the slim shape of a rowing hull the drag mostly is caused by water friction on the skin and there is almost no wave forming drag. The relationship between drag force (F_{drag}) and v_{boat} can be described as:

$$F_{drag} = k \cdot v_{boat}^2$$
<div align="right">Equation A5.1</div>

Thus, in still-water conditions, power dissipation due to drag can be described as:

$$P_{drag} = k \cdot v_{boat}^3$$
<div align="right">Equation A5.2</div>

To determine the magnitude of power losses due to velocity fluctuations in steady state rowing, it is best to write v_{boat} as $v_{mean} + \Delta v(t)$, with v_{mean} the average velocity and $\Delta v(t)$ as the deviation from the average velocity. Equation A5.2 then yields:

$$P_{drag} = k_b \cdot (v_{mean} + \Delta v(t))^3$$
$$= k_b \cdot (v_{mean}^3 + 3 \cdot v_{mean}2 \cdot \Delta v(t) + 3 \cdot v_{mean} \cdot \Delta v(t)^2 + \Delta v(t)^3)$$
<div align="right">Equation A5.3</div>

The power dissipation caused only by $\Delta v(t)$, denoted by $P_{\Delta v}$ can be written as:

$$P_{\Delta v} = k_b \cdot (3 \cdot v_{mean}^2 \cdot \Delta v(t) + 3 \cdot v_{mean} \cdot \Delta v(t)^2 + \Delta v(t)^3)$$
<div align="right">Equation A5.4</div>

A rowing cycle is assumed to be perfectly periodic. Averaged over n complete rowing cycles (n being a positive integer), Δv of course is zero. The average power lost to fluctuations will be:

$$\overline{P_{\Delta v}} = k_b \cdot (\overline{3 \cdot v_{mean} \cdot \Delta v(t)^2} + \overline{\Delta v(t)^3})$$
<div align="right">Equation A5.5</div>

If the shape of the velocity-time relationship has point symmetry, the third term of equation A5.5 equals zero. Investigation of available data[10] showed that for rowing at high stroke rates (28+ strokes·min⁻¹) this point symmetry is present to a good approximation. This implies that the average power lost due to velocity fluctuations depends most strongly on the average value of the square of $\Delta v(t)$. On our modified ergometer, this state of affairs could be mimicked when the resisting force, generated by the servo motor, would be in the form of:

$$F_{servo} = k_e \cdot v_{ergo}$$
<div align="right">Equation A5.6</div>

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Inititial testing revealed that with k_e = -50 kg·m^{-1}, $e_{velocity}$ would be in the required range.

Chapter 6

Estimation of the energy loss
at the blades in rowing;
common assumptions revisited

Hofmijster MJ, Koning JJ de, Soest AJ van

ABSTRACT

In rowing, power is inevitably lost as during push-off with the blades kinetic energy is transferred to the water. Power loss is estimated from reconstructed blade kinetics and kinematics. Traditionally, it is assumed that the oar is completely rigid and that force acts strictly perpendicular to the blade. The aim of the present study was to evaluate how reconstructed blade kinematics, kinetics and average power loss ($\overline{P}_{blade}$) are affected by these assumptions.

A calibration experiment with instrumented oars and oarlocks was performed to establish relations between measured signals and oar deformation and blade force. Next, an on-water experiment with a single female world-class rower rowing at constant racing pace in an instrumented scull was performed. Blade kinematics, kinetics and power loss under different assumptions (rigid versus deformable oars; absence or presence of a blade force component parallel to the oar) were reconstructed.

Estimated $\overline{P}_{blade}$ is 18% higher when parallel blade force is incorporated. Incorporating oar deformation affects reconstructed blade kinematics and instantaneous power loss, but has no effect on $\overline{P}_{blade}$ estimation.

Assumptions on oar deformation and blade force direction have large implications for the reconstructed blade kinetics and kinematics. Neglecting parallel blade forces leads to a substantial underestimation of $\overline{P}_{blade}$.

INTRODUCTION

Competitive rowing races take place over a distance of 2000 meters. By pulling on the oars, a rower causes a reaction force of the water on the oar blades, which propels the boat-oars-rower system against the water resistance force acting on the boat. As is the case in any aquatic mode of transport, it is inevitable that energy is lost to the water in the generation of the propulsive force; kinetic energy is given to the water at the blades. This energy is "lost" in the sense that it is unrelated to the energy needed to overcome drag. In earlier work we showed that the power equation is a helpful tool to analyze rowing performance[11, 12]. In its simplest form, the power equation for steady state rowing is given by: $\overline{P}_{rower} = -(\overline{P}_{drag} + \overline{P}_{blade})$.

In this equation (and throughout this study), $\overline{P}_{rower}$ represents the average net mechanical power produced by the rower, $\overline{P}_{drag}$ represents the average power dissipated through water resistance at the hull and $\overline{P}_{blade}$ represents the average power lost at the blades. Ideally, a rower simultaneously maximizes $\overline{P}_{rower}$, and minimizes $\overline{P}_{blade}$.

The characteristics of the oar and the shape of the blade are important determinants of $\overline{P}_{blade}$[1, 7, 9]. An optimal oar/blade combination allows the rower to generate a high propulsive force without resulting in high power loss at the blades. Blade force and power have been measured under controlled conditions, where the blade was immersed at different orientations in a flow tank[2]. However, as already noted by Barré and Kobus, the validity of such data that are obtained under steady state conditions is currently unclear because in reality the movement of the blade in the water is non-steady[2]. A promising new technique for estimation of blade force is based on a finite element method often referred to as Computational Fluid Dynamics (CFD)[10, 15]. With current computation power, high-resolution simulations, under non-steady conditions, are feasible. CFD therefore is a potentially powerful tool for the evaluation of new blade designs.

The only way to validate results obtained from flow tank experiments and from CFD simulations is to compare these to blade force and blade power data based on measurements under realistic conditions. Until now, blade kinetics and kinematics in on-water rowing were reconstructed from measurements of the oar angle in the horizontal plane and either the moment on the oar[1, 4, 14, 17] or the (perpendicular) force on the pin[11]. From these data, blade force and blade kinematics were reconstructed assuming that the oar is rigid and that the blade force is always perpendicular to the blade orientation[3, 5, 6, 11, 16, 18]. Furthermore it was often assumed that the point of application (p.o.a.) of the blade force is located at a fixed distance from the pin[4, 16], usually at the center of the blade[1, 3, 5, 6, 11, 18]. Instantaneous blade power can be

calculated by taking the dot product of the vectors of blade force and the velocity of its p.o.a.. In previous work $\overline{P}_{blade}$ was reported to be in the order of 20 to 30% of total mechanical power[1, 11, 14].

The assumption that the oar is rigid [3, 5, 6, 11, 16, 18] is clearly unrealistic, as considerable deformation of the oar can be observed by eye during rowing competitions. Neglecting this deformation leads to errors in the reconstructed trajectory of both the center and the orientation of the blade. The consequences of these errors for the reconstructed blade power are currently unclear. Similarly, the assumption that the blade force acts perpendicular to the blade [3, 5, 6, 11, 16, 18] is questionable, because the combination of translation of the hull and rotation of the oar results in a blade trajectory for which the angle of attack is by no means perpendicular to the blade at all times. Consequently, there is a power loss associated with the currently unknown force component that is parallel to the blade. The third assumption in the reconstruction of blade power concerns the p.o.a. of the blade force. Recent work using CFD[13] has revealed different blade pressure distributions at different angles of attack. These results imply that the assumption that the p.o.a. of the blade force always lies at the center of the blade may also need to be reconsidered.

In summary, there is reason to question the accuracy of the assumptions underlying current estimates of blade power losses in rowing. It is the aim of this study to evaluate the adequacy of two of these assumptions. More in particular we will report oar deformation and parallel blade force during racing conditions and we will evaluate how reconstructed blade kinematics, kinetics and power loss are affected by assumptions regarding oar rigidity and blade force direction.

METHODS

Outline of the study

In this study we evaluated the effects of assumptions on oar rigidity and blade force direction on blade kinematics, blade kinetics and, most importantly, power loss at the blades. First of all, we performed a calibration experiment with custom-made instrumented oars and oarlocks, aimed at establishing the relations between measured signals on the one hand and oar deformation and blade force (F_{blade}, in 2 dimensions) on the other hand. Next, we performed an on-water experiment in which a single world-class rower rowed at a constant racing pace. From the measured signals we reconstructed blade kinematics, blade kinetics and power loss at the blades under different assumptions (rigid versus deformable oars; absence or presence of a blade force component parallel to the oar). As the focus of this study lies on the comparison of results of different analysis methods, the statistical analysis of the data is in terms of descriptive measures.

Participant and protocol of the on-water rowing experiment

The single participant in this study was a world-class female rower, aged 23 years, body height 1.73 m, body weight 70 kg. The participant provided written informed consent. The study was approved by the local ethics committee. The participant rowed a distance of 500 meters at racing pace, i.e. 30-32 strokes per minute, starting from zero boat velocity, in an instrumented single scull. Remote-controlled data acquisition was started at zero boat velocity and was terminated slightly after the 500 m line was passed. Elapsed time after 100, 250 and 500 m was recorded using a stopwatch.

Measurement system

An instrumented racing single scull (Filippi, Italy) was used. Data from the impellor (Nielsen Kellerman, USA) mounted underneath the hull was sampled by the data acquisition system (see below). In addition, hull acceleration in the direction of travel was measured using an accelerometer (ADXL204, Analog Devices, USA). Oars were the commonly used "big blades" (Concept II, USA), the outboard parts of which were cut in order to mount custom-built oar shaft, such that the centre of the sensors were at 0.35 m from the pivoting point of the oar (Figure 6.1). Each sensor consisted of two individual strain-gauge force sensors, mounted at 45 degree angles relative to the length axis of the unloaded oar shaft. As explained below, the oar shaft sensors were used to reconstruct the blade force component that is parallel to the face of the oarlock ($F_{parallel}$). To keep the oars mechanically balanced, a counterweight was placed at equal distance from the pivoting point on the inboard section of the oar. The horizontal-plane angle between the parts of the oars near the oarlocks and the boat
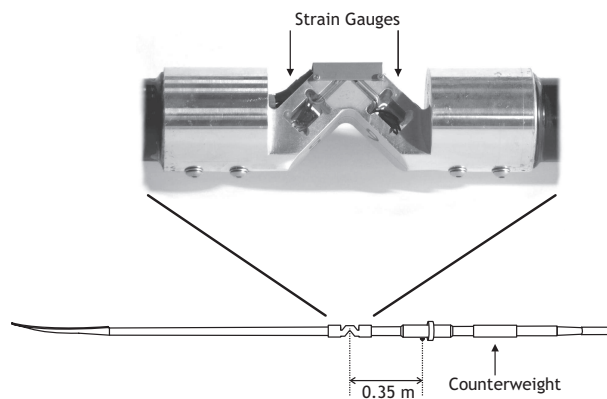
Figure 6.1. Oarshaft sensor.

