Power in Rowing

In search of effective feedback variables

Lotte L. Lintmeijer

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"*The farther backward you can look, the farther forward you can see.*"

Winston Churchill

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List of Symbols

$\vec{F}_{s,r}$	Vector of seat force acting on buttocks of the rower	N
$\vec{F}_{f,r}$	Vector of foot stretcher force acting on the rower's feet	N
$\vec{F}_{o,r}$	Vector of oar handle force acting on the rower's hands	N
$\vec{F}_{w,o}$	Vector of the net water force vector acting of the oar blade	N
$\vec{F}_{g}$	Vector of gravitational force acting on the rower's centre of mass	N
$\vec{M}_{F_{o,r}}$	Moment vector of $\vec{F}_{o,r}$ relative to oar pin	N m
$\vec{\Phi}_{b/w}$	Oar angular vector of the blade relative to its neutral unloaded position	rad
$\vec{\Phi}_{o/b}$	Oar angular vector relative to the boat	rad
$\vec{\omega}_{o/b}$	Oar angular velocity vector relative to the boat	rad s^{-1}
$\vec{a}_{rcom/w}$	Acceleration vector of the rower's centre of mass relative to the world	m s^{-2}
$\vec{a}_{rcom/b}$	Acceleration vector of the rower's centre of mass relative to the boat	m s^{-2}
$\vec{v}_{rcom/w}$	Velocity vector of the rower's centre of mass relative to the world	m s^{-1}
$\vec{v}_{b/w}$	Velocity vector of the boat relative to the world	m s^{-1}
$\vec{v}_{o/w}$	Velocity vector of the oar handle relative to the world	m s^{-1}
$\vec{v}_{s/w}$	Velocity vector of seat relative to the world	m s^{-1}
$\vec{l}_{i}$	Position vector of the point of application of $\vec{F}_{o,r}$ relative to the pin	m
$\vec{l}_{o}$	Position vector of the point of application of $\vec{F}_{w,o}$ relative to the pin	m
$\vec{r}_{PoA/w}$	Position vector of the point of the blade where the point of application is located at that time moment relative to the world	m
$\dot{\vec{r}}_{PoA/w}$	Time derivative of $\vec{r}_{PoA/w}$	m s^{-1}
$\vec{r}_{i}$	the moment-arm from location *i* on the oar shaft to location *i-1* on the oar shaft in an earth-bound frame of reference	m
M_i^z	The bending moment at location i of the oar shaft.	N m
$\Delta^y_{oar_i}$	The y-component of the position of location *i* in the loaded situation relative to its location in the unloaded position	m
P_{rower}	Instantaneous mechanical power output generated by the rower relative to an earth-bound frame of reference	W
$\overline{P}_{rower}$	The cycle average of P_{rower}	W
$\overline{P}_{residual}$	The difference between the true average mechanical power output and average power output using the common proxy. Can be expressed as the cycle average of $-m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}$	W
$\overline{P}_{proxy}$	Estimation of a rower's average mechanical power output using the common proxy; i.e., the cycle average of $\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}$	W

P_{blade}	Power loss due to the generation of propulsion	W
$\overline{P}_{blade}$	The cycle average of P_{blade}	W
$\overline{P}_{\Delta v}$	Power loss due to boat velocity fluctuations averaged over a stroke cycle	W
P_{defl}	Power output due to the deflection of the oar shaft	W
ΔE_{rower}	Change of rower's kinetic energy over a stroke cycle	J
m_r	mass of the rower	kg
T	Time duration of a stroke cycle	s
$ratio_{res./rower}$	Ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$	
$\overline{P}\Delta v_{stroke}rel$	The actual average power loss to boat drag per stroke cycle, relative to the hypothetical power loss associated with a constant speed based on the average velocity of that stroke cycle	
CoM	Centre of mass	
PoA	Point of application	
S	The beginning of the blade	
E	The end of the blade	

Dutch Preface (Voorwoord)

Toen ik een jaar of 15 was opperde mijn moeder om te gaan roeien. Ze had er zelf in haar jonge jaren erg veel plezier aan beleefd totdat zij samen met haar tweelingzus op haar hoofd in een skiff ging staan. Vanaf die dag waren beiden niet meer welkom op de vereniging.

'Roeien?' Dat leek mij nou de saaiste sport die ik kon bedenken. Ik fietste elke dag al 24 km heen en terug naar school en dan moest ik ook nog eens een simpele eentonige cyclische beweging op het water gaan maken: achteruit wel te verstaan.

Vijf jaar later schreef ik mij in bij de roeivereniging 'Orca' in Utrecht. Ik was op zoek naar een vereniging waar je kon sporten en vooral feesten. Ik kwam in een ploegje met dames van mijn lengte en realiseerde me al snel dat ik minstens 15 kg te licht was om hetzelfde vermogen te leveren als mijn ploeggenoten. Nadat ik een keer achteloos had laten vallen dat ik 'dat sturen wel geinig vond' werd ik uitgenodigd voor de stuurselectie en voordat ik het wist stuurde ik een wedstrijdboot. Vier keer per week sturen werd zes keer per week en op den duur werd het sturen coachen.

Tijdens mijn onderzoeksmaster 'Psychologie' aan de Utrecht Universiteit realiseerde ik me dat mijn weken bestonden uit ongeveer 50 % studeren en 50 % coachen. Het leek me efficiënt om dat te combineren en zo kwam ik op een masterthesis waarin ik de effecten van sport op angst en depressieklachten bij studenten onderzocht.

Mijn droombaan was onderzoek doen op het gebied van sport, prestatie en welzijn. Rond juni 2013 zag ik toevallig een vacature voor een onderzoeker (PhD) op het gebied van biomechanica van het roeien en het efficiënt aanleren van de roeibeweging. Ondanks dat ik geen achtergrond had in natuurkunde of bewegingswetenschappen waagde ik de gok. Tijdens het eerste sollicitatiegesprek vielen er twee dingen op: ik had geen idee wat de wetten van Newton waren en ik werd uitgedaagd om extra kritisch te zijn over het onderzoeksvoorstel.

Nu ligt hier een boekje over een onderwerp waarvan ik 17 jaar geleden lacherig zei dat het me intens saai leek. Roeien is inderdaad een cyclische beweging, maar roeiers zelf weten dat het aanleren van de techniek en de fysieke ontwikkeling jaren van intensieve training vergt.

Na deze thesis weet ik dat het begrijpen van een roeiprestatie en hoe deze kan worden verbeterd nog veel meer tijd kost. De combinatie van (1) de interactie tussen de roeiers en de boot, (2) de coördinatie tussen roeiers onderling, en (3) de complexe waterstromen rondom het roeiblad en de boot, maken het begrijpen van de roeiprestatie een lastige puzzel. Euler [21] en Alexander [3] legden al meer dan een eeuw geleden een wetenschappelijke basis voor de oplossing van die puzzel. Door steeds betere technologieën die het mogelijk maken om de kinetica en kinematica van het roeien in kaart te brengen vallen steeds meer puzzelstukken op hun plek. In deze thesis ga ik verder op dit spoor door methodes te ontwikkelen om belangrijke parameters voor de roeiprestatie in de dagelijkse praktijk te identificeren, te meten en terug te koppelen als feedback.

Chapter 1

General Introduction

"August 13^{th}, 2016 – Six boats are at the start of the Olympic final of the men's single sculls: a race in which the best heavy-weight male rowers from across the world compete over a race length of 2000 m. The two absolute favourites are the four-times world champion Ondréj Synek (Czechia) and the defending Olympic champion Mahé Drysdale (New Zealand), but it is Damir Martin (Croatia) who leads the first 1250 meter of the race in front of Synek (2^{nd}) and Drysdale (3^{rd}). After 1250 meter, Drysdale slowly starts to take over the leading position, but neither Synek nor Martin are giving up. The race ends in an exciting battle between Martin and Drysdale. The official clock shows that both rowers have finished in exactly the same time (6.41.34 min). A photo finish (see Figure 1.1) let the judges decide that Drysdale was just marginally (less than one 5000^{th} of a second) ahead of Martin."

1.1 Introduction

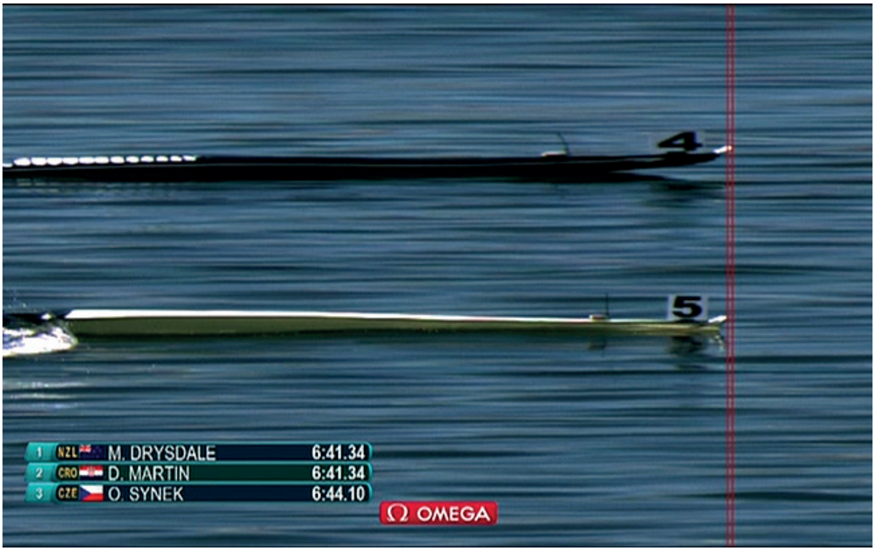

Figure 1.1. The photo finish of Mahé Drysdale (top) and Damir Martin (bottom) in the final of the men's single sculls final of the Olympic Games 2016 (source: BBC screenshot)

The race described on the previous page might have been one of the closest official finishes known in the history of competitive rowing. However — as in other cyclic sports — it is not uncommon that races are decided within very small margins. For example, four years earlier, four quadruple boats (i.e. four rowers in a boat with two oars each) were competing for the Olympic gold medal in the last 250 m of the race. South Africa, Great Britain and Denmark all finished within four tenths of a second. Australia just missed the bronze medal. Although the time differences between winning and losing a race can be marginal, the emotional — and in some cases financial — consequences can be major. To increase the chances of winning a medal, rowers and coaches are motivated to continuously search for means to improve performance — a search that can benefit from scientific knowledge and methods.

Many scientific studies have aimed to understand and improve rowing performance. The first one dating back as far as 1773. In this study, Euler [21] theoretically explained the mechanical principles of rowing. In 1925, Alexander [3] came up with an improved model to explain rowing performance. His model was enriched with first data on forces and velocities collected during on-water training sessions. With the increase of technological possibilities, the number of studies on rowing performance have grown exponentially. Despite this extensive base of research, coaches and rowers working in the field commonly lack relevant information and tools to improve performance effectively. This lack of information is partly due to inconclusive and/or contradictory results of studies, and partly due to problems in applying theoretical knowledge to (competitive) rowing practice.

The overarching aim of this thesis is to use scientific knowledge and technological advances in order to develop and evaluate innovative tools that contribute to the understanding and improvement of (individual) rowing performance. To this end, practical experience and knowledge, and multidisciplinary research are combined to ensure that the results contribute to both the practical and the scientific (rowing) community.

1.2 Rowing performance

Rowing regattas are usually held over a course of 2000 m. The races take place in boats with one, two, four, or eight rowers, in either sweep (one oar per rower) or sculling (two oars per rower) boats. As speed is at the essence of competitive rowing, performance can be quantified as the average boat velocity over a race distance. With repeated cycles of strokes, rowers discontinuously push-off from the water to bring and keep the boat in motion (see Figure 1.2 for an explanation of the rowing technique). In order to achieve a high boat velocity and thus a good rowing performance, the push-off needs to be powerful and efficient. This means that rowers' physical power and an optimal intrapersonal (and in the case of more than one rower interpersonal) movement coordination are crucial for realising a high average boat velocity.

Figure 1.2. The rowing technique during the stroke phase. The stroke phase starts with the catch when the rower puts the blade(s) in the water (A). Subsequently, (s)he pushes against the water by first extending the knees while pulling the oar with extended arms (B), then extending the hip (C) and ending with flexing the elbows (D). The stroke phase finishes when the rower puts the blade(s) out of the water (E). (source: Ellen de Monchy)

1.3 Improving rowing performance: the need for effective augmented feedback

To optimise rowing performance, rowers thus need to improve both their physical power as well as their intra- and interpersonal movement coordination. In the present thesis, I will confine myself to physical power and intrapersonal coordination, leaving interpersonal coordination aside.

In previous decades, improvements in rowing performance were brought about by increasing the number of training hours [24]. However, nowadays, rowers already train with such high training intensity and frequency that the number of training hours cannot be increased much more without running serious risks of injuries and overtraining (e.g. [61, 88]). Therefore, the focus should shift towards increasing the efficiency of training hours rather than of their quantity.

Augmented feedback plays a crucial role in the efficiency of training as it facilitates the acquisition of motor skills as well as the improvement of those skills (for reviews see, e.g., [62, 73, 79, 95]). Augmented feedback is defined as "any additional information provided to the athlete over and above what they gain intrinsically from their performance" ([76] in [69], p. 920). Examples of augmented feedback in rowing are verbal feedback on the movement of the boat provided by the coach, or digital feedback about stroke rate (number of strokes min^{-1}) provided by a display mounted on the boat. To ensure that augmented feedback (from now on referred to as 'feedback') indeed accelerates the acquisition and improvement of motor skills leading to performance improvements, feedback can be evaluated using the model of Philips, Farrow and Ball [69] which posits that variable(s) selected for feedback must adhere to the following criteria:

1. The variable must be a key variable related to improved performance.
2. The variable must be accurately and reliably measured by a system.
3. The variable must be able to be adapted or adjusted by the athlete.