(referred to as φ_{oar} in this study) was measured using servo-potentiometers (FCP12-AC, Feteris Components, the Netherlands) mounted in each of the oarlocks. Force on the pin (F_{pin}) was measured using custom made strain-gauge force transducers integrated in each of the oarlocks (Figure 6.2). The oarlock sensor data were used to reconstruct the component of the force between oar and oarlock that is perpendicular to the face of the oarlocks (see below). All sensor data were sampled at 1000 Hz and stored on-board on a data acquisition computer (PC 104 Prometheus, Diamond Systems, USA). After the experiment the data were transferred to a PC for offline analysis. The same system was used for data acquisition during the calibration experiment (see below).

***Figure 6.2**. Oarlock sensor, including force and angle transducers.*

Calibration procedure

The aim of the calibration procedure was to derive gains that allow reconstruction of oar deformation and net blade force components (in the frame of reference shown in Figure 6.3) from the custom force sensors in oarlock and oar shaft. To that aim, a horizontal-plane calibration experiment was carried out in the lab, in which oarlock and oar shaft custom force sensor signals were sampled at 1 kHz while an external horizontal force was applied to the center of the blade through a cable in which an independently calibrated 1-DOF force transducer (AST, Germany) was mounted. The force applied to the blade ranged between 0 and 150 N, being the expected range during on-water rowing, and was sampled synchronized with the oarlock and oar shaft custom force sensor signals. Simultaneously, oar kinematics was measured using an Optotrak 3020 position sensor (Optotrak, Northern Digital, Canada); see Figure 6.4 for the location of the active infrared markers. Calculation of the custom force sensor gains was based on calibration trials in which inward, perpendicular and outward forces were applied to the blade. Data from a separate trial during which blade force magnitude and direction were varied quasi-randomly was used to validate the calibration parameters; below we will refer to this trial as the validation trial. During all trials, the oarlock pin was fixed, allowing free oar rotation around a vertical axis, and the oar handle was supported at the assumed p.o.a. of the handle force (see below). Both oar deformation and blade force components are described in a frame of reference aligned with the face of the oarlock (see Figure 6.3).

In the reconstruction of relevant variables described below, two assumptions were made. First of all we assumed that the oar dynamics can be neglected; consequently we used a quasi-static approach in which oar deformation and blade force were reconstructed from the measured force data. Secondly, assumptions were made regarding the p.o.a. of the handle force and the net blade force during on-water rowing, as we were unable to reconstruct these p.o.a.'s from data.

Oar deformation was described in terms of deflection of the center of the blade ($d_{pos,blade}$) and orientation change of the blade ($d_{\varphi,blade}$), as illustrated in Figure 6.4. These quantities were found to be linearly related to the oarlock custom force sensor data. Least-squares optimal custom force sensor gains were calculated from the data obtained during the calibration trials; using these gains the oar deformation in the validation trial was predicted and subsequently compared to the kinematic data from the validation trial (Figures 6.5a and 6.5b); this resulted in r^2 of 0.82 (starboard) and 0.96 (port) for $d_{pos,blade}$ and 0.92 (starboard) and 0.97 (port) for $d_{\varphi,blade}$. More detailed analysis (data not shown) revealed that the relatively low value for the explained variation for $d_{pos,blade}$ for the starboard oar was caused by noise on the position data (obtained through the Optotrak system) for this trial.
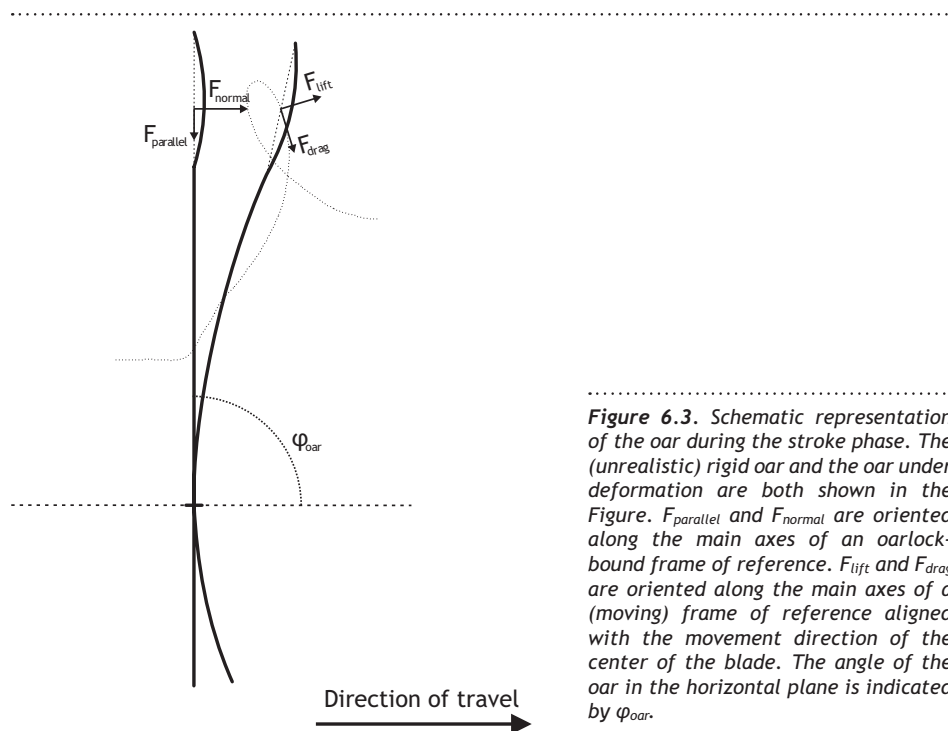
Figure 6.3. *Schematic representation of the oar during the stroke phase. The (unrealistic) rigid oar and the oar under deformation are both shown in the Figure. $F_{parallel}$ and F_{normal} are oriented along the main axes of an oarlock-bound frame of reference. F_{lift} and F_{drag} are oriented along the main axes of a (moving) frame of reference aligned with the movement direction of the center of the blade. The angle of the oar in the horizontal plane is indicated by φ_{oar}.*

Perpendicular blade force could be reconstructed most reliably from the oarlock custom force sensor data. It was assumed that handle force is applied at 0.85 m from the oarlock, and that net blade force is applied at the geometric center of the blade (1.80 m from the oarlock). During the calibration and validation trials, the forces were indeed applied at these points. Least-squares optimal force sensor gains were calculated from the data obtained during the calibration trials, using a linear model; using these force sensor gains the perpendicular force in the validation trial was predicted and subsequently compared to the actual perpendicular force as obtained from the independent force transducer (Figure 6.6); this resulted in r^2 of 1.00 (both starboard and port).

Parallel blade force was reconstructed from the oar shaft custom force sensor data, using a linear model. Least-squares optimal force sensor gains were calculated from the data obtained during the calibration trials; using these force sensor gains the parallel blade force in the validation trial was predicted and subsequently compared to the actual parallel force as obtained from the external force transducer (Figure 6.6); this resulted in r^2 of 1.00 (both starboard and port).

Data analysis for the on-water experiment

Kinematics.
From the combination of impellor data and stopwatch data (elapsed time after 100, 250 and 500 m), the boat displacement per full impellor revolution (which was in the order of 0.03 m) was calculated for each section of the 500 m trial. Using these values the average boat velocity was calculated for each full stroke cycle. Instantaneous boat velocity was calculated by numerically integrating the acceleration signal over stroke duration, using the average velocity calculated from the impellor data as the integration constant. Boat displacement was calculated by integrating instantaneous boat velocity over time. Blade position and velocity (relative to the earth) were calculated from the combination of boat kinematics relative to the earth and blade kinematics relative to the boat as reconstructed from the oar angle and oar deformation.

Kinetics.
Blade force components in the frame of reference shown in Figure 6.3 were reconstructed using the calibration parameters obtained in the calibration experiment (see above). During the recovery phase (identified as the phase where $|F_{pin}|<15$ N and $d\varphi_{oar}/dt<0$) the blade force was set to zero. For further data analysis the reconstructed blade force vector was decomposed in a component in the direction of the velocity vector of the center of the blade (F_{drag}) and a component perpendicular to that (F_{lift}); see Figure 6.3.

Energetics.
Instantaneous power lost to the water at each blade (P_{blade}) was calculated as the dot product of the reconstructed blade force vector and the reconstructed velocity vector of the center of the blade, relative to the earth. As there is no power associated with the lift force, P_{blade} can also be calculated as the product of F_{drag} and blade velocity. Instantaneous blade power was calculated under four different combinations of assumptions: regarding the reconstructed blade force, parallel blade force was or was not assumed to be zero; regarding the reconstructed blade kinematics, oar deformation was or was not assumed to be absent. Instantaneous blade power was numerically integrated over stroke time to obtain energy loss to the water at the blades for each stroke (W_{blade}); dividing this quantity by stroke cycle duration yielded average blade power ($\bar{P}_{blade}$); note that this average is calculated over the full stroke cycle, including the recovery phase.
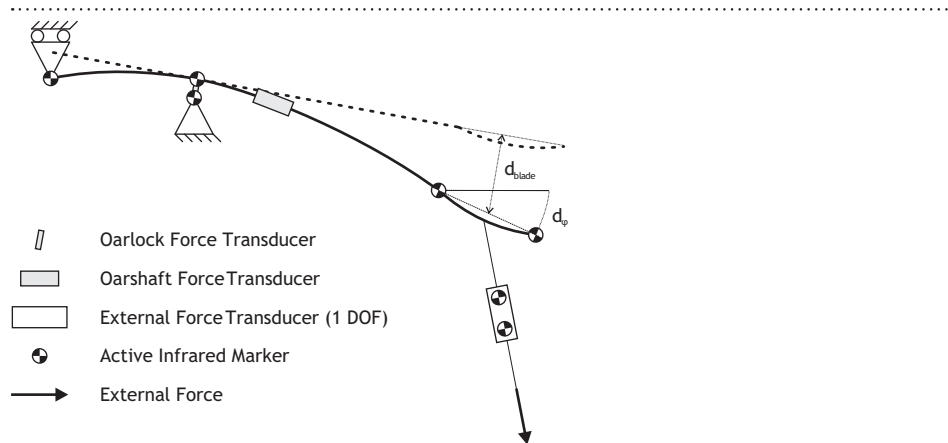
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Figure 6.4. Calibration setup. The arrow indicates the quasi randomly applied external force. The pin and handle were supported. The handle was able to translate freely from left to right, the pin with oarlock was able to rotate freely. Oar deformation was described in terms of $d_{pos,blade}$ and $d_{\varphi,blade}$ as defined in the Figure.

Descriptive statistics

For the analyses of blade kinetics and kinematics, 10 consecutive strokes cycles in the steady state situation were selected. When applicable, values were averaged over the 10 stroke cycle period. For the four combinations of assumptions that were analyzed, the 95% confidence interval for $\overline{P}_{blade}$ was calculated.
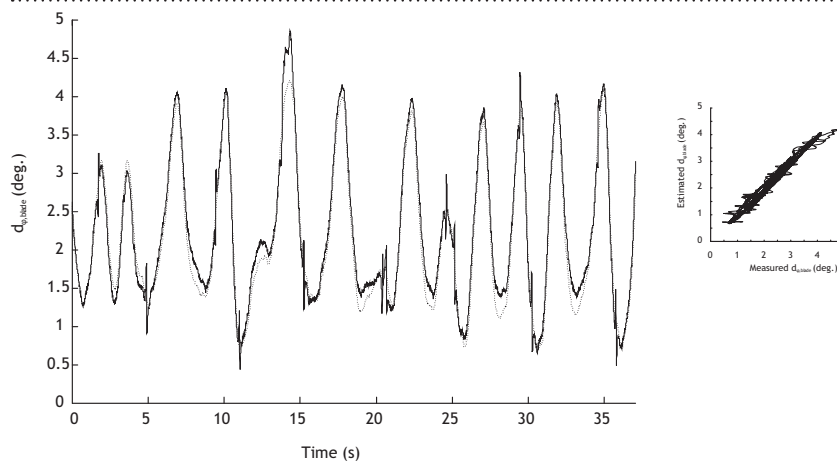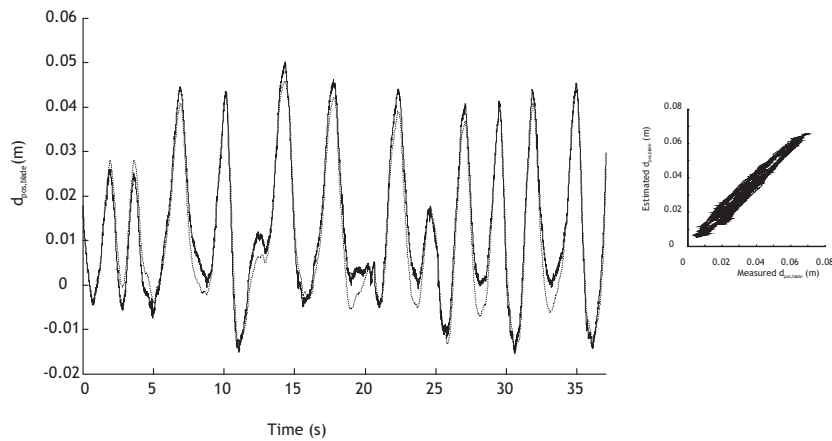
Figures 6.5a and 6.5b. *Results of the calibration trials for $d_{pos,blade}$ (a) and $d_{\varphi,blade}$ (b) for the port side oar. Solid lines indicate values calculated from Optotrak data, dashed lines indicate values reconstructed from the pin force sensor. The inserted Figures display the measured values plotted against the estimated values. There was some unexpected noise ('spikes' in the solid curve) in the measured $d_{\varphi,blade}$ signal, caused by noise in the signal of one of the position markers. As this noise is high frequent of nature, no effect on the quality of the fit is expected.*
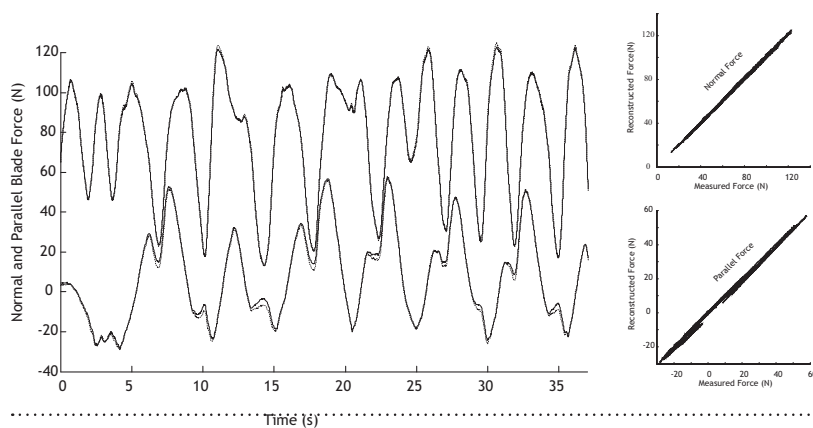

Figure 6.6. *Results of the calibration trials for F_{normal} (top curves) and $F_{parallel}$ (bottom curves). Solid lines indicate measured values, dashed lines indicate predicted values. The inserted Figures display the measured values plotted against the estimated values. Data correspond to those used in Figure 6.5.*

RESULTS

Blade kinematics

The blade kinematics for the rigid oar assumption and for the situation where oar deformation was taken into account are shown in Figure 6.7. For both conditions, the average kinematics as well as the range of values observed of the 10 selected strokes are displayed. The Figure shows that repeatability between the strokes is high. Figure 6.8 shows blade angle relative to the boat for the rigid and deformable oar assumptions. The Figures show that the effect of taking oar deformation into account has a substantial effect on the reconstructed blade kinematics.
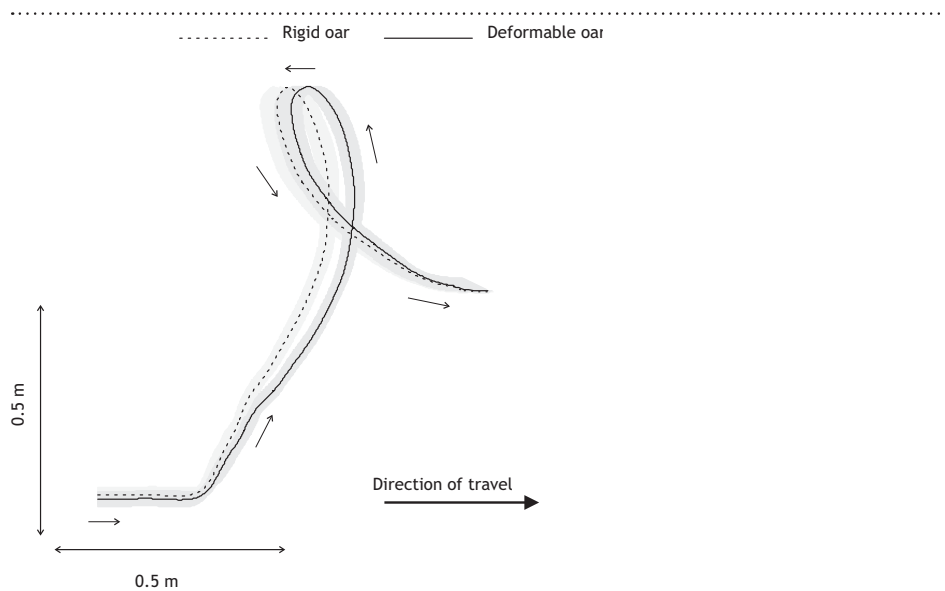
Figure 6.7. *Effect of assumptions on oar rigidity on the kinematics of the blade (port side oar). The dashed line represents the reconstructed path of the center of the blade, assuming a rigid oar. The solid line represents the reconstructed path of the center of the blade when oar deformation is taken into account. The shaded area indicates the range of values found for the 10 consecutive strokes on which this Figure is based. Small arrows indicate the direction of movement.*
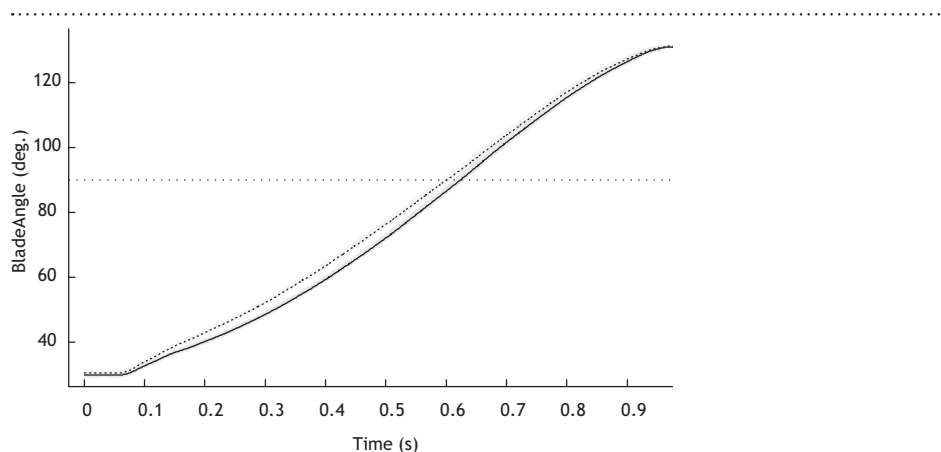
Figure 6.8. *Effect of assumptions on oar rigidity on the angle of the blade relative to the boat. The shaded area indicates the range of values found for the same 10 strokes as used in Figure 6.7. For each of the selected strokes, the start of the stroke phase is set at t = 0. The blade is perpendicular to the direction of travel of the boat at a blade angle of 90°, which is indicated by the dashed horizontal line.*

Blade force

Parallel blade force as measured by the oarshaft force sensors is shown in Figure 6.9. These data indicate that during the stroke phase, $F_{parallel}$ is non-negligible, acting inwards on the blade during the first half of the stroke, and acting outwards during the second half of the stroke (Figure 6.9).

Total blade force was decomposed in F_{drag} and F_{lift}. Note that this decomposition depends both on the incorporation of oar deformation and the incorporation of Fparallel. Figure 6.10 highlights the effect of incorporating oar deformation and $F_{parallel}$ on the decomposition of F_{blade} in F_{drag} and F_{lift}. It can be seen that when it is assumed that the oar is rigid and $F_{parallel}$ is zero, an underestimation of Fdrag is made in the first and last part of the stroke, whereas F_{drag} is slightly overestimated during the middle part of the stroke. Lift force appears to be overestimated during the second half of the stroke when it is assumed that the oar is rigid and $F_{parallel}$ is not present. Figures 6.11a and 6.11b show the same variables for one typical stroke, including (at discrete intervals) blade orientation and the blade force components.