The last criterion can be interpreted in two ways:(1) that the value of the variable should be a consequence of an athlete's movements or (2) that athletes should be able to adjust the variable based on feedback on this variable. Both aspects are crucial for effective feedback:

1. The variable must be able to be adapted or adjusted by the athlete.
    (a) The variable should be a consequence of an athlete's movements.
    (b) Feedback on the variable should enable athletes to improve the variable.

Following these criteria, the effectiveness of the available feedback variables in current rowing practice can be questioned. Consider, for example, the feedback variables intended to improve physical power. Physical power can be improved by training at different training intensities and these intensities, in turn, can be quantified as the rate of metabolic energy consumption [7, 60, 83, 84]. However, it is nearly impossible to provide (accurate) regular feedback on this quantity. Alternatively, rowers receive digital and verbal feedback on variables that are related to their training intensity, such as stroke rate, boat velocity, and/or heart rate frequency. However, as explained in **Chapter 5** of this thesis, those variables are invalid measures of training intensity as they are also affected by factors unrelated to metabolic energy consumption, such as the number of rowers in the boat or weather circumstances. The effectiveness of the feedback variables for improving intrapersonal movement coordination is even more questionable. This type of feedback is usually provided verbally and based on coaches' observations of boat motions and movement of the rowers. These observations lack precision due to, among other aspects, the distance between the coaches and rowers during the observation. Additionally, the actual key performance variables for intrapersonal movement coordination are rather unclear. To provide practice with effective feedback variables that adhere to the aforementioned criteria, new methods to accurately determine feedback variables need to be developed and tested, as well as tools that enable real-time feedback on those variables.

1.4 Outline of the thesis

The overarching aim of this thesis is to develop and evaluate methods and tools that contribute to the understanding and improvement of rowing performance. To accomplish this aim, this thesis starts with selecting key performance variables for rowing, based on a biophysical framework. Subsequently, and related to the second criterion of Phillips et al. [69], methods to determine key performance variables are developed and evaluated. Moreover, and with regard to the third criterion of Phillips et al. [69], it is evaluated whether these performance variables can indeed be used as effective feedback variables. To provide feedback on key performance variables a feedback tool has been developed.

1.4.1 Selection of key performance variables: a theoretical framework

Based on a biophysical framework — the so-called power balance for rowing [33, 89] — two key performance variables have been defined for rowers' physical power and intrapersonal movement coordination: (1) mechanical power output and (2) associated power losses. The advantage of this model compared to other models (see, e.g., [4, 5, 44, 93]) is that it provides information about how and to what degree the key performance variables are related to rowing performance (i.e. average boat velocity) instead of only information about which aspects correlate with performance. Moreover, this unifying model does not only provide better insight into rowers' physical power and intrapersonal movement coordination separately, but also in its combined effect on rowing performance.

In short, the power balance states that a rower exchanges mechanical power output with the boat plus oar(s) system to overcome water drag and generate velocity. As a rower's average mechanical power output per stroke cycle (from now on called average power output) is strongly related to a rower's rate of metabolic energy consumption [35], it is an objective measure for physical power. Part of this average power output, however, does not contribute directly to the average boat velocity (i.e. rowing performance) and can be seen as 'power loss'. This power loss can be split up into two factors. A small part of this power loss can be attributed to a rower's movements relative to the boat in combination with the discontinuous push-off [33]. These inherent rowing aspects cause large fluctuations in boat velocity. As the power dissipated by water drag is related to boat velocity cubed, it is most efficient to row at a constant speed (see Figure 1.3; [17, 34, 74]). The larger part of the power loss can be attributed to the generation of propulsion. Since rowers push off against water, water around the blade will brought into motion as well. This means that kinetic energy is transferred to the water that does not directly contribute to the average boat velocity [12, 36, 51]. As the rower is the only source of power in the boat, (s)he will provide this energy. Adjustments of the intrapersonal movement coordination most certainly affect the amount of power that is lost due to those inherent rowing aspects (see Figure 1.4 for a schematic overview of the power balance; see [33] for an extended overview of the power balance of rowing).

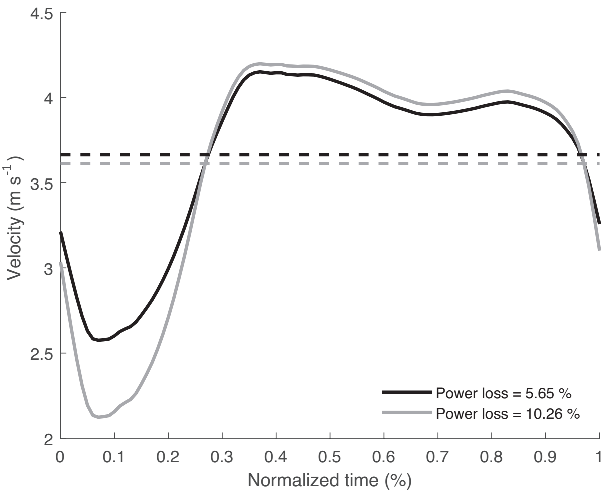

Figure 1.3. The effect of different velocity patterns (black and grey lines) on average boat velocity (dashed black and grey line) when rowing with the same average power output.

It follows from the power balance that rowers can improve performance by increasing their average power output and/or by decreasing their power losses. Power output in turn can mainly be increased by physical power, while power losses can be decreased by improving intrapersonal movement coordination. However, there is no evidence that average power output and power losses can be used as *effective* feedback variables: as of yet, (1) most of the variables cannot be determined accurately during on-water rowing and (2) it is unknown whether feedback on power variables enables rowers to adjust and master them.

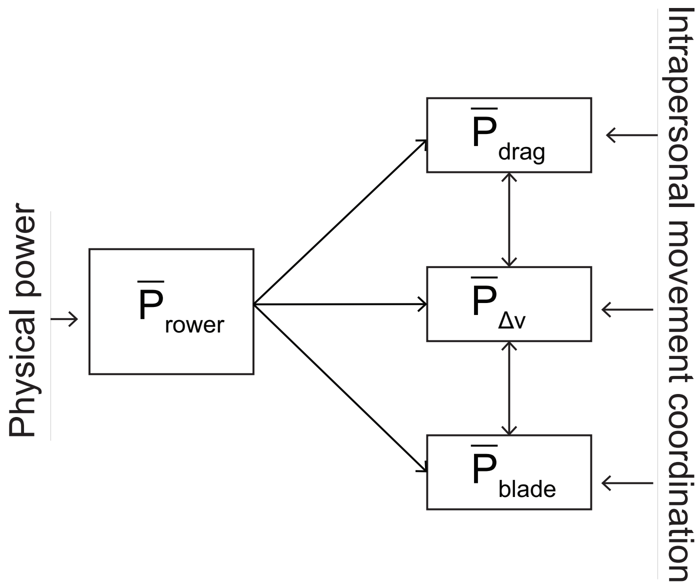

Figure 1.4. Schematic overview of the power balance for rowing and its relation with physical power and intrapersonal movement coordination, where $\overline{P}_{rower}$ is the average power output of a rower per stroke cycle. $\overline{P}_{drag}$, $\overline{P}_{\Delta v}$ and $\overline{P}_{blade}$ are the average power dissipated by water, the power loss due to velocity fluctuations and the power loss due to the generation of propulsion, respectively.

The following chapters aim to provide more insight into the potential of power variables as effective feedback variables for the rowing practice, whereby the main focus will be on the use of power output as an effective feedback variable (see **Chapter 2-5**). **Chapter 6** and **7** will focus on the effectiveness of power losses as feedback variables.

1.4.2 Power output as a feedback parameter

In previous research (e.g. [1, 2, 4, 8, 11, 12, 18, 22–24, 26, 28]) as well as in recently developed devices that determine power in rowing practice (i.e. the Empower Oarlock; Nielsen kellerman, Broothwyn, PA), power output has been determined from oar forces and oar movements alone. In **Chapter 2**, it is shown that this is incorrect. Alternatively, and in agreement with the second criterion of Phillips et al. [25] introduced before, a valid method is developed to calculate 'true' average power-output values. Moreover, using a simulation model, an indication of the difference between the true power-output values and the values calculated according to the most wide-spread method to determine power output (i.e. calculating the product of the moment around the oar and its angular velocity; e.g. [2, 5, 19, 71]) is provided.

It follows from **Chapter 2** that — in order to determine 'true' power-output values — the rower's horizontal centre of mass (CoM) acceleration is required. **Chapter 3** examines whether this CoM acceleration can be accurately obtained using 13 inertial sensors placed on different body segments in combination with a mass distribution model suggested by Zatsiorsky [99]. Using the method provided in **Chapter 3**, the difference in average power-output values calculated according to the commonly used method and 'true' power-output values is quantified for different rowers and different rowing conditions during on-water rowing in **Chapter 4**. The results of this experiment do not only provide an exact indication of the difference between true power-output values and power-output values calculated using the commonly used proxy, but also the effect of rowing with varying techniques and stroke rates on this difference.

Chapter 2-4 describe a new method to accurately determine average power output, but it does not yet imply that feedback on power output also enables rowers to control and adjust their delivered power (see criterion 3B) [69]. It follows from multiple motor learning studies that 'knowledge of results' feedback (i.e. feedback that provides information about the consequences of a rowers movement sequence) effectively and even automatically changes movement patterns in order to improve performance (see for reviews e.g. [62, 95, 97]). However most — if not all — of these studies included individual tasks. This means that conclusions of these studies cannot be simply generalised to crew rowing in which rowers have to coordinate their movement patterns with those of other crew members. In **Chapter 5** it is therefore examined whether feedback on average power output enables crew rowers to adapt and adjust their individual power output, despite of the movement limitations associated with crew rowing. To allow for real-time feedback on average power output while rowing, a feedback tool has been developed, which is described in the **Appendix**.

1.4.3 Power losses as feedback parameters

It follows from the power balance that average power output is not the only determinant of rowing performance. The part of power output that is lost to velocity fluctuations during a stroke cycle and the generation of propulsion during the stroke is crucial for performance as well. Rowers most likely can reduce these power losses by changing their intrapersonal movement coordination. However, it is as of yet unclear which aspects of their intrapersonal movement coordination should be adapted in order to accomplish this effectively. Knowledge of results feedback on such power losses may help rowers to reduce power losses without emphasising specific aspects of a rower's movement coordination.

Although power loss due to velocity fluctuations (1) is shown to be an important variable in explaining rowing performance and (2) can be determined with relative ease [33], it is uncertain whether feedback on this power loss can enable rowers to reduce it. This is because the movement sequence to reduce power loss due to velocity fluctuation consists of multiple degrees of freedom, whereas the variability in this power loss is relatively small (i.e. around 4 to 8 % of the average power output for single scull boats; own data). It is therefore uncertain whether feedback on power loss due to velocity fluctuations provides sufficient information to enable rowers to reduce this power loss. **Chapter 6** contains an evaluation of whether feedback on power loss due to velocity fluctuations will enable rowers to reduce this power loss, despite of the aforementioned reservations.

In **Chapter 7**, the focus is on the other power loss term: the power loss due to the generation of propulsion. In contrast with the power loss due to velocity fluctuations, power loss due to the generation of propulsion during on-water rowing cannot be readily determined. Previous studies rely on unrealistic assumptions [12] and/or too bulky systems [33] that cannot be used regularly. However, since this power loss has been estimated to be much higher than the power loss due to velocity fluctuations (i.e. > 20 %; [2, 34, 36, 51]), it is worth developing a practical method to accurately determine this power loss. Therefore, in **Chapter 7** a light-weight, cost-effective method is presented to determine crucial parameters that are required to assess the power loss due to the generation of propulsion.

In **Chapter 8**, the main results of this thesis are summarised and reviewed. Additionally, directions for future research are discussed, as well as the possibilities for implementation of the results and tools being developed in competitive rowing practice and beyond.


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Chapter 2

Mechanical power output in rowing should not be determined from oar forces and oar motion alone

Based on:
Hofmijster, A.J., **Lintmeijer, L.L.**, Beek, P.J., van Soest, A.J. Mechanical power output should not be determined from oar forces and oar motion alone. Journal of Sports Science, **36**, 2147-2153. DOI:10.1080/02640414.2018.1439346 (2018).

Mechanical power output is a key performance-determining variable in many cyclic sports. In rowing, instantaneous power output is commonly determined as the dot product of handle force moment and oar angular velocity. The aim of this study was to show that this commonly used proxy is theoretically flawed and to provide an indication of the magnitude of the error. To obtain a consistent data set, simulations were performed using a previously proposed forward dynamics model. Inputs were previously recorded rower kinematics and horizontal oar angle, at 20 and 32 strokes min^{-1}*. From simulation outputs, true power output and power output according to the common proxy were calculated. The error when using the common proxy was quantified as the difference between the average power output according to the proxy and the true average power output (*$\overline{P}_{residual}$*), and as the ratio of this difference to the true average power output (*$ratio_{res./rower}$*). At stroke rate 20,* $\overline{P}_{residual}$ *was 27.4 W and* $ratio_{res./rower}$ *was 0.143; at stroke rate 32,* $\overline{P}_{residual}$ *was 44.3 W and* $ratio_{res./rower}$ *was 0.142. Power output in rowing appears to be underestimated when calculated according to the common proxy. Simulations suggest this error to be at least 10 % of the true power output.*

2.1 Introduction

Performance in many cyclic sporting activities critically depends on the mechanical power output that can be sustained for the duration of the race [89]. Mechanical power output is thus an important variable to be monitored and/or controlled both during training and competitive events. As an example of the importance of this, cyclists now routinely use a power monitor during both training and racing [43]. In training situations, (instant) mechanical power-output feedback may help the athlete to exercise at the intended intensity and to prevent over- or undertraining, whereas during competition mechanical power-output feedback may be used to optimise race pacing [6].