Figure 6.9. *Parallel blade force. The shaded area indicates the range of values found for the same 10 strokes as used in Figure 6.7. For each of the selected strokes, the start of the stroke phase is set at t = 0.*

Figure 6.10. *Effect of neglecting $F_{parallel}$ on the decomposition of total blade force in F_{lift} and F_{drag}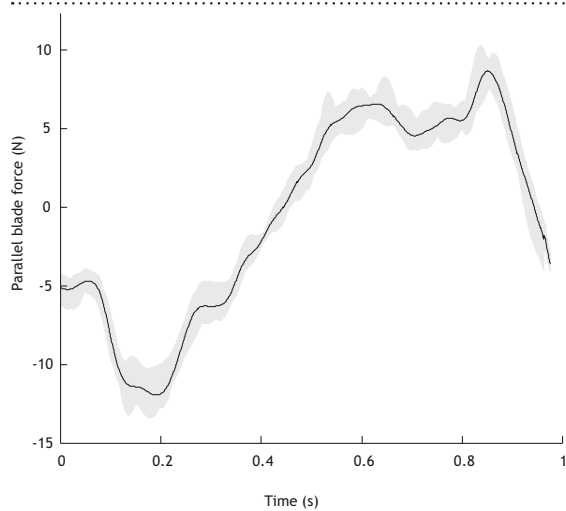. The shaded area indicates the range of values found for the same 10 strokes as used in Figure 6.7. For each of the selected strokes, the start of the stroke phase is set at t = 0*
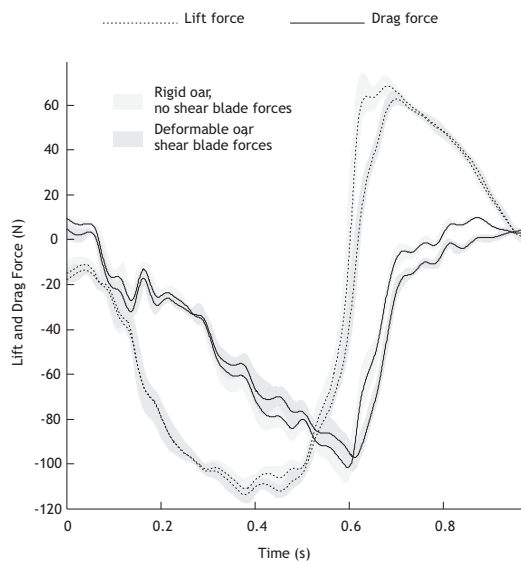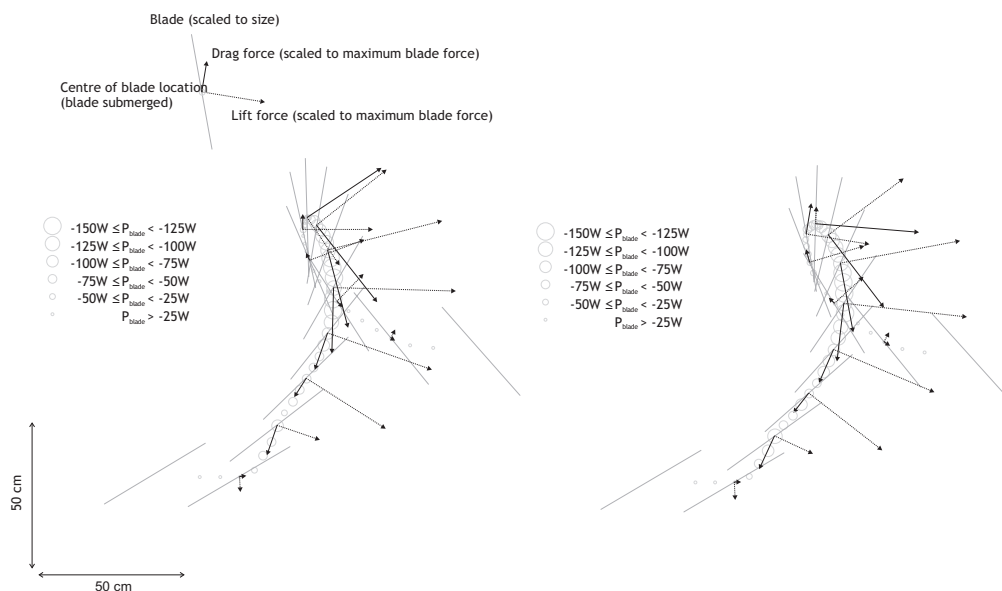
Figure 6.11a and 6.11b. *Comparison of estimated blade kine(ma)tics for two situations: (a) The oar is assumed to be rigid, blade force acts only perpendicular to the blade. (b) The oar is deformable and Fparallel is also present. This Figure is based on a typical example of a stroke. The position of the blade is plotted at 0.02 second intervals, the size of the circle provides an indication of the power dissipation at the blade at that point in time. Lift force (dashed arrow) and drag force (solid arrow) on the blade (gray line) are plotted at 0.08 second intervals.*

Power lost at the blades

Table 6.1 shows $\overline{P}_{blade}$ and W_{blade} for both oars calculated for the four situations described. The table shows that taking oar deformation into account has very little effect on the values calculated for $\overline{P}_{blade}$ and W_{blade}. When $F_{parallel}$ is taken into account however, the estimated values for both $\overline{P}_{blade}$ and W_{blade} are 18% higher. This implies that the assumption that blade force only acts perpendicular to the blade results in a substantial underestimation of the power lost to drag. In Figure 6.12, P_{blade} is compared between the situation in which oar deformation and $F_{parallel}$ are assumed to be absent and the situation where oar deformation and $F_{parallel}$ are taken into account. The Figure shows that especially at the beginning and the end of the stroke, P_{blade} is underestimated when oar deformation and $F_{parallel}$ are ignored. This is due primarily to an underestimation of F_{drag} at the beginning and end of the stroke (as can be seen in Figure 6.10) and not so much to a different oar velocity profile resulting from incorporating oar deformation. This follows from the fact that $\overline{P}_{blade}$ has similar values between the

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situation of rigid oar assumption and the situation where oar deformation is taken into account (See Table 6.1).

		Oar deformation neglected		Oar deformation incorporated	
Parallel blade forces	$\overline{P}_{blade}$ (W)	-45.7	(-49.8 – -41.5)	-45.8	(-50.0 – -41.6)
neglected	$\overline{P}_{blade}$ (J)	-91.9	(-99.5 – -84.4)	-92.2	(-99.8 – -84.5)
Parallel blade forces	$\overline{P}_{blade}$ (W)	-53.7	(-59.7 – -49.6)	-53.9	(-58.1 – -49.7)
incorporated	$\overline{P}_{blade}$ (J)	-108.1	(-115.7 – -100.5)	-108.4	(-116.0 – -100.8)

Table 6.1: Effect of assumptions regarding rigidity of the oar and direction of the force vector at the blades on the estimated value of $\overline{P}_{blade}$ and Wblade and on the 95% confidence interval for $\overline{P}_{blade}$ and Wblade (between parentheses).

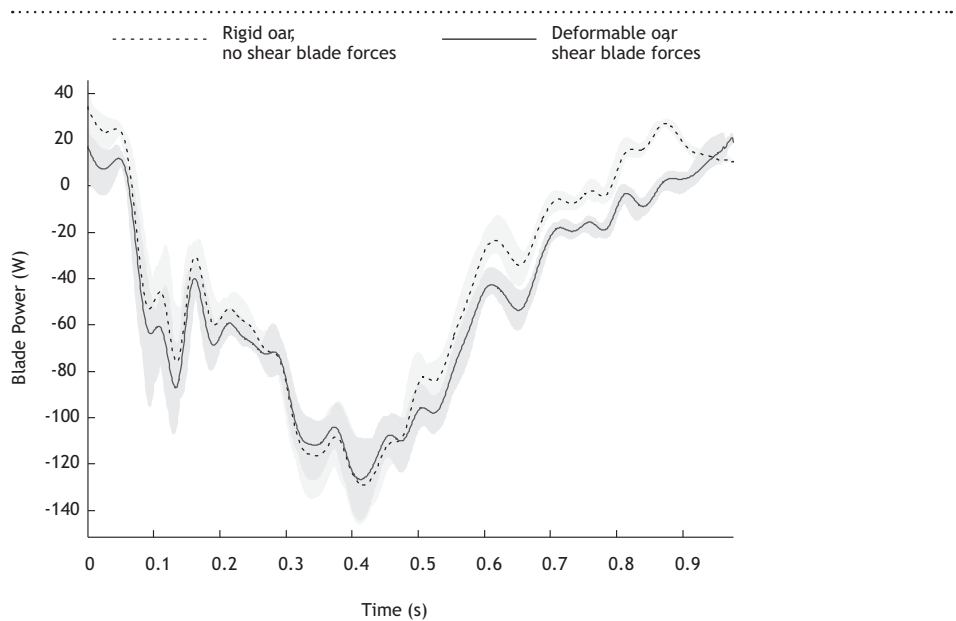*Figure 6.12. Comparison of estimated Pblade for two situations. In the first situation (dashed line), the oar is assumed to be rigid and a parallel blade force is assumed to be absent. In the second situation (solid line), the oar is assumed to be deformable, and Fparallel is assumed to be present. The shaded area indicates the range of values found for the 10 selected strokes.*

DISCUSSION

The results of this study indicate that the rigid-oar assumption and the no-parallel-blade-force assumption that were commonly adopted in the reconstruction of blade kinematics and kinetics in previous studies [3, 5, 6, 11, 16, 18] are untenable. Regarding kinetics, it was found that neglecting parallel blade forces results in an underestimation of $\bar{P}_{blade}$ of almost 20%. Regarding kinematics, it was found that the reconstructed blade kinematics is substantially affected when oar deformation is taken into account. Both the reconstructed path of the center of the blade in the water and the angle of the blade in relation to the boat are substantially different from the actual situation when the oar is assumed to be rigid. Somewhat surprisingly, these differences in blade kinematics had a negligible effect on the estimated average power loss at the blades. More detailed analysis indicated that incorporating oar deformation in the reconstruction of blade kinematics had an effect on P_{blade}; however, on average, power loss at the blade was not affected. While this study has elucidated the effect of the rigid-oar assumption and the no-parallel-blade-force assumption on the corresponding value for $\bar{P}_{blade}$, we would like to stress at this point that this study in no way clarifies the desirability of oar deformation and/or parallel blade force. This is because the actual values of these quantities were not varied; all values for $\bar{P}_{blade}$ were calculated from the same data-set, using different assumptions affecting the reconstructed blade kine(ma)tics.

This study is based on data obtained from a single participant who was an expert rower. It is possible that the effects of the rigid-oar assumption and the no-parallel-blade-force assumption vary between different rowers. However, although the actual hydrodynamics around the blade are rather complex, the kinematics of oar and blade are fairly straightforward. Oars will bend when forces are exerted on handle and blade, and similar blade trajectories have been reported in several independent studies in the past [1, 11, 18]. There is no reason to expect that the consequences of different sets of assumptions, which is the topic of this study, are highly sensitive to the relatively small differences in movement execution between expert rowers. Therefore, it is in our view acceptable that this study is based on data obtained from a single participant. The extent to which the amount of power lost at the blades differs between rowers, and the relation between movement execution and these power losses are interesting topics for future research. This study points out that in such studies, at least parallel blade forces and oar bending should be taken into account.

Although the magnitude of the parallel blade force seems small, the contribution of this force to the drag force is not negligible. This is especially true at the start and

end of the stroke phase, where the drag force is almost parallel to the blade. In these parts of the stroke, power losses are substantially underestimated when parallel blade forces are neglected. From our results, it would appear that it is favorable to somehow minimize this force component at the first part of the stroke phase. It is unknown if this is possible by either changing the blade design or by adapting the rower's technique.

In this study, we assessed two of the commonly made assumptions regarding blade kinetics and kinematics. Due to technical limitations, we were not able to investigate the validity of the assumption regarding the p.o.a. of the blade force. In line with earlier work of both ourselves and several other authors [3, 11, 18], we assumed the p.o.a. of the blade force to be at the center of the blade. However, simulation results obtained from CFD models suggest that the location of p.o.a. changes during the stroke from outwards at the start of the stroke to inwards at the finish of the stroke[13]. In order to get a first impression of the sensitivity of our results for the location of the assumed p.o.a., we recalculated all our results for a p.o.a. located either 0.10 m more inward or 0.10 m. more outward. Most importantly in the context of the present study, it was found that our conclusions regarding assumptions on oar rigidity and blade force direction are not at all sensitive to the assumed p.o.a. However, it was also found that the value of P_{blade} is highly sensitive for the assumed p.o.a.; in other words, the values for power loss at the blades reported in this study depend strongly on the assumed p.o.a. In our view this indicates that there is a need for experimental determination of the p.o.a. under racing conditions.

Another aspect of the bending of the oar that was not assessed in this study is the energy needed to deform the oar. If the oars are perfectly elastic, this energy, being a fraction of the mechanical energy produced by the rower, is stored and subsequently 'given back' in a later stage of the rowing cycle. Otherwise, a part of this energy is lost, meaning that this would be an additional power loss term. The magnitude of this term is unknown, but it is obvious that for optimal performance the energy dissipated in the oars should be minimal.

Computational Fluid Dynamics is a promising technique for future research on blade hydrodynamics. Direction of the force factor, as well as its point of application can be obtained from reliable simulations. For future modeling using CFD, obtaining the correct kinematic data for the blades is important. CFD models reconstruct hydrodynamic forces as a function of the prescribed movement of the blade in the water[15]. For these models to produce meaningful results it is therefore crucial that the correct kinematic data is used as input. Thus, when reconstructing on-water kinematics of the blades from measurements of oar angle and boat displacement, it is important to take the

deformation of the oar into account.

Previous estimates of $\bar{P}_{blade}$ were in the order of 20 to 30 percent of the rower's power output[1, 11, 14]. Results of this study indicate that $\bar{P}_{blade}$ is in fact substantially higher. Thus, rowers spend a substantial part of their power in the process of generating a propulsive force on the blade. We therefore expect that improvements in blade design may result in a substantial improvement in performance. The latest large improvement in blade design already dates back to 1992, when 'Macon' blades were replaced by big blades. Recently, Caplan and Gardner[9] suggested a small improvement in blade efficiency when a more rectangular blade shape is used. However, as also is pointed out in a follow-up study by the same group[10], at this point transfer of their results to actual on-water rowing is questionable. Tests were done under steady state conditions and a scale model was used. Consequently, tests were performed at a Froude number that is different from that in the actual situation. Again, this points out the need for reliable field measurements.

Several authors stated that lift forces are the main contributor to the propulsive force during the first and last part of the stroke phase, whereas drag forces are the main contributor to the propulsion in the mid part of the stroke phase [3, 8]. As can be seen from Figures 6.10 and 6.11a and b, our data do not support this view. Both figures show that, irrespective of the assumptions used, lift force is the main contributor to the propulsion for almost the entire stroke phase.

In summary, our study shows that assumptions on oar deformation and the direction of blade force have large implications for the reconstructed blade kinetics and kinematics. Most importantly, neglecting parallel blade forces leads to a substantial underestimation of the average power lost at the blades. Energy losses during push-off appear to be even larger than previously expected. The magnitude of these losses calls for future research on the possibilities of minimizing $\bar{P}_{blade}$, for instance by optimizing blade design or improving the rower's technique.

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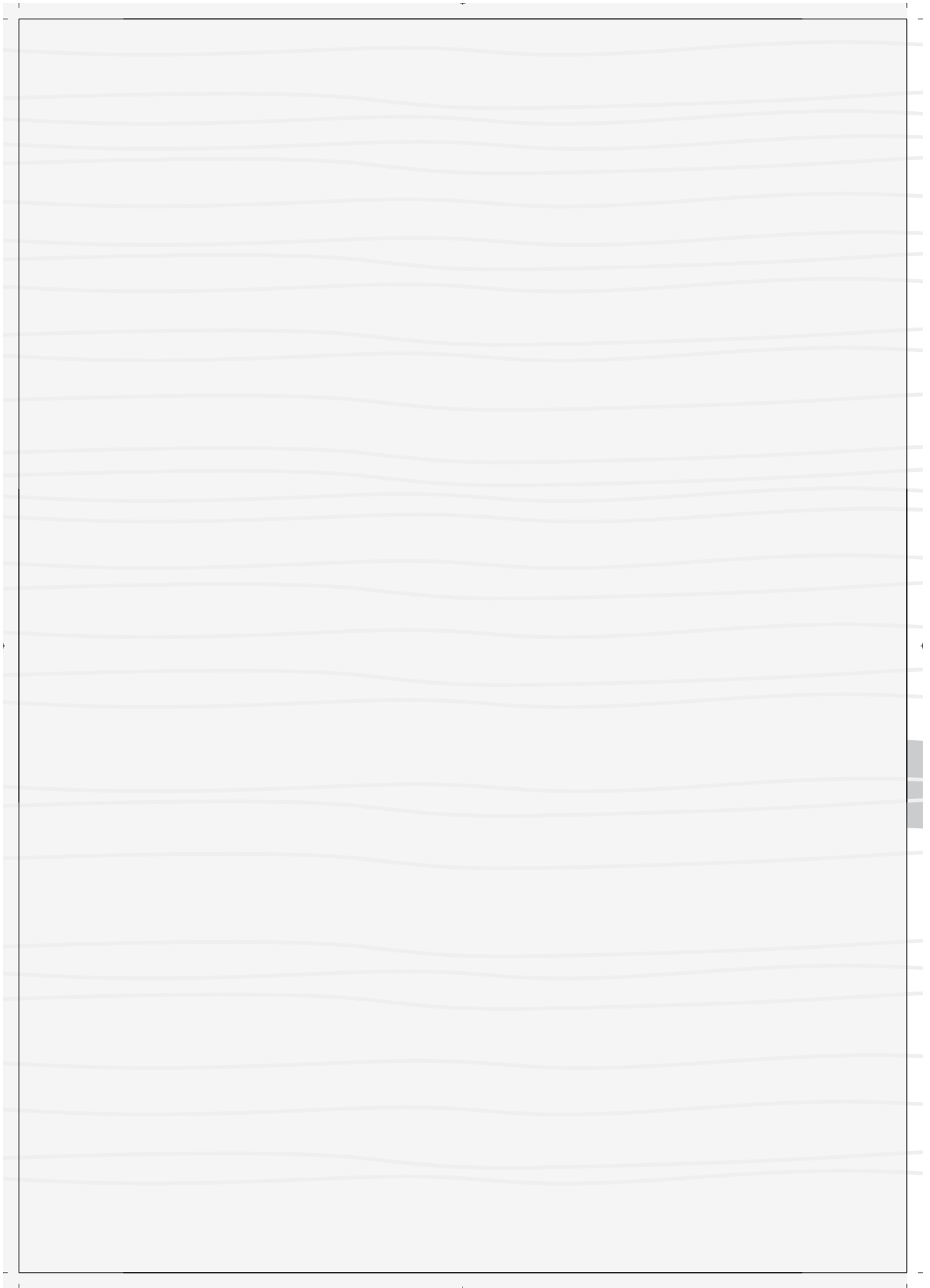
Chapter 7

General discussion

Coat and Badge vs. Olympic final, revisited

In the introductury chapter, a comparison was made between competing Watermen in London in 1715 and the Olympic Finalists for the men's single scull in Beijing, 2008. The question was put forward why the winner in 2008, Olaf Tufte, could achieve a so much higher average velocity than the winner of the coat and badge race, early 18th century. The potential of the power equation was illustrated by analyzing the differences between both cases in terms of energy production and dissipation.

Each of the chapters in this thesis focusses on one aspect of the power equation. Each of the Chapters therefore can explain part of the observed difference between the average velocities of the Coat and Badge racers and the 2008 Olympic Finalists.

In Chapter 2 we analyzed the mechanical power output of the rower, the fraction of this power contributing to average velocity and the power losses caused by pushing water away with the blades as well as the power losses caused by velocity fluctuations. It was found that the production and distribution of mechanical power are affected by stroke rate[4].

Although it is unknown whether the stroke rates adopted in the two different races differ a lot, it can be stated that apparently, the production and distribution of mechanical power was in favor for Tufte. Also, had they both produced equal mechanical power, then Tufte would achieve a higher boat speed, since he had the 'faster' boat. More likely, Tufte was also able to produce more mechanical power, not in the last place because he was able to use more of his leg muscles because he had a sliding seat.

Chapter 3 addressed the so-called 'internal power losses'. The suggestion that 'the energy spent to move the rower's body back and forth'[2] depends on stroke rate was investigated. However, it was found that gross efficiency is not affected by stroke rate, which suggests that internal power losses are also not influenced by stroke rate[6].

On the comparison between the Coat and Badge race and the Olympic Final, gross efficiency is most likely not a factor contributing to the large difference in average velocity.

In Chapter 4, the effect of strapping a rower to his sliding seat was investigated. It was found that rowing performance during the start, quantified by the power output on a rowing ergometer during the first five strokes, improved by 12% when a rower attaches himself to his seat. This would translate to a gain of 1 to 2 meters after the first 5 strokes[10].

To our knowledge, neither the 18th century Waterman nor Tufte strapped himself to his seat. Would they have done so, Tufte would most likely benefit the most since

he, contrary to the Waterman, used a sliding seat allowing him to pull harder on the oars.

Chapter 5 explains how rowing skill can affect power losses. First of all, the relative contribution of velocity efficiency to performance was investigated. Furthermore, it was investigated which kinematic and/or kinetic variables defining the rower's technique are related to differences in $e_{velocity}$. It was shown that optimal coordination of timing between forces applied on handle and footstretcher results in less power losses due to velocity fluctuations[5].