Determining the mechanical power exchange between an athlete and the environment is relatively straightforward: it can be achieved by obtaining the external forces acting on the athlete and the velocities of the points of application of these forces. In cycling for example, several systems exist to measure pedal force (or, equivalently, the moment of this force relative to the crank axis) and pedal velocity relative to the bicycle frame (or, equivalently, the angular velocity of the crank). The net mechanical power production over a complete cycle can then be determined by calculating the product of pedal force and velocity, and averaging this over a complete cycle. In rowing, mechanical power output is commonly estimated using a similar approach (e.g. [5, 19, 71, 98]). In particular, the average mechanical power output is determined as the stroke-cycle average of the product of the oar angular velocity in the horizontal plane ($\vec{\Phi}_{o/b}$) and the moment of the oar handle force relative to the oar pin ($\vec{M}_{F_{o,r}}$; see Figure 2.1 for a schematic representation; see List of Symbols for an overview of the definitions of all abbreviations in the text).

Unfortunately, in contrast to cycling, this method for estimating the mechanical power output of a rower is incorrect. The following thought experiment is elucidating in this regard. Consider a rower in a boat without oars, with the feet attached to the foot stretcher. Now assume that this rower moves back and forth in the boat in a strictly periodic fashion. In steady state, this will result in periodic back and forth motion of the boat relative to the world. This implies that the free body "rower plus boat" is in the exact identical state at the beginning of each cycle, and hence there is no net kinetic energy change over a full cycle. The resulting motion of the boat relative to the world will result in a frictional force of the water on the boat, which is always opposing the boat

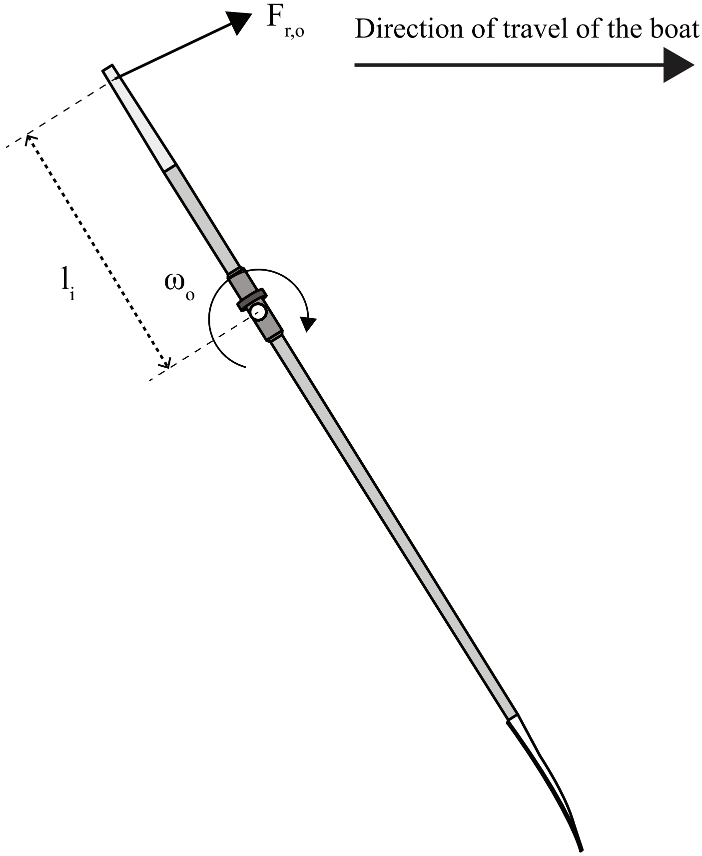

Figure 2.1. Schematic diagram of the oar. Force from the rower at the oar handle is indicated by $\vec{F}_{r,o}$. Note that $\vec{F}_{r,o} = -\vec{F}_{o,r}$, $\vec{F}_{o,r}$ being the force from the oar handle at the rower. $\vec{l}_i$ represents the position vector of the point of application of $\vec{F}_{r,o}$ relative to the oar pivot (pin). Note that the moment of the oar handle force relative to the oar pin ($\vec{M}_{F_{o,r}}$) is determined according to $\vec{M}_{F_{o,r}} = \vec{l}_i \times \vec{F}_{o,r}$.

velocity. Hence, power will be dissipated by water friction. It is evident that in steady state, the (negative) average power dissipated by the frictional force must be equal and opposite to the (positive) average mechanical power delivered by the rower. It is also evident that, due to the absence of a moment of the handle force, the mechanical power output of the rower — according to the standard method described above — is zero. Thus, the standard method for calculation of the mechanical power delivered by the rower must be incorrect.

It is easy to identify the flaw in the standard method by considering how the rower delivers power to the boat in our thought experiment: the rower exerts a force on the boat at the foot stretcher, and because the velocity of the foot stretcher relative to the world is nonzero, the mechanical power of this force is nonzero as well. Thus, because the boat is moving (and as we shall argue in this thesis, in particular because it is moving at a non-constant velocity while the rower simultaneously moves relative to the boat), the true mechanical power delivered by the rower is not equal to what is calculated using the standard method. Thus, the standard method only provides a proxy of the rower's mechanical power output, while it is not immediately clear how good this proxy is.

The flaw described above has been recognised before by Kleshnev [49], who, based on experimental data, reported that true power output was on average over 16 % larger than power output calculated according to the common proxy. This finding, however, is neither widely recognised in the scientific community, nor in rowing practice. Kleshnev derived true power output from foot stretcher and oar forces, but only provided limited detail about the experimental procedure. Since those forces during the stroke cycle are high and opposing, relatively small errors in sensor accuracy potentially have large implications for the calculated true power. Errors in sensor readings might add up, which may well result in a low signal-to-noise ratio of the resultant signal, as this signal itself is much closer to zero. Thus, we propose to determine the error in the proxy using a modelling and simulation approach, in which measurement inaccuracies play no role. Note that the main goal for performing these simulations is to obtain a data set that provides a fully consistent description of all relevant kinematic and kinetic variables during on-water rowing; in the context of the question addressed in this study, the internal consistency is more important than a high level of similarity between simulation results and experimental data. In this largely theoretical paper, we will derive an expression to determine the average true mechanical power output starting from the general power equation, as described by van Ingen Schenau [89]. Next, we will show that this expression is not equal to the commonly used proxy for the rower's mechanical power output, i.e., the cycle average of $\vec{M}_{F_{o,r}} \cdot \dot{\vec{\Phi}}_{o/b}$, and we will derive an expression for the difference. As the practical relevance of the theoretical results depends on the magnitude of this difference, we will subsequently use an existing model of the dynamics of rowing to obtain an indication of the magnitude of this difference.

2.2 Methods

2.2.1 Theory

The instantaneous mechanical power production of an athlete ($P_{athlete}$) can be determined in an inertial frame of reference according to [89]:

$$P_{athlete} = -\sum \vec{F}_{ext} \cdot \vec{v}_{ext} - \sum \vec{M}_{ext} \cdot \vec{\omega}_{ext} + \sum dE_{kin}/dt. \tag{2.1}$$

In this equation, $\sum \vec{F}_{ext} \cdot \vec{v}_{ext}$ is the sum of the dot products of all external forces acting on the athlete and the velocities of their respective points of application with respect to the frame of reference. $\sum \vec{M}_{ext} \cdot \vec{\omega}_{ext}$ is the sum of the dot products of all external pure moments acting on the athlete and the rotational velocities of the body segments on which these moments act. $\sum \vec{F}_{ext} \cdot \vec{v}_{ext}$ and $\sum \vec{M}_{ext} \cdot \vec{\omega}_{ext}$ describe the mechanical power exchanged with the environment. $\sum dE_{kin}/dt$ is the time derivative of the sum of kinetic energy of all body segments.

When Equation 2.1 is applied to a rower, we observe that no pure moments act on the rower; external forces are acting from the seat on the rower ($\vec{F}_{s,r}$), from the foot stretcher on the rower ($\vec{F}_{f,r}$), from the oar handle on the rower ($\vec{F}_{o,r}$) and from gravity on the rower ($\vec{F}_g$). Figure 2.2 shows a simplified description of the free body diagram of the rower. The equation of motion can be written as:

$$\vec{F}_{f,r} + \vec{F}_{o,r} + \vec{F}_{s,r} + \vec{F}_g = m_r \cdot \vec{a}_{rcom/w}. \tag{2.2}$$

Here, m_r represents the mass of the rower and $\vec{a}_{rcom/w}$ represents the acceleration of the rower's centre of mass relative to the world.

Adopting a frame of reference that is fixed to the world, the point of application of $\vec{F}_{f,r}$ has velocity $\vec{v}_{b/w}$, which is the velocity of the boat relative to the world.

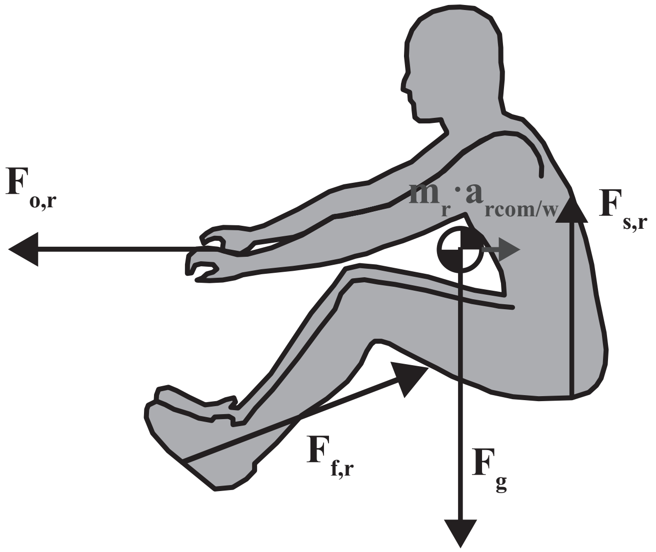

Figure 2.2. Schematic diagram of the rower, showing all external forces: force from the oar handle to the rower ($\vec{F}_{o,r}$), force from the foot stretcher to the rower ($\vec{F}_{f,r}$), force from the seat to the rower ($\vec{F}_{s,r}$), the gravitational force ($\vec{F}_g$) as well as the resultant force ($m_r \cdot \vec{a}_{rcom/w}$).

The velocity of the point of application of $\vec{F}_{o,r}$ relative to the world is indicated by $\vec{v}_{o/w}$, the velocity of the point of application of $\vec{F}_{s,r}$ relative to the world is indicated by $\vec{v}_{s/w}$. $\vec{F}_g$ acts at the centre of mass of the rower; the velocity of the rower's centre of mass relative to the world is indicated by $\vec{v}_{rcom/w}$. In an earth-bound frame of reference, the general instantaneous power equation for the rower thus reads:

$$\begin{aligned} P_{rower} = & -\vec{F}_{f,r} \cdot \vec{v}_{b/w} - \vec{F}_{o,r} \cdot \vec{v}_{o/w} - \vec{F}_{s,r} \cdot \vec{v}_{s/w} \\ & -\vec{F}_g \cdot \vec{v}_{rcom/w} + \sum dE_{kin}/dt. \end{aligned} \tag{2.3}$$

If we assume that the seat only moves in the horizontal direction and that frictional forces on the seat are negligible, then there is no mechanical power exchange at the seat. In steady-state rowing, there is no net change in kinetic energy over a full rowing cycle. Similarly, the cycle-average power of the force of gravity is zero because the vertical coordinate of the centre of mass has the same value at the start of each rowing cycle. Taking these considerations into account, we find that the power equation of rowing, averaged over a complete stroke cycle with period T in steady state conditions reads:

$$\overline{P}_{rower} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-\vec{F}_{f,r} \cdot \vec{v}_{b/w} - \vec{F}_{o,r} \cdot \vec{v}_{o/w})\mathrm{d}t. \tag{2.4}$$

Here, $\overline{P}_{rower}$ indicates the cycle average of P_{rower}. As outlined in the introduction, it is our aim to show that this expression is different from the commonly used proxy for average mechanical power output of the rower, which is the cycle average of $\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}$. In order to achieve this, we first note that $\vec{\omega}_{o/b}$ is related to the velocity of the oar handle relative to the boat:

$$\vec{\omega}_{o/b} \times \vec{l}_i = \vec{v}_{o/w} - \vec{v}_{o/b}. \tag{2.5}$$

In this equation, $\vec{l}_i$ represents the position vector of the point of application of relative to the oar pivot (pin). Next, we note that $\vec{M}_{F_{o,r}}$ is related to $\vec{F}_{o,r}$:

$$\vec{M}_{F_{o,r}} = \vec{l}_i \times \vec{F}_{o,r}. \tag{2.6}$$

Combining Equations 2.5 and 2.6 using cross product properties results in:

$$\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b} = \vec{F}_{o,r} \cdot (\vec{v}_{o/w} - \vec{v}_{v/b}) \tag{2.7}$$

See also Figure 2.1 for a free-body diagram of the oar.

By combining Equation 2.2 with equation 2.4 we can eliminate $\vec{F}_{f,r}$ from Equation 2.4. Assuming once again that there is no work done against $\vec{F}_{s,r}$, the power equation of the rower then becomes:

$$\overline{P}_{rower} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-(m_r \cdot \vec{a}_{rcom/w} - \vec{F}_{o,r}) \cdot \vec{v}_{b/w} - \vec{F}_{o,r} \cdot \vec{v}_{o/w}) \mathrm{d}t, \quad (2.8)$$

which can be rewritten into:

$$\overline{P}_{rower} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-\vec{F}_{o,r} \cdot (\vec{v}_{o/w} - \vec{v}_{b/w}) - m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}) \mathrm{d}t. \quad (2.9)$$

Or, by combining Equation 2.9 with Equation 2.7:

$$\overline{P}_{rower} = \frac{1}{T} \cdot \int_{t_0}^{t_0+t} (-\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b} - m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}) \mathrm{d}t. \quad (2.10)$$

When we now compare Equation 2.10, defining the true value of the cycle-average mechanical power delivered by the rower, to the common proxy (average P_{rower} determined by $\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}$), we see that the common proxy for average P_{rower} is indeed incorrect because it neglects the second term on the right-hand side of Equation 2.10: $m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}$. We denote the average difference between this proxy and the true value as $\overline{P}_{residual}$ in the remainder of this thesis, which is thus expressed as:

$$\overline{P}_{residual} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}) \mathrm{d}t. \quad (2.11)$$

In our rower-without-oars example (see the introduction of this chapter), the cycle average of P_{rower} would thus equal the cycle average of -$m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}$, instead of zero. Note that $\overline{P}_{residual}$ is unrelated to within-cycle fluctuations in kinetic energy of the rower (which is, as argued elsewhere [35]; zero on average in steady state), but to the part of mechanical power output that is neglected when the common proxy is used.