The Watermen sat on fixed seats and rowed in much heavier boats compared to the modern racing shells. Fluctuations of boat velocity would be much lower since both the displacement of the rower's center of mass is much smaller, and any displacement of the rower's mass would have much less influence on the boat velocity due to the much larger mass of these watertaxis. Power losses to velocity fluctuations would thus be (much) lower for the Watermen. The fact that the sliding seat is adopted by every competitive rower in the world indicates that the benefit of being able to produce more (mechanical) power with the leg muscles outweighs the negative effect of higher velocity fluctuations resulting from using a sliding seat.

In Chapter 6, power losses at the blades are examined. More specifically, the effect of certain commonly made assumptions regarding oar kinetics and kinematics on the estimation of the power losses at the blades are investigated. The main conclusion of Chapter 6 is that both kinetics and kinematics of the oar blade differ substantially between conventional methods (where a rigid oar and only perpendicular blade forces are assumed) and our more realistic method (where oar bending and parallel blade forces are reconstructed or measured and taken into account). In the more realistic model, the estimated power losses at the blades are much higher[3].

It is hard to tell how these results might affect estimated blade losses of both described cases, as obviously there is no real time data of both races. However, on the topic of blade losses, it is plausible that the relative power losses at the blades would be lower for Tufte. He used 'big-blades', where the Coat and Badge racers had blades with a much smaller area. Also, he rowed at a higher velocity, which, as explained in Chapter 2, positively affects propelling efficiency .

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OPEN QUESTIONS

The examples above show that the aspects of the energetics and mechanics of rowing that are tackled in this thesis can very well explain the differences in performance between the Coat and Badge race and the Olympic final. More in general, the same aspects of the energetics and mechanics of rowing can explain differences in performance between different rowers. However, this thesis is by no means exhaustive. Obviously, aspects such as the mental state of the rower or his or her proneness to injury can have a tremendous effect on rowing performance. These aspects are beyond the scope of this thesis and therefore not considered in any of the Chapters. Also on the subject of rowing mechanics and energetics, many things are still not fully understood.

In this thesis, the rower is regarded as a "machine", from which the internal mechanics are taken for granted. This machine burns fuel (fat and carbohydrates, its expenditure is estimated by O_2 measurement), which result into forces that are exerted onto the environment (in the case of rowing; on the footstretcher, handle and seat). Apart from a crude estimation of muscle contraction velocities (by reporting joint angular velocities) and internally dissipated energy (by reporting negative work within each stroke cycle)[5], little attention is paid to the internal mechanics of this machine. Not much is known about the individual muscle forces as well as the inter-muscular coordination during rowing.

A similar black-box approach is used to estimate power losses at the blades. Power transfer can be calculated from the reconstructed blade force and the velocity of the reconstructed point of application of this force (Chapter 6). At the same time, the actual hydrodynamics acting around the blade are still poorly understood. In order to understand the relation between technique or movement coordination and blade power losses, or in order to design more efficient blade shapes, more knowledge is required about these often complex dynamics. Recent technologies such as computational fluid dynamics (CFD)[1, 8] might help to enhance the understanding of blade hydrodynamics.

Another aspect of this thesis that warrants further investigation is the implementation of a mechanical constraint at the rower's pelvis that prevents lifting of the buttocks from the seat (Chapter 4). This constraint was found to allow huge improvement in starting performance. The results were noticed by the rowing community, which lead to the development of the "SuperSeat", designed to enhance (on-water) rowing performance, especially during the start. The SuperSeat is an adaptation to the regular

rowing seat, allowing the seat to roll under near frictionless conditions while the rower pulls on it.

Some preliminary experiments have been performed considering the use of the SuperSeat in the single scull, and the results are promising. A similar improvement in starting performance as found on the ergometer appears to be possible in the single scull.
It is an open question if, apart from the start, rowers can also benefit from the SuperSeat for the remainder of the race, or that they are physically not able to produce more mechanical power. In another pilot experiment, this time on the ergometer, the same principle was tested over a longer distance (1000m). Again, a positive effect appears to occur when the rower is strapped to the seat, resulting in a faster finishing time. It is too soon to draw conclusions from these preliminary data. However, a further examination of the SuperSeat in on-water rowing, over longer distances is definitely warranted. And perhaps, the 2012 Olympics in London will have all Dutch rowers strapping themselves to their seats?

Where to go from here?
For optimal performance, rowers must maximize mechanical power production. To that aim, both metabolical energy expenditure as well as gross efficiency should be maximal. At the same time, power losses should be kept to a minimum. Velocity fluctuations should be minimized, so that velocity efficiency is maximal and power loss at the blades should be kept to a minimum, so that propelling efficiency is also maximal. Maximum velocity efficiency and propelling efficiency result in maximum power dissipation to drag associated with average boat speed. Boats have to be designed to have minimum drag, so that average boat speed is maximal at given power transfer.
It is unlikely that rowers can achieve optimal values for all the variables that make up the power equation. Consider the following example: A velocity efficiency that approaches the maximum of one is possible when the accelerations of the rower are kept to a minimum. In order to achieve this, rowers should only use their arms. Obviously, in this case boat speed would be very low.

It is not always simply the most powerful athlete that wins in rowing. In Chapter 5, this is illustrated by the fact that the participant that had the highest power output during a simulated 2000 m race did not 'win'; i.e. did not have the highest average (virtual) boat speed. The optimal rowing technique therefore does not constitute the movement execution that results in the optimization of only one of the aspects of the power balance. Rather, the optimal rowing technique results in the optimal combination of all factors that make up the power balance, resulting in an optimal; i.e. as high as possible; average boat speed. This implies that for achieving maximum average boat

velocity, there is an optimal trade-off between those factors.

In order to improve our understanding of this trade-off, a systematic approach is necessary. First of all, the individual processes need to be understood. This thesis sheds light on some of those processes: power output and power losses to velocity fluctuations are related to movement execution; gross efficiency likely is not. Possibly, power losses at the blades are related to movement execution as well, but at this point this remains an open question.

In order to investigate the movement coordination that results in the optimal trade-off and thus in the maximal average velocity, a combination of inverse and forward mechanics could be useful. Forward dynamic approaches have been applied successfully in several tasks, such as vertical jumping[11] or cycling[9]. By optimizing for maximum jump height (vertical jumping) or maximum mechanical power production (cycling), optimal coordination patterns between muscles can be found. With increasingly more computational power becoming available, models of the human body can become more complex. It should now be possible to construct a reliable model of a rower, incorporating not only the legs, but also trunk, shoulders and arms. Inverse dynamics can on the one hand act as a validation method of the results of the forward dynamical model. On the other hand, inverse dynamics can provide information about processes that are still poorly understood; such as the relative complex dynamics of the shoulder joints, but also on for instance the interaction between blade and water.

As a first step, such forward dynamical simulations should be applied to establish coordination patterns for maximum power output. In later stages, the models could be extended with the dynamics of the oar and hull. At this time, joining forces with hydrodynamics experts is probably a good idea.

When all these steps are taken, it becomes possible to optimize for average velocity. By manipulating different factors, an impression of the importance of each of those factors can be obtained. Such 'sensitivity' analyses can provide valuable information, also for rowers and coaches, as it points out in which direction rowing technique should develop as well as on what aspects of rowing technique time and effort should be invested.

Forward dynamics models have large potential in the science of rowing; however they by no means render real time on-water investigations obsolete. First of all, model results should always be validated 'in the real world', for which reliable measuring equipment is necessary. Second, many of the processes that are involved in rowing are still poorly understood (see 'open questions).

Publications or Medals?

In 2008, Tufte won the Olympic Gold in a time of 6 min. 59.8 seconds. The silver medal was awarded to Ondrej Synek, who finished in a time of 7 min. 00.6 seconds. Is it now possible to tell why Olaf Tufte was 0.8 seconds faster than the Olympic runner-up? Probably not! Did Tufte have a faster boat, was he just a bit stronger or more efficient or did he just have a little more luck?

Differences in finishing times in high performance rowing are often very small. Many times it is impossible to tell why one rower is faster than the other. Then again, these tiny differences imply that small improvements in technique, physique or material can mean the difference between a gold and a silver medal. For example, an improvement of $e_{velocity}$ of 0.005 will, with everything else being equal, lead to an improvement in finish time of almost a second. This poses a challenge for future research on the topic of rowing. On the one hand, changes that at first sight appear only marginal can have dramatic consequences (winning the gold medal instead of missing out on the podium). On the other hand, since rowing is an outdoor sport, suffering from environmental influences, the 'noise' on rowing data is quite high, especially concerning finishing times. This means that in order to be able to distinguish an effect as small 0.8 seconds in finish time, one literary has to perform dozens of trials. Since most of the research concerns high level rowing, requiring high level rowers as test participants, this simply isn't possible. By integrating scientific research into the training programme, a part of this problem can be solved. This requires testing protocols and equipment that don't interfere with the daily work-outs. On the other hand, rowers and athletes should realize the potential gains of an increasing knowledge about their sport. This might imply that sometimes they have to invest time and effort into scientific research.

All in all, future research on on-water rowing is by no means fruitless. As explained above, reliable models of boat, rower and oars can provide valuable information for scientist as well as rowers and coaches. Measurements of on-water kinematics and kinetics are of paramount importance for scientific progress. At the same time, this information can provide valuable information that can be used in the training and coaching of rowers. Three decades ago, heart rate monitors were introduced in the sport practice, and nowadays a large percentage of both professional and recreational athletes in many sports use these monitors in their daily work-outs. A few years back, power measurement at the crank or rear hub became available for cyclists, and nowadays, many professional cyclists monitor their mechanical power output to regulate their training. In the sport of rowing, some on-water measuring equipment is available. However, apart from monitoring the stroke rate or boat speed, on-water sensors are not widely used in everyday practice. Most likely, the reason that these sensor technologies are not widely adopted in competitive rowing lies in the fact that

the interpretation of the gathered data is unclear.

In the past, a lot of focus has been put on the shape of the so called force-curve; i.e. force or moment at the oar or oarlock, plotted against time or stroke length[7, 12]. However, as argued above, singling out a single variable in the complex rower-boat-oars system might not be very helpful. The 'ideal' force curve might be highly dependent on individual rower characteristics. This makes the search for a general optimal shape of the force-time profile a futile attempt. Rather, there is likely an ideal trade-off among several factors, as argued above.

With technology progressing and with more and more knowledge about the (bio) mechanics and energetics of rowing becoming available, it seems time for a (re-)introduction of innovative sensor technology in rowing. In the future, collaboration between science and sport practice can be fruitful for both parties.

Nevertheless, there exists a field of tension between both worlds. Researchers should realize the demands that are put on individual athletes, meaning that it is not always possible to perform many time-consuming or exhausting experiments. On the other hand, coaches and rowers have to accept that in order to get the answers they want, scientific research is needed. Finding the answers to the important questions sometimes needs a systematic approach that takes time and effort. In order to let the introduction of science in rowing to become a success for both worlds, scientific measurements and analysis have to be fully integrated in the training program. Nowadays, the accompanying staff already consists not only of a coach, but physiologists, strength trainers and doctors are also included. Why not add a (biomechanics) scientist to the team? In countries like Australia and Great Britain science is interwoven with sports for quite some time now. In the past years, these countries are very successful in rowing competitions*, which might be partly attributed to years of systematic research.

In the end, sport science and sport practice share a common goal; increasing the knowledge. A scientist might not always be interested in the practical implications of his research, which is a pre-requisite for athletes and coaches. Athletes or coaches might not always have a clear theory or hypothesis for the questions they want answers on, which in turn is a pre-requisite for any good scientist. However, for both the researcher and the rower it goes that large gains are possible with good cooperation. It should be clear that aiming for medals or aiming for publications is not at all mutually exclusive. So medals or publications? The answer should be both!

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*　　At the Olympic Games in Beijing, Great Britain and Australia were the best performing countries of the rowing tournament. Great Britain won 2 Gold, 2 Silver and 2 Bronze medals. Australia won 2 Gold medals and 1 Silver.

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SUMMARY

Rowing performance can be judged by a single variable; the rower or crew that has the highest average boat velocity obviously is the best performer. While this clearly states the obvious, the processes that result in average boat velocity deserve investigation. During a race, rowers produce a large amount of mechanical power. For optimal performance, the fraction of this mechanical power contributing to average boat velocity should be maximal. However, power is inevitably lost. About 20% of the net mechanical power production is lost at the blades, where water is put in motion during the push-off. Another 5% of the net mechanical power production is lost to fluctuations in boat velocity.

In this thesis the mechanics and energetics of competitive rowing is investigated and discussed. Subject of these investigations are both the biological system, the rower as the engine of the boat, and the mechanical system of boat and oars.

Chapter 2 reports a study in which the effect of stroke rate on the production and distribution of mechanical power is investigated. It was found that at increasing stroke rates, power production as well as the overall efficiency increases. At increasing stroke rate, a slight decrease of $e_{velocity}$ as well as a large increase of $e_{propelling}$ is reported. Power production increases because the work per stroke appeared to be relatively invariant between all stroke rates. Propelling efficiency increases because the work at the blades is reduced with increases in stroke rate. Velocity efficiency decreases because of the larger magnitude of the accelerations of the rower that occur at increasing stroke rates, causing larger accelerations and decelerations of the boat.

Chapter 3 addresses the assumption that at increasing stroke rate e_{gross} will decrease. This would suggest that rowers perhaps should adjust their boat setup or technique in such a way that the amount of mechanical work per stroke is maximal, thus allowing them to row at low stroke rates while keeping a high power output. However, it was found that the ratio between energy consumption and production is in fact invariant with respect to stroke rate. In other words, stroke rate and gross efficiency were found to be unrelated. The implication of this finding is that the choice of stroke rate for rowing competitions is unlikely to be related to its effect on e_{gross}.

Chapter 4 reports about the investigation of the effect of applying a mechanical constraint on the maximum mechanical power production on a rowing ergometer. Analogue to clip-in pedals in cycling or spikes in track running events, enforcing a constraint in such a way that the normal movement can still be executed can either

have a beneficial effect, or in the worst case have no effect on performance. It was found that by tying the rower to his seat by means of a simple strap, and thus preventing any vertical motion of the rower's buttocks, rowers are able to produce up to 12% more mechanical power. This translates to a benefit of 2 to 3 meters after the first 10 seconds of the race for a rower that is attached to his seat.

Chapter 5 addresses the relation between technique and the distribution of mechanical power in rowing. In the chapter, the relation between movement execution and $e_{velocity}$ is discussed. It was found that a good coordination between forces exerted on the foot stretcher and on the handle is important in minimizing power losses to velocity fluctuations. By means of a regression analyses, Chapter 5 points out that good rowers not only can produce a high mechanical power and have a high maximum oxygen uptake, but that they also have a good technique, at least in the sense that they can keep the inevitable velocity fluctuations as low as possible.

In Chapter 6, the power losses at the blades get a closer look. Custom made sensors allowed measurement of forces acting parallel to the blade. Besides blade forces, the deformation of the oar was reconstructed as well. It was found that neglecting the parallel blade force component in the calculations lead to a substantial underestimation of the estimated energy losses during the push off. It was also found that estimated energy losses did, on average, not depend on assumptions on the rigidity of the oars. Reconstructed kinematics were however substantially different when oar deformations were taken into account. In this chapter it was shown that in future investigations on blade dynamics, oar deformation or parallel blade forces should not be neglected.

In chapter 7 the conclusions of this thesis are presented. It is stated that the aspects of the mechanics and energetics of rowing that are covered in this thesis can explain differences in performance between different rowers. However, it is also stated that many aspects of the mechanics and energetics of rowing are still not fully understood. For instance the effect of strapping the rower to his or her seat on performance has to be examined for on-water rowing, as well as for rowing efforts of a longer duration. Despite the findings described in chapter 6, the hydrodynamics at the blades are still poorly understood. A collaboration with a research group that has expertise in this field of research seems a good idea for further investigations.

To be able to find the optimal rowing technique – i.e. the coordination pattern that results in the highest average boat velocity over the race distance – a forward dynamics approach is suggested. By building reliable models and subsequently 'tweaking' parameters of this model a sensitivity analyses can be performed. Studying the

effects on performance could provide indications to what aspects of rowing technique researchers, rowers and coaches should spent their time on.

This thesis concludes with the statement that despite known existing fields of tension between sport practice and research labs, applied sport research such as described in this thesis should be continued and where possible intensified. Integrating sport into research and vice-versa will yield favorable results for both parties. Therefore, one should strive for both good research and good performance, ultimately resulting in publications and medals.

SAMENVATTING

Mechanica en Energetica van het Roeien

Roeiprestatie kan met één enkele variabele beoordeeld worden; de roeier of ploeg die de hoogste gemiddelde bootsnelheid weet te bereiken is uiteraard de beste. Alhoewel dit natuurlijk een open deur is, zijn de onderliggende processen die resulteren in deze gemiddelde snelheid een onderzoek waard. Roeiers leveren tijdens een race een grote hoeveelheid mechanisch vermogen. Voor een optimale prestatie dient het deel van dit mechanisch vermogen dat bijdraagt aan de gemiddelde bootsnelheid zo groot mogelijk te zijn. Echter, een deel van het vermogen gaat onherroepelijk verloren. Ongeveer 20% van het netto geproduceerde mechanische vermogen gaat verloren bij de bladen. Ook raakt er circa 5% van het netto geproduceerde mechanische vermogen kwijt aan fluctuaties van de bootsnelheid.

In dit proefschrift worden de mechanica en energetica van wedstrijdroeien onderzocht en bediscussieerd. Het onderwerp van deze onderzoeken zijn zowel het biologische systeem, namelijk de roeier die in wezen de motor van de boot is, als het mechanische systeem van boot en riemen.

In Hoofdstuk 2 wordt een studie beschreven waarin het effect van slagtempo op de productie en verdeling van mechanisch vermogen wordt onderzocht. Bij toenemend slagtempo werden zowel een toename van de vermogensproductie als van de algehele efficiëntie gevonden. Er werden een geringe toename van de snelheidefficiëntie ($e_{velocity}$) en een grote toename van de voortstuwingsefficiëntie ($e_{propelling}$) bij toenemend slagtempo gevonden. De vermogensproductie neemt toe omdat de arbeid per haal op elk slagtempo zo goed als constant is. De voortstuwingsefficiëntie neemt toe omdat de arbeid bij de bladen afneemt bij toenemend slagtempo. De snelheidsefficiëntie tenslotte neemt af omdat de versnellingen van de roeier grotere waardes bereiken, die grotere versnellingen en vertragingen van de boot veroorzaken.

In Hoofdstuk 3 wordt de aanname besproken dat de mechanische efficiëntie (e_{gross}) af zou nemen bij toenemend slagtempo. Als dit zo zou zijn, dan zouden roeiers wellicht een bootafstelling moeten kiezen, dan wel een techniek moeten toepassen die hen in staat zou stellen per haal zoveel mogelijk mechanische arbeid te leveren, zodat ze op een laag tempo kunnen roeien en toch veel vermogen leveren. De ratio tussen (metabool) energieverbruik en vermogensproductie bleek echter onafhankelijk van slagtempo te zijn. Met andere woorden, er is geen relatie tussen slagtempo en e_{gross}. Deze bevinding impliceert dat de keuze voor slagtempo gedurende een race waarschijnlijk niet gerelateerd is aan een mogelijk effect op e_{gross}.

In **Hoofdstuk 4** wordt een onderzoek naar het effect van het aanbrengen van een mechanische beperking op de roei-ergometer op de maximale mechanische vermogensproductie beschreven. Analoog aan klikpedalen bij wielrennen of spikes bij atletiek zal het opleggen van een beperking die ervoor zorgt dat de normale beweging nog steeds uitgevoerd kan worden ofwel een positief effect hebben, of, in het ergste geval, geen effect op de prestatie. Het vastbinden van de roeier aan zijn bankje door middel van een simpele riem, waardoor verticale bewegingen van de billen van de roeier onmogelijk gemaakt werden, bleek roeiers in staat te stellen tot 12% meer vermogen te leveren. Dit laat zich vertalen tot een voordeel van 2 à 3 meter in de eerste 10 seconden van een race voor een roeier die is verbonden met zijn bankje.

In **Hoofdstuk 5** wordt de relatie tussen techniek en de verdeling van het mechanische vermogen bij roeien beschreven. In dit hoofdstuk wordt de relatie tussen de bewegingsuitvoering en $e_{velocity}$ bediscussieerd. Het bleek dat een goede coördinatie tussen de krachten uitgeoefend op het voetenbord en de handel belangrijk is om vermogensverliezen aan snelheidsfluctuaties te minimaliseren. Door middel van een regressie analyse laat hoofdstuk 5 zien dat goede roeiers niet alleen in staat zijn tot het leveren van veel mechanisch vermogen en dus een hoge maximale zuurstofopname hebben, maar dat ze ook een goede techniek hebben, in ieder geval voor wat betreft het minimaliseren van de onvermijdelijke snelheidsfluctuaties.

In **Hoofdstuk 6** worden de vermogensverliezen aan de bladen nader bekeken. Speciaal hiervoor gemaakte sensoren werden toegepast om krachten parallel aan het blad te kunnen meten. Naast bladkrachten werd ook de vervorming van de riem gereconstrueerd. Het negeren van de parallelle bladkrachten bleek tot een substantiële onderschatting van de energieverliezen tijdens de afzet te leiden. Tevens bleek het berekende gemiddelde bladverlies niet af te hangen van aannames betreffende de stijfheid van de riem. De gereconstrueerde kinematica van het blad bleek echter substantieel te verschillen wanneer rekening gehouden werd met riemvervormingen. Dit hoofdstuk laat zien dat riemvervorming of parallelle bladkrachten in toekomstig roeionderzoek niet genegeerd zouden moeten worden.