2.2.2 Outline of the simulation study

A priori it is not straightforward to provide an estimation of the (relative) magnitude of the difference between the true average mechanical power output and the commonly used proxy. To correctly and unequivocally determine this difference, all elements of the power equation of the rower (i.e., all forces, as well as the kinematics of the points of application of the forces and of the rower's centre of mass) have to be known, and have to be dynamically consistent. Since inevitable inaccuracies in sensor readings might severely influence results, it is difficult to determine the magnitude of this error based on experiments alone. For this reason, we chose not to base our conclusions on experimental data alone. Instead we performed simulations using a previously designed forward dynamics model of rowing [10], where the simulation outcomes provide us with a data set that is complete and fully consistent by definition. The original model has kinematics of the rower as inputs and boat kinematics as well as forces on boat, rower and oars as outputs. We derived the model inputs from kinematics of a single scull rower and oars obtained in a previous study [34]. Subsequently, model outputs were used to calculate the relevant power terms. The study was approved by the university ethics committee.

Model inputs and parameter values

Data were collected during steady-state rowing. Data of one participant were taken from this data set and used to obtain inputs for the forward dynamics model proposed by Cabrera et al. [10]. This participant provided written consent prior to the experiments (see [34] for details on data collection). We selected trials in which the rower was rowing at a stroke rate of 20 and 32 strokes min^{-1} respectively to provide an indication of the dependency of the magnitude of $\overline{P}_{residual}$ on stroke rate. From both trials, a single-stroke cycle was selected from a steady state part of rowing. The start of a stroke cycle was defined as the instant when the oar handles were at the stern-most position (i.e., at maximum oar angle). In contrast to Cabrera et al. [10], detailed kinematics of the rower were not available; we therefore calculated oar angular velocity in the horizontal plane ($\vec{\omega}_{o/b}$) directly from oar kinematics by taking the first time derivative of the measured oar angle. An approximation of the rower's fore-aft centre of mass position with respect to the boat was obtained by assuming it to coincide with the seat position [34]. We used the second time derivative of the measured seat position with respect to the boat to obtain rower's centre of mass acceleration with respect to the boat ($\vec{a}_{rcom/b}$). To ensure perfect periodicity for both $\vec{\omega}_{o/b}$ and $\vec{a}_{rcom/b}$, both input signals were detrended. The inputs were subsequently parameterised by calculating the periodic cubic spline coefficients, in order to allow interpolation to any point in time.

With the exception of the rower's mass, which was 80 kg in our study, all parameter values were taken directly from Cabrera et al. [10]. A schematic representation of the modelling procedure is provided in Figure 2.3.

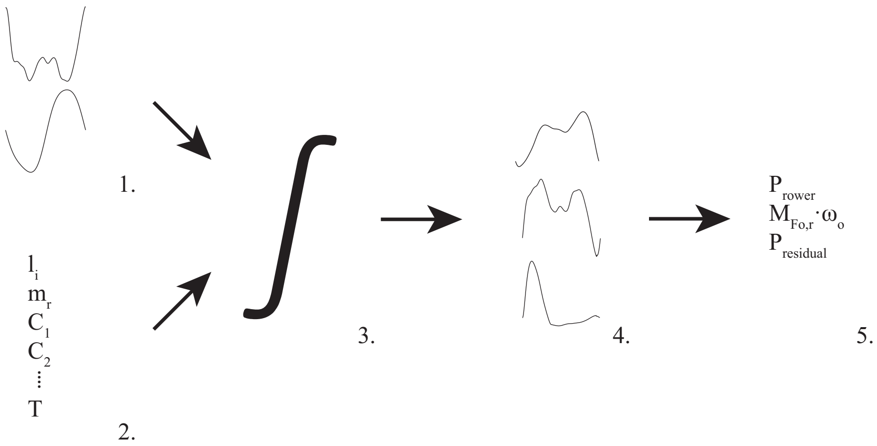

Figure 2.3. Schematic description of the simulation procedure. The model was driven by the acceleration of the rower's centre of mass with respect to the boat ($\vec{a}_{crom/w}$) and oar angular velocity ($\vec{\omega}_{o/b}$), which were obtained in an earlier experiment [34]. Using model parameters taken from Cabrera et al. [10], a forward dynamics simulation was performed (3) to obtain a kinetically and kinematically consistent data set for boat, rower and oars (4), from which in turn all relevant instantaneous power terms could be calculated (5), which were subsequently averaged over a full cycle to obtain the average power terms relevant in this study

Simulation

Using the forward dynamics model described by Cabrera et al. [10], boat, rower and oar kinematics and kinetics were predicted from $\vec{\omega}_{o/b}$ and $\vec{a}_{rcom/b}$; For this purpose, we used a standard numerical differential equation solver (ODE113) in MATLAB 2015b (The MathWorks, Natick, Massachusetts, United States). To ensure that the simulation reached steady state, simulation duration was set to 60 s. The last stroke cycle in this 60 s time-frame was seen as representative of steady-state rowing and analysed.

To verify if steady state was indeed reached, the change of kinetic energy of the rower over the stroke cycle (ΔE_{rower}) was evaluated. The assumption was rejected when the absolute value of ΔE_{rower} was greater than 5 J.

Calculation of power terms

After determining boat velocity, rower acceleration and the reaction forces between the rower and oar from the simulation outputs, we calculated the cycle average of true P_{rower}, the average of the proxy for P_{rower}, and the difference term $\overline{P}_{residual}$.

The relative magnitude of $\overline{P}_{residual}$ with respect to $\overline{P}_{rower}$ is captured in $ratio_{res./rower}$ and thus provides an indication of the relative magnitude of the error when mechanical power is calculated according to $\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}$. $ratio_{res./rower}$ was calculated according to:

$$ratio_{res./rower} = \frac{\overline{P}_{residual}}{\overline{P}_{rower}}. \tag{2.12}$$

To provide an indication for the sensitivity of the model results on input values, we manipulated m_r, the boat drag constant and the outboard length of the oar each by scaling them to 80, 90, 110, and 120 % of the original value and calculated $ratio_{res./rower}$ for all those manipulations.

2.3 Results

2.3.1 Boat kinematics

For both conditions, the steady state assumption was not violated ($|\Delta E_{rower}|$ $<$ 1 J in both cases). According to the simulation, average boat velocity was 3.4 $\mathrm{m\,s^{-1}}$ and 4.0 $\mathrm{m\,s^{-1}}$ for a stroke rate of 20 and 32 strokes $\mathrm{min^{-1}}$, respectively. This is somewhat lower than the measured boat speed obtained from the data set that was used as input for the simulation. Note that all results are simulation outcomes; hence the standard deviation of all results is zero. Figure 2.4 allows for a comparison of measured and simulated boat velocity, acceleration and handle force at 20 and 32 strokes min^{-1}. It can be seen that despite the underestimation of boat velocity the simulation outcomes provide a reasonable match with the actual data.

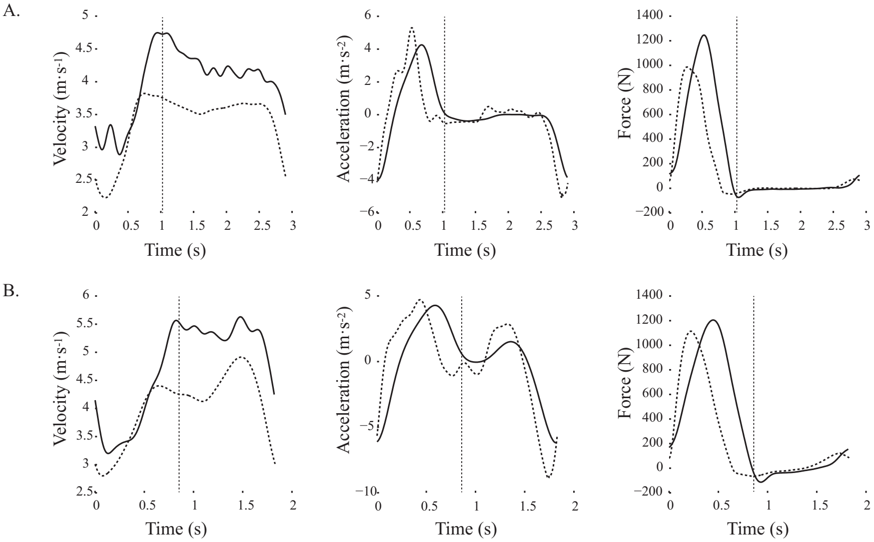

Figure 2.4. Comparison of simulation results and measured data at rowing frequencies of 20 strokes min^{-1} (A) and 32 strokes min^{-1} (B). Solid lines indicate measured data, dashed lines indicate simulation results. The data shown depict exactly one stroke cycle. For reference, the stroke finish, defined to occur when the oar handle was in the bow-most position, is indicated by a vertical dashed line. Note that since the model is partly driven by measured oar angle in time, the finish occurs at the same instant in both measured data and simulation data.

2.3.2 Power terms

Average P_{rower} was 191 W and 311 W for stroke rate conditions '20' and '32', respectively. This is considerably higher than values obtained from $\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}$ (the common proxy; $\overline{P}_{proxy}$; used to estimate mechanical power output) which were 163 W and 267 W for stroke rate 20 and 32, respectively. For $ratio_{res./rower}$ this implies a value of 0.143 for stroke rate 20 and 0.142 for stroke rate 32. An overview of all the relevant power terms at the two stroke rate conditions is provided in Table 2.1. Table 2.2 shows the results of the limited sensitivity analysis. Manipulations of m_r and the boat drag constant only had limited effect on $ratio_{res./rower}$. Manipulation on the outboard length of the oar showed that

$ratio_{res./rower}$ decreased when outboard oar length increased. Note that in all instances, $ratio_{res./rower}$ was well over 0.10.

Table 2.1. Power terms resulting from the simulations. All terms are average values over a complete stroke cycle, in which SR is the actual stroke rate min^{-1}. Total average power output is denoted by $\overline{P}_{rower}$. Power output calculated according to the common proxy is denoted as $\overline{P}_{proxy}$. The absolute difference between $\overline{P}_{rower}$ and $\overline{P}_{proxy}$ is indicated by $\overline{P}_{residual}$. The ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ is indicated by $ratio_{res./rower}$. Note that since all values are the results of the same numerical simulation, standard deviation is zero and is therefore not provided.

Condition	SR (min^{-1})	$\overline{P}_{rower}$ (W)	$\overline{P}_{proxy}$ (W)	$\overline{P}_{residual}$ (W)	$ratio_{res./rower}$
20	20.6	191	163	27.4	.143
32	32.8	311	267	44.3	.142

Table 2.2. Effect of manipulation of model constants on simulation results. The reference value for the mass of the rower (m_r) was 80 kg, for boat drag constant was 3.19 kg min^{-1} and for outboard length was 1.805 m. Except for m_r, reference values are taken from Cabrera et al. [10]. Note that boat drag constant is the ratio between boat drag force and boat velocity squared.

Manipulated variable	m_r		Drag constant		Oar outboard length	
stroke rate	20	32	20	32	20	32
-20%	.138	.136	.144	.142	.181	.180
-10%	.141	.140	.144	.143	.160	.160
Reference	.143	.142	.143	.142	.143	.142
+10%	.146	.146	.143	.142	.131	.129
+20%	.147	.147	.143	.142	.119	.118

2.4 Discussion

A theoretical analysis of the mechanics of rowing revealed that a part of the true mechanical power produced by the rower is not taken into account when power is calculated according to the common proxy. In several previous studies [5, 19, 71, 98], $\overline{P}_{rower}$ appears to be incorrectly determined. When mechanical power is calculated according to the common proxy, it is (implicitly) determined in a boat-bound frame of reference. This is, due to the inevitable accelerations of the boat, a non-inertial frame of reference in which Newton's laws of motion in their standard form are not valid. Our simulation results suggest that the cycle average of P_{rower} is substantially underestimated in those investigations. The theoretical analysis revealed that the value for this neglected part depends on the mass of the rower, the accelerations of the rower's centre of mass and the velocity of the boat (Equation 2.11). Results from the simulation study indicate that the cycle average of this neglected term is more than 10 % true mechanical power output, and thus not negligible

We made no effort to manipulate either input data or parameter values so as to obtain a higher level of consistency between simulated and measured data, as we feel this is beyond the scope of this study and not quite relevant in the light of the aim of this study. Unlike Cabrera et al. [10], our simulation results did not closely match the experimental data regarding the dependent variables (in particular boat velocity). Cabrera et al. [10] describe an optimisation routine on the input data to minimise differences between measured data and the results of their model, which most likely is the reason that the consistency between simulated and measured data in their study is higher.

However, the simulations did provide us with a reasonable approximation of the system's behaviour that was dynamically consistent. Thus, the simulation results allowed us to determine that the missing power term, $\overline{P}_{residual}$, is not negligible. Manipulations of the model inputs suggest that the residual power term is relatively robust to changes in m_r and boat drag constant and relatively sensitive to changes in oar outboard length. The latter is most likely caused by the fact that the model is constructed in such a way that both boat kinematics and $\vec{M}_{F_{o,r}}$ are directly affected by a change in outboard length. Note that the sensitivity of $\overline{P}_{residual}$ on outboard length choice is most likely a result of the inevitable simplifications of the simulation model; this might not be the case in actual on water rowing. Without exception, in all conditions, $\overline{P}_{residual}$ was larger than 10 % of $\overline{P}_{rower}$, which is in the same order of magnitude as the experimental results reported earlier by Kleshnev [49].