In **Hoofdstuk 7** worden de conclusies van dit proefschrift gepresenteerd. Er wordt gesteld dat de aspecten van de mechanica en energetica van het roeien die in dit proefschrift behandeld worden verschillen in prestaties tussen roeiers kunnen verklaren. Er wordt echter ook gesteld dat veel aspecten van de mechanica en energetica van het roeien nog steeds niet volledig begrepen zijn. Het effect van het vastbinden van de roeier aan zijn bankje op de roeiprestatie bijvoorbeeld dient onderzocht te worden tijdens het 'echte' roeien op het water, evenals tijdens langere roei-inspanningen.

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Ondanks de bevindingen die beschreven staan in hoofdstuk 6, is de hydrodynamica rond de bladen nog steeds moeilijk te begrijpen. Het lijkt een goed idee om in de toekomst samen te gaan werken met een onderzoeksgroep die expertise heeft op dit onderzoeksgebied.

Om in staat te zijn om de optimale roeitechniek te vinden (het coördinatiepatroon dat resulteert in de hoogste gemiddelde bootsnelheid over de wedstrijdafstand), wordt een voorwaarts dynamische benadering gesuggereerd. Door een betrouwbaar model te maken en daarbij vervolgens verschillende parameters van het model systematisch bij te stellen kan een soort van gevoeligheid analyse uitgevoerd worden. Door de effecten op de prestatie te bestuderen kunnen aanwijzingen gevonden worden over die aspecten van de roeitechniek waaraan onderzoekers, roeiers en coaches het beste hun tijd kunnen besteden.

Dit proefschrift concludeert met de stelling dat ondanks de bekende spanningsvelden tussen de sportpraktijk en onderzoekslabs, toegepast sportonderzoek zoals beschreven in dit proefschrift vervolgt zou moeten worden en waar mogelijk geïntensifieerd. Het integreren van sport in wetenschappelijk onderzoek en vice-versa zal uiteindelijk gunstige resultaten opleveren voor beide partijen. Men moet daarom streven naar zowel goed onderzoek als goede sportprestaties, zodat dit uiteindelijk zal resulteren in zowel publicaties als medailles.

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DANKWOORD

Roeien is eigenlijk maar een rare sport. Hoe meer je je best doet, hoe harder je achteruit gaat… De afgelopen vijf jaar leek wetenschappelijk onderzoek doen soms best een beetje op roeien. Maar, er zijn meer parallellen te verzinnen.

Een roeier is niets zonder zijn coach. Gelukkig had ik een topcoach. Knoek; jij bent de afgelopen jaren echt een mentor voor mij geweest. Als ik in de afgelopen jaren ook maar een beetje van jouw enorme analytische vermogen heb overgenomen, dan zijn ze voor mij geslaagd. Ik hoop in de toekomst nog vaak samen met je te mogen werken. Als Knoek mijn coach was, dan was Jos misschien wel mijn manager. Jos: jij hebt me vooral ook de 'wereldse' kanten van de wetenschap bijgebracht. Dat het soms handig is bepaalde standpunten in een artikel iets subtieler te brengen. Maar ook dat het belang van netwerken niet te onderschatten is. Deze vaardigheden gaan me in de komende tijd vast van pas komen.
In de eindsprint van mijn project kreeg ik er nog een derde coach bij. Peter Hollander, zoals afgesproken was je in de eerste fase van mijn promotie vooral op de achtergrond aanwezig. In de eindfase dus ook meer op de voorgrond. Ik heb er bewondering voor hoe je vaak met een paar simpele opmerkingen precies de kern van de zaak weet te raken.

Elke roeier die wat bereiken wil heeft een sponsor nodig. Gelukkig had ik die in de vorm van TNO Industrie en Techniek. Zonder hun financiële injectie was mijn onderzoek nooit van de grond gekomen. Sytze en projectteam: bedankt. Het Personal Rowing Coach project is inmiddels afgesloten, maar wie weet komen we elkaar in de toekomst weer tegen.

Om hard te kunnen roeien is goed materiaal van cruciaal belang. Voor het doen van goed onderzoek geldt dit misschien nog wel meer. Dankzij Concept 2 Benelux kon ik altijd over de beste materialen beschikken. Jacques en Paul, heel erg bedankt voor het feit dat ik voor mijn project belangeloos gebruik kon maken van een prachtige skiff en diverse ergometers. Hiermee hebben jullie een belangrijke bijdrage aan de totstandkoming van dit proefschrift geleverd.

Dit mooie materiaal is vervolgens 'getuned' met vele sensoren. Gelukkig heb ik altijd de ondersteuning mogen genieten van een uitstekend team van technici. Allen zeer bedankt! Een viertal wil ik hier graag expliciet noemen:
Erik: elektronicus en klimmer. Dat eerste kwam vaak van pas als de meetboot weer

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eens kuren vertoonde. Dat tweede vooral toen de meetboot het onderzoekslab op de 6e etage ingetakeld moest worden. Omdat het ding acht meter lang is kon dit alleen via de gevel, en dan is het best handig als iemand verstand heeft van touwen en knopen.

Ook opvolger Guido bedankt. Nadat Erik vertrokken was naar een nieuwe baan heb jij je alle meetboot elektronica bijzonder snel eigen gemaakt, zodat ik me nooit zorgen hoefde te maken over technische ondersteuning tijdens de soms hectische meetperiodes.

Huybert, toen werkzaam bij de instrumentmakerij van het AMC: Zonder jou was er helemaal geen meetboot geweest. Voor een instrumentmaker is het wellicht een droom om tientallen sensoren te mogen ontwerpen en maken, af en toe leek het meer op een nachtmerrie. Wat kon er veel stuk aan die boot! En dan heb ik het nog niet eens over mijn standaardopmerking als jij weer een sensor af had: "Ja, eh, mooi, maarreh, kan het ook lichter?".

Hans! Als ik alles zou opschrijven dat jij voor al mijn projecten en projectjes gemaakt en gedaan hebt, dan wordt dit een heel lang dankwoord. De huidige versie van de SuperSeat is van jouw hand bijvoorbeeld. Voor mij een voorbeeld van een prachtig staaltje perfect functionerende eenvoud. Zouden er in 2012 in Londen Nederlandse roeiers varen met jouw creatie onder hun kont?

Roeiers en coaches zijn vaak heel erg op hun doel gefocussed. Het is daarom goed als ze mensen in hun omgeving hebben die een brede(re) visie hebben. Ook hier is weer makkelijk een parallel te trekken. Een drietal mensen met visie wil ik hier graag noemen:

Gery: als toenmalige innovatie coördinator bij NOC*NSF heb je ervoor gezorgd dat ik voor één dag in de week gedetacheerd kon worden bij de Nederlandse roeibond. Zo kwam het voor dat ik in één jaar in de koude wintermaanden een aantal keer naar zuid-Spanje of Portugal mocht vliegen om daar de roeiers wetenschappelijk bij te staan. Niet vervelend natuurlijk, maar veel belangrijker is dat deze detachering zorgde voor een permanente koppeling van mijn project met de roeipraktijk.

Koen: topsportcoördinator bij de roeibond. Bedankt voor het inzien van het belang van wetenschap in de (roei)sport. Als niet roeier in een soms conservatieve omgeving kan ik me voorstellen dat het vaak moeilijk was anderen te overtuigen van het belang van innoveren. Ik ben blij dat je dit wel gedaan hebt. Jammer dat je weggaat bij de KNRB.

Peter Beek: dank voor het in mij gestelde vertrouwen het afgelopen jaar. Ondanks deze 'moeilijke tijden' heb je me toch een baan aangeboden. Ik ga mijn uiterste best doen om met mijn onderzoek een succesvolle bijdrage aan NeSSI te doen. Ik heb daar alle vertrouwen in!

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Een atleet gedijt het best in een goede omgeving. En dat gaat natuurlijk net zo hard op voor een promovendus. Een groep leuke collega's, waarvan ik er inmiddels een heel aantal mijn vrienden mag noemen, heeft ervoor gezorgd dat ik over mijn omgeving niets te klagen heb gehad.

Johan, bedankt voor de leuke tijd in A617 én daarbuiten. Ik denk dat onze wetenschappelijke discussies op één hand te tellen waren, wat niet gezegd kan worden over onze discussies over vrouwen, bier en wielrennen (to name a few). Ik hoop je gauw op te komen zoeken in Zwitserland. Ik ben er trots op dat je mijn paranimf wilt zijn.

Menno, gelukkig blijf jij wel in Nederland. Bovendien ben je nu ook weer mijn kamergenoot tussen de professoren. Alhoewel we in sommige opzichten misschien wel tegenpolen zijn; jij: rustig en beheerst, ik: ...niet echt, klikt het bijzonder goed tussen ons. Ik ben er trots op dat je mijn paranimf wilt zijn.

Ook Melanie, Kerry, Alistair, Jan-Willem, Teatske, Astrid, Paulien, Marcel, Floor, Margot, Martijn: Bedankt voor de support, interesse en gezelligheid.

Aan het einde van de 'race' is er dan dit proefschrift; de bundeling van vijf jaar werk. Alhoewel het natuurlijk vooral om de inhoud gaat, is het leuk als het er ook een beetje mooi uitziet natuurlijk. Naar mijn mening is dat in dit geval bijzonder goed gelukt. Barbara, dank voor het design, Jonathan (met hulp van Alistair) bedankt voor het maken van de mooie coverfoto, en Willem Jan, bedankt dat je durfde te poseren.

De kans dat iemand een goede atleet wordt, wordt voor een heel groot deel bepaald door de genen die hij van zijn ouders mee krijgt. Of dit ook opgaat voor promovendi weet ik niet, maar pa en ma, heel erg bedankt voor alle steun die ik kreeg en voor alle interesse die jullie toonden in de afgelopen 5 32 jaar.

En dan tenslotte, het thuisfront. Froukje, love of my life! Bedankt dat je het al bijna 14 jaar met me weet uit te houden. Bedankt voor je interesse en steun, vooral ook als ik soms zwaar gestrest thuis kwam na een hectische periode van meten. Met net een huis en een kind gaan we een hele nieuwe fase van ons leven in. Ik heb er zin in!

Fleur: ik kan me nu nog niet voorstellen dat je ooit zo oud bent dat je kan begrijpen wat je pa in deze dik 150 pagina's heeft opgeschreven. Jou te mogen zien opgroeien is misschien wel de allermooiste race.

Mathijs