The model used is a simplified representation of actual on-water rowing that only concerns horizontal forces. In reality, the rower also moves into the vertical direction and work is also done against vertically oriented forces (i.e., gravity and seat force and the vertical component of foot stretcher force). Although average mechanical work against gravity equals zero in steady-state rowing and the work against the seat reaction force is likely to be of small magnitude, this implies that the underestimation of true $\overline{P}_{rower}$ by the common proxy could be somewhat larger than suggested by our simulations.

It is relevant to understand to what extent $ratio_{res./rower}$ depends on rowing conditions such as rowing style or boat type. Since our results confirm that mechanical power output is substantially underestimated using the commonly used proxy, this warrants further experimental investigation, in which the error term is determined as directly as possible (i.e., by determining rower mass, rower acceleration and boat velocity) for a range of rowing conditions. For this reason, we recently performed a series of on-water experiments in which we manipulated stroke rate. In this study we showed that $ratio_{res./rower}$ for on-water single scull rowing was in the order of 0.12, which confirms our simulation results. We also found that $ratio_{res./rower}$ in the single scull was relatively invariant between different stroke rates [56].

2.5 Practical Implication

The results found in this study have direct implications for rowing practice. Given the current rate of technological developments, we expect that it is only a matter of time before feedback on mechanical power output will be widely used in competitive (on-water) rowing in training and perhaps also in racing. Our results suggest that, until the relation between rowing conditions and $\overline{P}_{residual}$ is known, it is necessary to also either obtain foot stretcher forces or rower acceleration for a valid determination of $\overline{P}_{rower}$.

2.6 Conclusions

We showed that the common proxy for the mechanical power generated by a rower is theoretically flawed, and that the difference between this proxy and the true mechanical power generated by a rower equals the cycle average of $m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}$. Average mechanical power in rowing should thus be calculated according to Equations 2.4, 2.9 or 2.10. Based on our simulation results, it appears that, averaged over a full cycle, the relative error resulting from the use of the common proxy is larger than 10 %, and as such not negligible. In order to provide meaningful (real-time) information on $\overline{P}_{rower}$, it is important to first determine this difference experimentally, under different rowing conditions, and as directly as possible.


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Chapter 3

An accurate estimation of the horizontal acceleration of a rower's centre of mass using inertial sensors: a validation

Based on:
Lintmeijer, L.L., Faber, G.S., Kruk, H.R., van Soest, A.J., Hofmijster, M.J. An accurate estimation of the horizontal acceleration of a rower's centre of mass using inertial sensors: a validation. European Journal of Sport Science, **18:7**, 940-946. DOI: 10.1080/17461391.2018.1465126 (2018).

For a valid determination of a rower's mechanical power output, the anterior-posterior (AP) acceleration of a rower's centre of mass (CoM) is required. The current study was designed to evaluate the accuracy of the determination of this acceleration using a full-body inertial measurement units (IMUs) suit in combination with a mass-distribution model. Three methods were evaluated. In the first two methods IMU data were combined with either a subject-specific mass distribution or a standard mass distribution model for athletes. In the third method a rower's AP CoM acceleration was estimated using a single IMU placed at the pelvis. Experienced rowers rowed on an ergometer that was placed on two force plates, while wearing a full-body IMUs suit. Correspondence values between AP CoM acceleration based on IMU data (the three methods) and AP CoM acceleration obtained from force plate data (reference) were calculated. Good correspondence was found between the reference AP CoM acceleration and the AP CoM accelerations determined using IMU data in combination with the subject-specific mass model and the standard mass model (ICC $>$ .988 and nRMSE $<$ 3.81 %). Correspondence was lower for the AP CoM accelerations determined using a single pelvis IMU (.877 $<$ ICC $<$ .960 and 6.11 % $<$ nRMSE $<$ 13.61 %). Based on these results, we recommend determining a rower's AP CoM acceleration using IMUs in combination with the standard mass model. Finally, we conclude that accurate determination of a rower's AP CoM acceleration is not possible on the basis of the pelvis acceleration only.

3.1 Introduction

A key characteristic of rowing is that the rower's centre of mass (CoM) moves relative to the boat. This relative motion contributes substantially to the fluctuations of boat velocity within each stroke cycle (e.g. [4, 10, 11, 40, 59]). Furthermore, as Hofmijster et al. [38] have argued, this whole-body CoM motion complicates the determination of a rower's mechanical power output. The authors have shown that the common approximation of a rower's mechanical power output (the product of the moment around the oar and the oar angular velocity) is theoretically flawed. The difference between the common proxy and the true mechanical power output of a rower depends on the rower's CoM acceleration relative to the world. In order to calculate a rower's true mechanical power output and to understand the effect of a rower's movement on boat velocity, a valid determination of the rower's CoM acceleration relative to the world is thus required.

In previous studies on rowing (e.g. [5, 34, 59, 91]), the second derivative of seat displacement (which can be determined with relative ease) has been used as an approximation of a rower's CoM acceleration relative to the boat. However, the validity of this simplified measure is questionable.

Recently, it has been shown that small inertial measurement units (IMUs), in combination with a model of mass distribution, are suitable to determine the whole-body CoM acceleration relative to the world in a movement task in which displacements were primarily in vertical direction [22]. These IMUs are feasible to be used in on-water rowing studies since they are unobtrusive and waterproof. However, it is not guaranteed that the conclusions of Faber et al. [22] can be generalised to the largely horizontal movements that occur in rowing, because of the differences in the accuracy with which rotations around different axes can be measured [23].

The current study was therefore designed to evaluate how accurate a rower's CoM acceleration in the anterior-posterior (AP) direction (largest horizontal movement in rowing) relative to the world can be determined using IMUs in combination with a mass distribution model. Three methods were evaluated. In the first two methods a rower's CoM acceleration was determined from full-body IMU data in combination with either a subject-specific mass distribution model based on individual anthropometric measures (detailed anthropometry method), or a standard mass distribution for male and female athletes (standard anthropometry method) [18, 99]. Given previous studies (e.g. [5, 34, 59, 91]), we also evaluated whether the pelvis acceleration provides an accurate estimate of a rower's AP CoM acceleration.

3.2 Methods

3.2.1 Outline of the study

Each participant rowed on an ergometer that was placed on force platforms (see Figure 3.1). Force plate data were used to estimate the rower's CoM acceleration using ground-reaction forces (GRFs); this was considered to be the most accurate measure to determine whole-body CoM acceleration and used as reference. During the trials, participants wore a full-body IMUs suit consisting of 18 IMUs (see Figure 3.2 for the placement of IMUs). IMU data were used to estimate the CoM acceleration using (1) the detailed anthropometry method, (2) the standard anthropometry method or (3) an IMU placed on the pelvis. These determinations of the whole-body CoM acceleration were compared to the reference. In order to cover a wide range of acceleration amplitudes, rowers performed three trials at different stroke rates (15, 25 and 35 strokes min^{-1}).

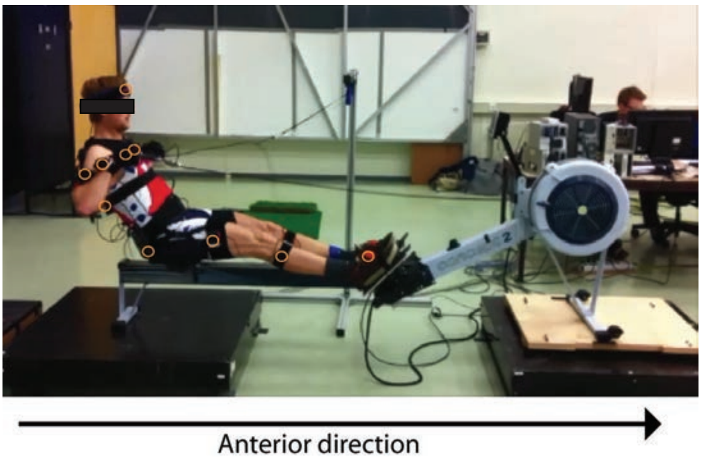

Figure 3.1. An overview of the experimental setup. The visible IMUs are highlighted with orange circles. The positive x-direction points towards the rower's anterior direction.

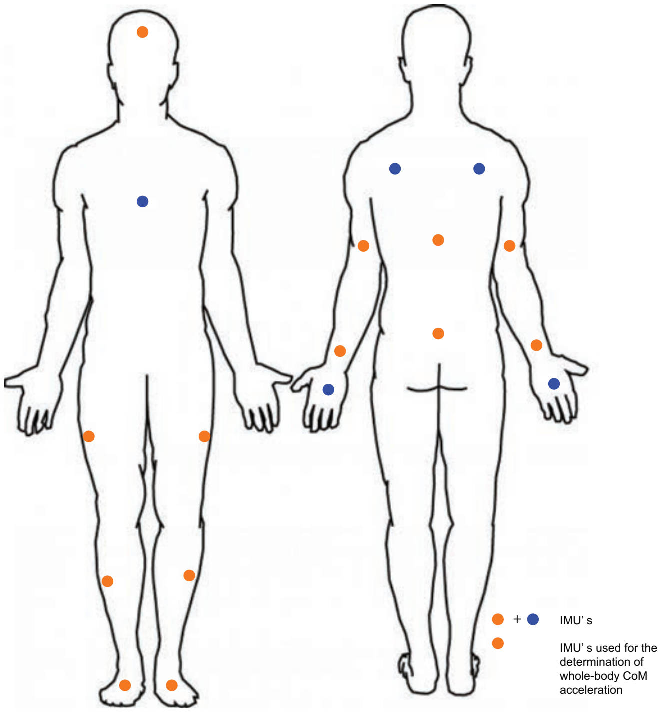

Figure 3.2. The related schematic overview of the placement of the IMUs of the full-body Xsens MVN suit. The orange dots illustrate the IMUs that have been used to determine a rower's whole-body AP CoM acceleration. The blue dots illustrate the IMUs that are also part of the MVN system but that were not used to calculate a rower's AP CoM acceleration.

3.2.2 Participants and experimental procedure

Four female and five male rowers (mean age = 25.3, SD= 7.7 years; mean mass = 78.8 kg, SD= 10.9 kg) participated in the experiment that was approved by the local ethical committee. Prior to the experiment, participants were informed about the aim and the protocol after which they provided a written informed consent. Subsequently, body segment lengths and circumferences were measured and the IMUs were placed on all body segments. Participants' body mass was measured using the force plates. Finally, subjects performed the three rowing trials in random order. Prior to the first trial, the IMUs system was calibrated (see below) on a wooden platform in order to minimise possible magnetic distortions on the IMU orientation about the global vertical due to ferromagnetic metals in the rowing ergometer. Additionally, to reset possible IMU drift due to the magnetic distortion during the rowing trials, in between the trials the IMUs were reinitialised while the rower was standing on the wooden platform.

3.2.3 Instrumentation

Body segment accelerations were measured with a full-body Xsens MVN system (120 Hz MVN, Xsens technologies B.V., Enschede, the Netherlands) consisting of 17 IMUs [72]. In addition, one extra IMU was placed on the back. Data were recorded using Xsens software (MVN Studio 3.0, Xsens technologies B.V., Enschede). Calibration of the system was done by recording an upright calibration posture (described in [72]). The calibration was conducted to enable the Kinematic Coupling ($\mathrm{KiC_{TM}}$) algorithm to compensate for possible magnetic disturbance of the ergometer on the IMUs.

GRFs were measured at 120 Hz using two 1.0 m $\times$ 1.0 m custom-made strain gauge force plates (described in [45]). The positive x-axis of the frame of reference pointed in the rower's anterior direction and the positive y-axis in the lateral direction. Calibration of the force plates was done by exerting horizontal forces using a rope and pulley system.

3.2.4 Calculation of the reference-based rower's CoM acceleration

The reference-based rower's CoM acceleration ($\vec{a}_{com}FP$) was calculated using the unfiltered net forces obtained from the force plates ($\vec{F}_{fp1}$ and $\vec{F}_{fp2}$) and the rower's mass (m_r):

$$\vec{a}_{com}FP = \frac{\vec{F}_{fp1} + \vec{F}_{fp2}}{m_r}. \tag{3.1}$$

3.2.5 Calculation of the IMU-based rower's CoM acceleration

The IMU-based rower's CoM acceleration ($\vec{a}_{com}IMU$) was calculated based on the unfiltered IMU data using three different methods. In the detailed and standard anthropometry method ($\vec{a}_{com}IMU_{DA}$ and $\vec{a}_{com}IMU_{SA}$, respectively), the whole-body CoM acceleration was calculated based on the mass and acceleration of the CoM acceleration of 13 body segments (based on [99]); pelvis, abdomen plus thorax, head, the left and right thighs, shanks, feet, upper arms and the forearms plus hands:

$$\vec{a}_{com}IMU = \frac{\sum_{i=1}^{n} \vec{a}_{segmenti} \cdot m_{segmenti}}{m_r}, \tag{3.2}$$

where, $\vec{a}_{segmenti}$ is the CoM acceleration of segment *i*, $m_{segmenti}$ is the mass of segment *i*, and n is the number of segments. To obtain $\vec{a}_{segmenti}$s, IMUs were located at the approximate longitudinal CoM locations for most of the body segments. Only for the thorax plus abdomen segment, the extra IMU on the back was used, which was placed at approximately the intersection plane between the abdomen and thorax segment.

Segment masses were based on an anthropometric data set reported by Zatsiorsky [99]. In the detailed anthropometry method, a rower's mass distribution over the 13 segments was based on individual segment lengths and circumferences. In the standard anthropometry method, the mass distribution was based on a standard mass distribution for male and female athletes.

In the simplified method, the whole-body CoM acceleration was defined by the acceleration measured by the pelvis IMU ($\vec{a}_{com}IMU_{pelvis}$).

3.2.6 Alignment and synchronisation of IMUs and FP

IMU accelerations were measured in the local IMU frame. Before the $\vec{a}_{com}IMU$s were calculated, the locally measured accelerations were rotated to a global-coordinate system using the orientation matrices of the corresponding IMUs which were outputted by the Xsens software. In this global-coordinate system, the positive x-axis points towards the magnetic north and the positive y-axis towards the west. Rotation of the horizontal plane of the $\vec{a}_{com}IMU$-coordinate systems towards the same horizontal plane of the $\vec{a}_{com}FB$ coordinate system was done by means of a principal component analysis (see Figure 3.3).

After rotation, time synchronisation of the $\vec{a}_{com}IMU$s and the $\vec{a}_{com}FP$ was done by means of a cross-correlation algorithm using the AP component of the $\vec{a}_{com}IMU_{DA}$ and the AP component $\vec{a}_{com}FP$.

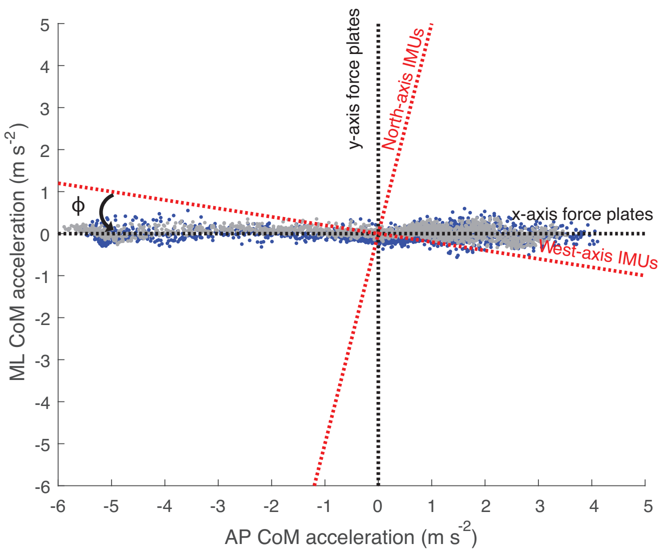

Figure 3.3. A typical example of the $\vec{a}_{com}IMU_{DA}$ data (blue) and the $\vec{a}_{com}FP$ data (grey) in the horizontal plane in which the positive x-axis points toward the rower's anterior direction. In order to obtain the orientation of the IMU global frame of reference (red) relative to the force plate frame of reference (black), a principal-component analysis was conducted. All samples of the IMU data were rotated over the rotation angle (Φ) around the gravitational axis. Note that the rotation was only done in the horizontal plane, since both the IMU frame of reference and the force plate frame of reference have a vertical component in gravitational direction. Also note that the magnitude of the lateral CoM acceleration is negligibly small relative to the magnitude of the AP CoM acceleration.

3.2.7 Statistical analyses

Analyses were conducted using Matlab 2015b (the Mathworks Inc, Natick, MA, USA). For every trial, 20 s of steady-state rowing at the beginning of the trial were selected, and the outcomes of the AP component of the $\vec{a}_{com}IMU_{DA}$, $\vec{a}_{com}IMU_{SA}$ and $\vec{a}_{com}IMU_{pelvis}$ were compared to the AP component of the $\vec{a}_{com}FP$. Correspondence was quantified using intraclass correlation coefficients (ICCs) (3,1) [53], since it reflects deviations from the identity line. In addition, the absolute and normalised root mean square errors (RMSE and nRMSE, respectively) were calculated. nRMSEs were based on the absolute RMSEs divided by the amplitude of the AP component of $\vec{a}_{com}FP$.

3.3 Results

3.3.1 Typical example

In Figure 3.4 and 3.5, we present a typical example. The AP component of $\vec{a}_{com}IMU_{DA}$ and $\vec{a}_{com}IMU_{SA}$ are very similar to the AP component of $\vec{a}_{com}FP$. Correspondence of the AP component of $\vec{a}_{com}IMU_{pelvis}$ and $\vec{a}_{com}FP$ is lower, specifically during high positive accelerations.

3.3.2 Agreement of CoM acceleration obtained from IMUs

Correspondence between the AP component of $\vec{a}_{com}IMU_{DA}$ and $\vec{a}_{com}IMU_{SA}$ on the one hand and the AP component of $\vec{a}_{com}FP$ was good, with ICCs above 0.988, RMSEs below 0.538 $\mathrm{m\,s^{-2}}$ and related nRMSEs lower than 3.8 %. Correspondence between the AP component of $\vec{a}_{com}IMU_{pelvis}$ and the AP component of $\vec{a}_{com}FP$ was lower with ICCs between 0.877 and 0.960, RMSEs between 0.248 $\mathrm{m\,s^{-2}}$ and 2.026 $\mathrm{m\,s^{-2}}$ and related nRMSEs between 6.11 % and 13.61 % (see Table 3.1).

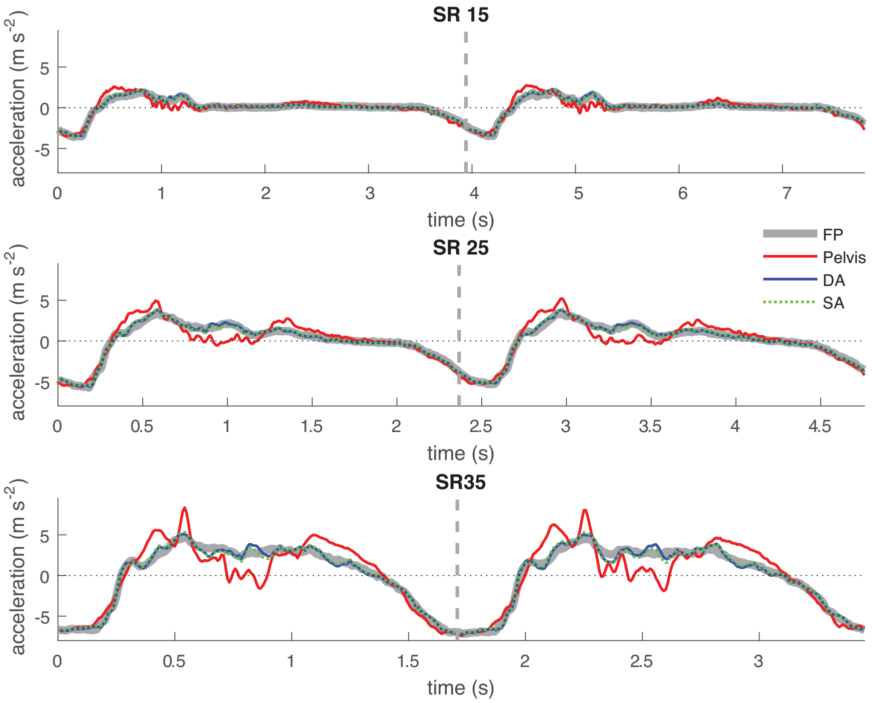

Figure 3.4. Typical examples of the AP component of the $\vec{a}_{com}IMU_{DA}$ (blue), $\vec{a}_{com}IMU_{SA}$ (green), $\vec{a}_{com}IMU_{pelvis}$ (red) and $\vec{a}_{com}FP$ (grey) of a rower rowing 15, 25 or 35 strokes per minute. The vertical grey dotted line indicates the start of a new stroke.

3.4 Discussion

In this study, we evaluated the accuracy of the determination of a rower's AP CoM acceleration using segment accelerations measured by IMUs in combination with a mass distribution model. Most importantly, we found that — over a wide range of acceleration amplitudes — a rower's AP CoM acceleration is captured very accurately when using data of 13 IMUs of the full-body IMU suit in combination with both the subject-specific and standard mass distribution model.

Because a rower's CoM acceleration was represented by the AP acceleration of the pelvis/seat in previous studies (e.g. [5, 34, 59, 91], we also tested whether an IMU placed on a rower's pelvis provides an accurate estimate of a

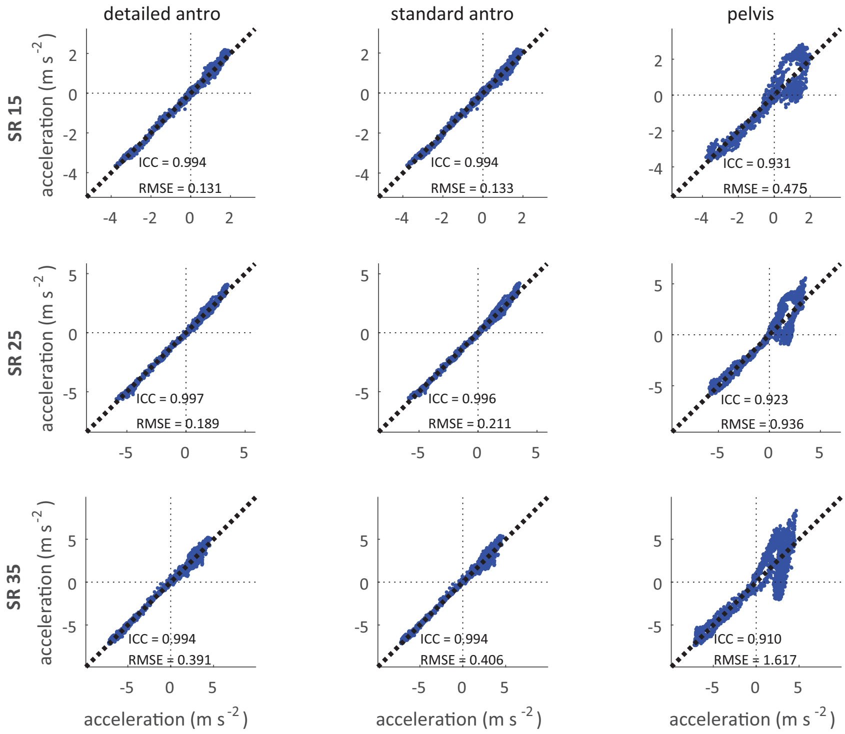

Figure 3.5. The related identity lines (black dotted line) of the typical example of all $\vec{a}_{com} IMU$ components in AP direction.

rower's AP CoM acceleration. Although ICCs were good (classification based on [70] in [53]), RMSEs and nRMSEs were high. Figure 3.4 indicates that the pelvis acceleration over and underestimates positive peak accelerations during the end of the stroke and during the recovery. These differences in pelvis and CoM acceleration are due to the fact that the pelvis movement and rower CoM movement do not coincide, as there is considerable trunk flexion and extension during the stroke cycle, causing the trunk (which has considerable mass) to move with respect to the pelvis. Based on the findings of the current study, we advise against the use of the pelvis or seat acceleration as a proxy for a rower's CoM acceleration in future studies in which high accuracy of a rower's AP CoM acceleration is required.

One limitation of the study is a possible bias in correspondence values in favour of the detailed anthropometry method. This is because synchronisation of the

Table 3.1. Means, SDs and the ranges of all correspondence values (i.e. intraclass correlation coefficients [ICC]; root mean square errors [RMSE]; and the normalized root mean square errors [nRMSE]) of the rower's AP CoM acceleration estimated with IMUs and a body mass distribution model (three methods) and the AP CoM acceleration estimated using force plates data (the reference).

	ICC values (3,1)		**RMSEs ($m\,s^{-2}$)**		**nRMSEs (%)**	
	Mean (SD)	**range**	**Mean (SD)**	**range**	**Mean (SD)**	**range**
$\vec{a}_{com}IMU_{DA}$						
SR 15	.992 (.003)	.988 - .995	.136 (.024)	.101 - .175	2.4 (.72)	1.52 - 3.81
SR 25	.995 (.001)	.994 - .997	.234 (.050)	.167 - .310	2.27 (.28)	1.80 - 2.64
SR 35	.994 (.002)	.991 - .997	.410 (.073)	.268 - .538	2.84 (.41)	2.34 - 3.29
overall	.994 (.002)	.988 - .997	.260 (.126)	.101 - .538	2.53 (.54)	1.52 - 3.81
$\vec{a}_{com}IMU_{SA}$						
SR 15	.992 (.002)	.988 - .995	.135 (.033)	.097 - .199	2.38 (.53)	1.80 - 3.35
SR 25	.994 (.002)	.991 - .997	.247 (.066)	.124 - .330	2.34 (.29)	1.97 - 2.83
SR 35	.993 (.003)	.988 - .997	.451 (.092)	.250 - .536	3.11 (.50)	2.25 - 3.67
overall	.993 (.003)	.988 - .997	.277 (.148)	.097 - .536	2.61 (.56)	1.80 - 3.67
$\vec{a}_{com}IMU_{pelvis}$						
SR 15	.923 (.012)	.881 - .951	.447 (.180)	.248 - .793	7.44 (.97)	6.11 - 8.98
SR 25	.924 (.025)	.888 - .960	.940 (.272)	.489 - 1.317	8.91 (1.19)	7.19 - 10.95
SR 35	.911 (.016)	.877 - .959	1.607 (.322)	.919 - 2.026	11.10 (1.71)	8.30 - 13.61
overall	.921 (.025)	.877 - .960	.998 (.547)	.248 - 2.026	9.15 (1.99)	6.11 - 13.61

Note: nRMSEs were based on the absolute RMSEs divided by the amplitude of the AP component of the $\vec{a}_{com}FP$.

IMU data and the force plate data in time was done by means of a cross-correlation algorithm using the rower's AP CoM acceleration obtained from the detailed anthropometry method and the AP CoM acceleration obtained from force plates. However, similar results were obtained when synchronization of the IMU and force plate data in time was done using the rower's AP CoM acceleration obtained from the standard anthropometry method and the CoM acceleration obtained from the pelvis acceleration. This implies that the conclusions of this study remain unchanged.

Two concerns related to the generalisation of our results are worth mentioning. Firstly, only healthy subjects with a mass distribution that was close to the mass distribution of the standard anthropometry model participated in the study. Determination of the whole-body AP CoM acceleration in other populations with a non-standard mass distribution (e.g. obese people) could be less accurate, especially when the standard model for mass distribution is used.

Assuming (sub)-elite rowers to have a standard mass distribution, we suggest that the use of the standard mass distribution model is adequate to obtain the AP CoM acceleration of (sub)-elite rowers.

Secondly, IMU data can be influenced by non-homogeneous magnetic fields due to, for example, ferromagnetic materials in an ergometer. In order to minimise magnetic distortion in our study, we reinitialised the IMUs on a wooden platform prior to every trial. In studies where no homogeneous magnetic field is available, magnetic distortion can result in heading (rotation about global vertical) errors in the AP acceleration direction. During on-water measurements, however, this will probably not be an issue since modern rowing boats usually do not contain substantial amounts of ferromagnetic materials.

3.5 Conclusion

In summary, a rower's AP CoM acceleration relative to the world can be adequately estimated from data obtained from IMUs placed on body segments and a mass distribution model. In contrast, the pelvis AP acceleration — and therefore most likely the AP seat acceleration — does not accurately approximate a rower's AP CoM acceleration. With respect to an accurate estimation of an (athletic) rower's CoM acceleration in on-water rowing studies, we therefore recommend the use of IMUs in combination with the standard model for mass distribution.

Chapter 4

Improved determination of mechanical power output in rowing: Experimental results

Based on:
Lintmeijer, L.L., Hofmijster, M. J., Schulte Fischedick, G. A., Zijlstra, P. J., & van Soest, A. J. An improved determination of mechanical power output in rowing: experimental results. Journal of Sports Science, **36**, 2138-2146. DOI:10.1080/02640414.2017.1367821 (2018).

In rowing, mechanical power output is a key parameter for biophysical analyses and performance monitoring and should therefore be measured accurately. It is common practice to estimate on-water power output as the time average of the dot product of the moment of the handle force relative to the oar pin and the oar angular velocity. In a theoretical analysis we have recently shown that this measure differs from the true power output by an amount that equals the mean of the rower's mass multiplied by the rower's centre of mass acceleration and the velocity of the boat. In this study we investigated the difference between a rower's power output calculated using the common proxy and the true power output under different rowing conditions. Nine rowers participated in an on-water experiment consisting of seven trials in a single scull. Stroke rate, technique and forces applied to the oar were varied. On average, rowers' power output was underestimated with 12.3 % when determined using the common proxy. Variations between rowers and rowing conditions were small (SD = 1.1) and mostly due to differences in stroke rate. To analyse and monitor rowing performance accurately, a correction of the determination of rowers' on-water power output is therefore required.

4.1 Introduction

Rowing performance critically depends on the average shell velocity achieved over a distance of 2000 m. Races take place in boats with one, two, four or eight rowers, in either sweep (one oar per rower) or sculling (two oars per rower) boats. The average velocity of the boat depends on a crew's combined ability to optimise the trade-off between delivered mechanical power output and power losses unrelated to average shell velocity [37]. Since a rower's power output is the only power source in rowing, it is not only a key parameter in biophysical analyses [33], but also for performance monitoring and possibly even controlling a rower's physical status and training load [82]. Adequate monitoring and controlling of mechanical power output is expected to lead to improved efficiency of training and, ultimately, to improved rowing performance. Therefore, an accurate quantification of a rower's mechanical power output is critically important.

A rower mainly exchanges mechanical power via his/her hands at the handle of the oar and via his/her feet at the foot stretcher, assuming power associated with the seat force and vertical displacements of the rower's centre of mass to be negligible (see Figure 4.1 for a schematic overview of a rower's relevant forces and velocities). Hence, theoretically, the average mechanical power output of a rower ($\overline{P}_{rower}$) during a stroke cycle in steady-state rowing can be calculated as:

$$\overline{P}_{rower} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-\vec{F}_{f,r} \cdot \vec{v}_{b/w} - \vec{F}_{o,r} \cdot \vec{v}_{o/w})\mathrm{d}t. \tag{4.1}$$

In which T is the time duration of a stroke cycle. $\vec{F}_{o,r}$ and $\vec{F}_{f,r}$ are the force vectors of the oar handle and the foot stretcher on the rower respectively, while $\vec{v}_{o/w}$ and $\vec{v}_{b/w}$ are the velocity vectors of the oar handle and the boat relative to an earth bound frame of reference respectively (see List of Symbols for a list of all abbreviations).

Measurement of all these terms during on-water rowing is not trivial. This may explain why it is common practice to estimate mechanical power output per stroke cycle as the time average of the dot product of the moment of the

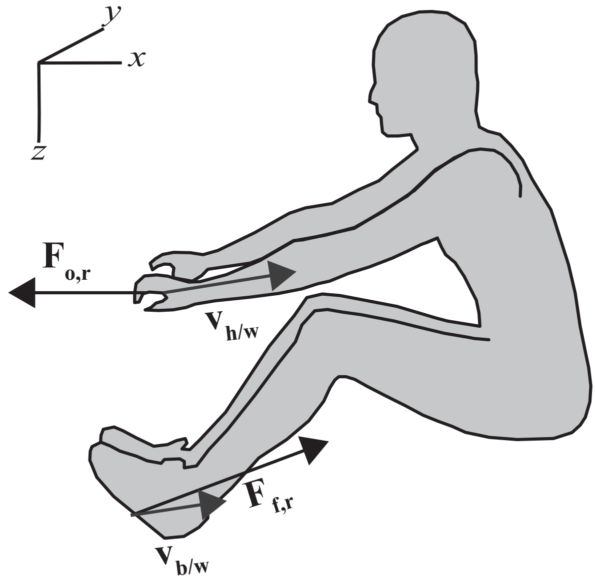

Figure 4.1. Schematic diagram of a rower in an earth-bound frame of reference in which the positive x-axis is in the direction of travel of the boat, and the z-axis is aligned with the gravitational acceleration. $\vec{F}_{o,r}$ and $\vec{F}_{f,r}$ are the force vectors of the handle of the oar on the rower and the footplate of the boat on the rower respectively. The velocity vectors of the handle and the footplate (boat) are depicted as $\vec{v}_{o/w}$ and $\vec{v}_{b/w}$ respectively.

handle force relative to the oar pin ($\vec{M}_{F_{o,r}}$) and the oar angular velocity ($\vec{\omega}_{o/b}$) (e.g. [5, 19, 71, 98]). So, the common approximation of a rower's average power output per stroke cycle ($\overline{P}_{proxy}$) is:

$$\overline{P}_{proxy} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}) \mathrm{d}t. \tag{4.2}$$

However, as is addressed before by Kleshnev [49], using this "common proxy" (as described in Equation 4.2) results in an underestimation of a rower's true average mechanical power output per stroke cycle. In a previous article [38], we have shown on theoretical grounds that this true power output of a rower averaged over a stroke cycle ($\overline{P}_{rower}$) is related to the common proxy ($\overline{P}_{proxy}$), but that it differs from the common proxy with an amount that we will refer to as the residual power output ($\overline{P}_{residual}$). This $\overline{P}_{residual}$ is related to the mass of the rower (m_r), the rower's centre of mass (CoM) acceleration ($\vec{a}_{rcom/w}$), and the velocity of the boat ($\vec{v}_{b/w}$) according to:

$$\overline{P}_{residual} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}) \mathrm{d}t. \tag{4.3}$$

From Equations 4.2 and 4.3 it follows that $\overline{P}_{rower}$ can be calculated as:

$$\begin{aligned}\overline{P}_{power} &= \overline{P}_{proxy} + \overline{P}_{residual} \\ &= -\frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-\vec{M}_{F_{o,r}} \cdot \vec{\omega}_{o/b}) \mathrm{d}t \\ &\quad - \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-m_r \cdot \vec{a}_{rcom/w} \cdot \vec{v}_{b/w}) \mathrm{d}t.\end{aligned} \tag{4.4}$$

Simulation results suggest [38] that $\overline{P}_{residual}$ is a non-negligible part of $\overline{P}_{rower}$. However, the precise value of $\overline{P}_{residual}$ is currently unknown, as well as its potential dependence on rower characteristics and rowing conditions. It follows from Equations 4.3 and 4.4 that both $\overline{P}_{residual}$ and $\overline{P}_{rower}$ depend on the rower's mass, the CoM acceleration pattern, the boat velocity pattern and the phase relation between those last two variables. The CoM acceleration pattern as well as the boat velocity pattern in turn are affected by stroke rate (number of strokes min^{-1}), technique, and forces applied at the oar [4, 34, 50, 74].

As mentioned, it is clear that $\overline{P}_{residual}$ and $\overline{P}_{rower}$ are both affected by the mass of the rower, stroke rate, technique and forces applied to the oar. However, it is unclear whether the ratio between $\overline{P}_{residual}$ and $\overline{P}_{rower}$ is influenced by changes in those variables. This uncertainty is partly due to the mediating effect of the phase shift between a rower's CoM acceleration pattern and the boat velocity pattern. Thus, in order to evaluate the practical implications of the findings of our simulation study, an empirical study is required in which $\overline{P}_{residual}$ is determined for different rowers under different rowing conditions.

In this study we quantified the difference between average mechanical power output determined using the common proxy and the true averaged power output per stroke cycle. In particular, we determined the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$

for different rowers under different rowing conditions. Subsequently, we investigated whether variations in the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ can be explained by differences in a rower's mass, stroke rate, technique and forces applied to the oar handle.

4.2 Methods

4.2.1 Design

In order to determine the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ for different rowers under different rowing conditions, a within-subject design was adopted in which participants had to row seven trials under different instructions (see Table 4.1 for the specific instructions per trial). Each trial consisted of two times 250 m rowing in opposing directions of travel in order to minimise possible effects of current and wind. Participants were instructed to keep stroke rate constant and to row steady state. All tests were carried out in a single scull rowing boat in order to exclude possible effects of interaction between rowers on boat velocity patterns and/or (net) rower acceleration patterns.

Table 4.1. Circumscription of the seven rowing conditions.

	Strokes min^{-1}	**Technique**	**Force**
Reference	18	'Normal'	Medium
Stroke rate 25	25	'Normal'	Medium
Stroke rate 32	32	'Normal'	Medium
Early Knee extension	18	First knee extension than hip extension	Medium
Early Trunk Extension	18	First hip extension than knee extension	Medium
Low Force	18	'Normal'	Low
High Force	18	'Normal'	High

4.2.2 Conditions

In the reference condition, participants were instructed to row with regular training-based strokes (medium intensity) at 18 strokes min^{-1}. In the six remaining conditions we manipulated the rower's CoM acceleration pattern and the boat velocity pattern by instructing participants to alter their stroke rate (25 and 32 strokes min^{-1}), their technique (an early knee extension versus an early trunk extension during the stroke), or the forces applied to the oar (low versus high force applied at the oar during the stoke). Technique manipulations were based on two common technical "errors". In the "early knee extension" condition participants were instructed to extend their knees completely before extending the hip joint during the drive phase. In contrast, in the "early trunk extension" condition participants were asked to extend the joint hip first before extending the knees. Force conditions (see Table 4.1) were based on the subjective feeling of the participant: rowers were instructed to either apply lower or higher force during the stroke than during regular training based strokes. In all force and technique conditions participants were instructed to row at stroke rate 18.

4.2.3 Participants

Nine (sub-)elite rowers (five male and four female) participated in this study. Participant characteristics are displayed in Table 4.2. The study was approved by the local ethical committee.

Table 4.2. Age, mass, years of experience, and years of experience in single scull for all participants, as well as the corresponding mean values (M) and standard deviations (SD).

Participant number	1	2	3	4	5	6	7	8	9	M (SD)
Age (y)	19	27	26	22	24	26	42	26	36	27.5 (7.1)
Mass (kg)	61.1	71.6	87.4	60.2	51.5	72.1	57.0	74.8	75.6	71.2 (10.2)
Rowing experience (y)	2.5	4	12	3	9	4	20	8	14	8.7 (6.0)
Experience in single scull (y)	2.5	4	4	2	7	1	20	3	3	5.3 (5.8)

4.2.4 Instrumentation

Two instrumented single sculls were used: a shell designed for rowers of an average weight of 85 kg (Empacher, Eberbach, Germany) and a shell designed for rowers of an average weight of 70 kg (Empacher, Eberbach, Germany). Force in the direction of travel of the boat and the transverse direction at both oar pins, as well as oar angles in the horizontal plane, were measured using strain gauges and a reed sensor in the oarlocks, while an accelerometer determined the acceleration of the hull in direction of travel of the boat (Peach Innovations Ltd., Cambridge, United Kingdom). Sensor output was sampled at 100 Hz and stored on an SD card using a custom made Arduino based DAQ (Vrije Universiteit (VU), Amsterdam, the Netherlands), which was mounted on the boat.

The low-frequency component of boat speed was obtained with a GPS Tracking system (LOCOSYS, Taipei City, Taiwan; 10 Hz sample frequency). A "Stroke-Coach" monitor (Nielsen Kellerman, Boothwyn, USA) provided the participant with feedback on stroke rate. A video camera (GoPro, San Mateo, USA) was installed at the stern of the boat to check for calamities during the measurement.

In order to estimate the rower's CoM acceleration, inertial sensors (MVN Biomech Awinda, Xsens, Enschede, Netherlands) were placed on 13 body segments: pelvis, sternum, head, upper arms, forearms, upper legs, lower legs, and feet (see [72] for an extended overview of the mechanism and placement of the Xsens sensors). Sensor signals were sampled at 60 Hz and sent to a receiver using a WiFi connection (Awinda, Xsens, Enschede, Netherlands) linked to a Windows tablet computer, which was placed in a waterproof box near the stern of the boat.

4.2.5 Determination of variables

Analyses were restricted to forces and motions in the horizontal plane (see Figure 4.2 for an overview of the frames of reference). This implies that moments (e.g. $\vec{M}_{F_{o,r}}$) and angular velocities (e.g. $\vec{\omega}_{o/b}$) have components in the z-axis direction only. Assuming energy exchanges related to lateral and vertical boat displacements to be negligible, $\overline{P}_{residual}$ was calculated using kinematics

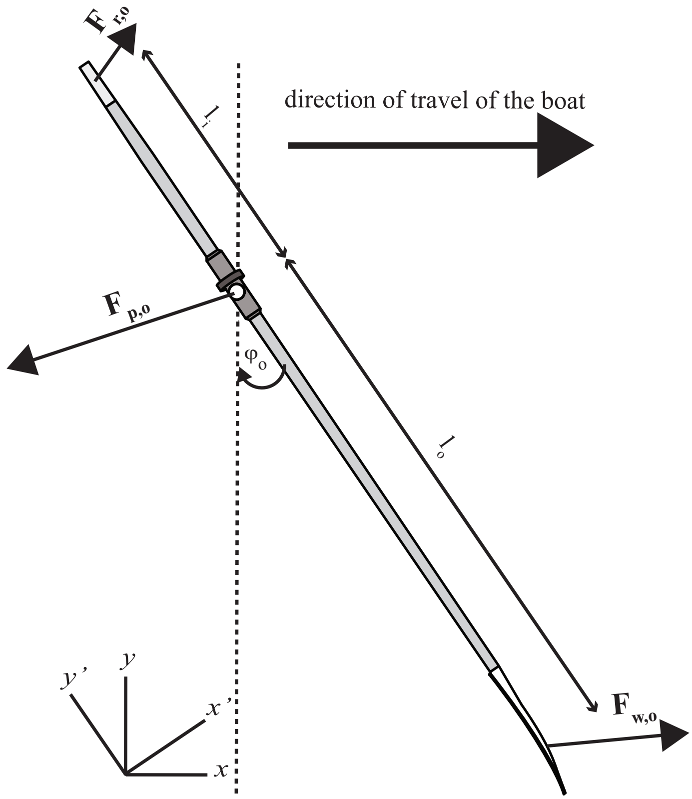

Figure 4.2. Schematic diagram of a top view of one oar and the frames of reference used in this study. The x-y frame is an earth-bound frame of reference, in which positive x-axis is the travel direction of the boat. The x'-y' frame is an oar-bound frame of reference, in which the positive x'-axis is perpendicular to the oar and points towards the front of the blade. The positive y'-axis runs parallel to the oar and points from the oarlock towards the end of insight of the oar. Oar angle ($\vec{\Phi}_{o/b}$) is defined as the angle between the oar and the perpendicular line with the boat (dashed line). Oar angular velocity in the horizontal plane ($\vec{\omega}_{o/b}$) is positive during the stroke phase. Forces acting from the rower, the water and the oarlock on the oar are represented by $\vec{F}_{r,o}$, $\vec{F}_{w,o}$ and $\vec{F}_{p,o}$ respectively. Based on previous research [48, 98], the points of application of $\vec{F}_{r,o}$ and $\vec{F}_{w,o}$ were assumed to be 0.05 m away from the tip of the handle and 0.2 m away from the end of the blade respectively. The inboard length of the oar ($l_i^{x'}$) was determined as the distance of the point of application of $\vec{F}_{r,o}$ to the oar pin, while the outboard length of the oar ($l_o^{x'}$) was determined as the distance of the point of application of $\vec{F}_{w,o}$ to the oar pin.

in travel direction of the boat (as indicated by "x" in subscript):

$$\overline{P}_{residual} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (-m_r \cdot a^x_{rcom/w} \cdot v^x_{b/w}) \mathrm{d}t. \tag{4.5}$$

m_r was measured using a pre-calibrated conventional digital scale. $a^x_{rcom/w}$ was calculated from the acceleration of the 13 body segments in boat movement and the related masses of the segments relative to the rower's total mass according to the Zatsiorsky-Seluyanov's relative body segment model [18, 99]. This IMU-based estimation of $a^x_{rcom/w}$ was previously shown to yield valid results regarding the rower's CoM acceleration in the travel direction of the boat [57].

$v^x_{b/w}$ was computed by combining the average boat velocity ($\overline{v}^x_{b/w}$) of at least seven steady-state stroke cycles determined by GPS, and the integral of the acceleration of the boat in the direction of travel ($\int a^x_{b/w}$):

$$v^x_{b/w} = \int_{t_0}^{t_0+T} (a^x_{b/w})\mathrm{d}t - \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (a^x_{b/w})\mathrm{d}t + \overline{v}^x_{b/w}. \tag{4.6}$$

$\overline{P}_{rower}$ was calculated according to classical Newtonian mechanics (see [38] for an extended overview):

$$\begin{aligned} \overline{P}_{rower} = &- \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (M^z_{F_{o,r(p)}} \cdot \omega^z_{o/b(p)} + M^z_{F_{o,r(s)}} \cdot \omega^z_{o/b(s)})\mathrm{d}t \\ &- \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (m_r \cdot a^x_{rcom/w} \cdot v^x_{b/w})\mathrm{d}t. \end{aligned} \tag{4.7}$$

To obtain oar angular velocities of the portside and starboard oar ($\omega^z_{o/b(p)}$ and $\omega^z_{o/b(s)}$, respectively) the time derivative of the measured oar angles were taken. Assuming oar inertia to be negligible, the equation of motion of an oar was used to calculate the moment around the portside and starboard oar ($M^z_{F_{o,r(p)}}$ and $M^z_{F_{o,r(s)}}$, respectively):

$$\vec{F}_{p,o} = -\vec{F}_{r,o} - \vec{F}_{w,o} \tag{4.8}$$

and:

$$F^{x'}_{r,o} \cdot {l_i}^{x'} = F^{x'}_{w,o} \cdot {l_o}^{x'}. \tag{4.9}$$

Since:

$$M_{F^{z'}_{o,r}} = -M_{F^{z'}_{r,o}} = -(F^{x'}_{r,o} \cdot {l_i}^{x'}), \tag{4.10}$$

$$M_{F^{z'}_{o,r}} = \frac{l^{x'}_i \cdot l^{x'}_o}{l^{x'}_i + l^{x'}_o} \cdot F^{x'}_{p,o}. \tag{4.11}$$

Finally, the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ $(ratio_{res./rower})$ was calculated as:

$$ratio_{res./rower} = \frac{\overline{P}_{residual}}{\overline{P}_{rower}}. \tag{4.12}$$

4.2.6 Protocol

At the start of the experiment participants were informed about the aim and the protocol of the study after which they provided written informed consent. After a warming up in which participants familiarised themselves with the experimental setup, participants were weighed, and the inertial sensors were placed on the participant's body segments using lightweight Velco-straps. Subsequently, trials were performed in randomised order with short breaks between trials.

4.2.7 Data analyses

Data collected with inertial sensors, measured at 60 Hz, were interpolated linearly to 100 Hz in order to match the sampling frequency of the Peach data. Data were high-pass filtered with a cut-off frequency of 0.05 Hz using a bi-directional fourth-order Butterworth filter to remove potential offset from boat acceleration. Data from the boat and rower were synchronised using a cross-correlation algorithm using the boat acceleration signal and the acceleration signal of the feet. To calculate $\overline{P}_{rower}$ and $\overline{P}_{residual}$, the start of strokes had to be determined. Stroke start was defined as the instant at which the filtered (low-pass filtered with 4 Hz cutoff) average of the two oar angular signals changed sign from negative to positive (see Figure 4.3 for a typical example). For every trial the average P_{rower} and $P_{residual}$ of at least 7 to 12 consistent stroke cycles in each direction of travel were selected for statistical analyses. For five trials, only data from one direction of travel were included since data from the opposite direction were not available.

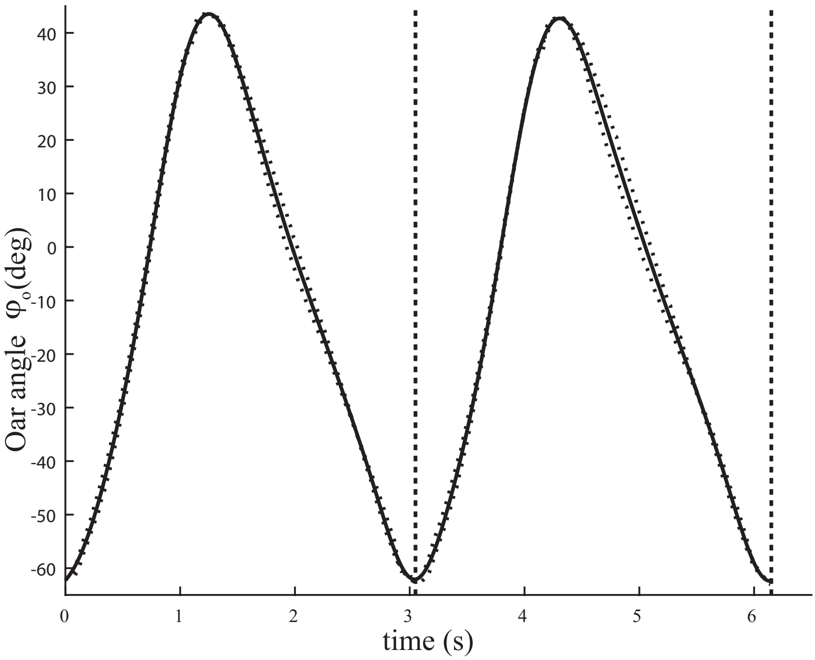

Figure 4.3. A typical example of the portside and starboard oar angle signals (dashed lines) and the averaged oar angle of the portside and the starboard oar (black). The vertical dashed lines indicate the occurrence of the catch, which is defined as the average of the two oar angular signals changed sign from negative to positive.

To check adherence to stroke rate and force instructions in every condition, stroke rate and forces were averaged over the selected strokes. Inspired by Lamb's vector loop modelling [54], the adherence to the technique instructions was evaluated by calculating the average relative contribution of the hip velocity to shoulder velocity in boat direction ($v^x_{hip/b}$ and $v^x_{sh/b}$, respectively) for the first 33 % of every stroke:

$$v^x_{sh/b} = v^x_{hip/b} + v^x_{sh/hip}, \tag{4.13}$$

$$ratio_{v^x_{hip/b}} = \frac{v^x_{hip/b}}{v^x_{sh/b}}. \tag{4.14}$$

4.2.8 Statistical analyses

Statistical analyses were performed using SPSS 21. Means and SDs were calculated to check whether participants complied with the prescribed stroke rate. Repeated measures ANOVAs and post-hoc tests (LSD) with significance levels of 0.05 were conducted to check for compliance to the technique and force instructions.

In order to quantify the difference between a rower's mechanical power output calculated using the common proxy and the true power output for different rowers under different rowing conditions, descriptive statistics (means and SDs) of $ratio_{res./rower}$ values were calculated. A linear-mixed model analysis with restricted maximum likelihood estimation was applied to examine whether variation in $ratio_{res./rower}$ values was due to differences in rower's mass, stroke rate, technique and/or forces applied to the oar:

$$ratio_{res./rower_{ij}} = \gamma_{00} + \gamma_{1j} \cdot condition_{ij} + \gamma_{01} \cdot m_{rj} + e_{ij} + u_{0j}. \tag{4.15}$$

In which $ratio_{res./rower_{ij}}$ is the predicted $ratio_{res./rower}$ value per rower (j) per rowing condition (i), and $condition_{ij}$ the specific rowing condition per rower. m_{rj} is the mass per rower and e_{ij} is the residual error at rowing condition level, while u_{0j} is the residual error at rower level.

4.3 Results

4.3.1 Compliance to the rowing conditions

Regarding stroke rate, participants deviated on average not more than 1.5 strokes min^{-1} from the imposed stroke rate.

As is illustrated in Table 4.3, a repeated measures ANOVA showed that, participants' relative contribution of the hip velocity to shoulder velocity was higher during the first 33 % of the stroke in the early knee extension condition compared to the reference trial, whereas it was lower in the early trunk extension condition compared to the reference trial.

Regarding the force trials, a repeated measures ANOVA showed that, as instructed, participants applied on average less force in the low force trial compared to the reference trial, whereas they applied more force during the stroke in the high force trial (see Table 4.3).

Together, these results indicate that participants satisfactory complied with the instructions, which resulted in a data set containing a wide range of rowing conditions.

4.3.2 Typical examples

Figures 4.4 and 4.5 illustrate a typical example of one rower rowing 4 strokes cycles at a frequency of 25 strokes min^{-1} (the vertical dashed lines implicate the finish of the strokes). It can be observed from these figures that behaviour during these four stroke cycles was very similar, indicating not only that between-stroke-cycle variations were small, but also that behaviour was mostly periodic in all respects.

Table 4.3. Mean values (M) for every rowing condition and standard deviations (SD) between rowers for stroke rate, force and technique.

	n	**Stroke rate (min^{-1})** M (SD)	**Hip velocity contribution (%)** M (SD)	**Force (N)** M (SD)
Reference	9	19.1 (.9)	.71 (.08)	142.4 (38.4)
Stroke rate 25	9	25.2 (.3)	.73 (.06)	181.8 (50.9)**
Stroke rate 32	8	32.0 (1.0)	.72 (.09)	237.2 (54.8)**
Early knee extension	9	18.9 (1.1)	**.76 (.10)***	133.1 (36.5)
Early trunk extension	9	19.3 (1.2)	**.64 (.11)****	130.6 (44.2)
Light stroke	9	18.1 (1.0)	.70 (.07)	**100.7 (28.1)****
Strong stroke	9	19.0 (.9)	.70 (.10)	**164.1 (40.9)****

**Differs from reference trial with $p < .05$ (not tested for stroke rate)*
*** Differs from reference trial with $p < .01$ (not tested for stroke rate)*

4.3.3 Average magnitude of $ratio_{res./rower}$ values

The overall mean $ratio_{res./rower}$ value of all conditions and rowers was 0.123 (SD = .011) (see Table 4.4). This implies that, on average, true mechanical power output was underestimated with 12.3 % when calculating power output using the common proxy (Equation 4.2).

Table 4.4. Mean values (M) and standard deviations (SD) of $\overline{P}_{residual}$, $\overline{P}_{rower}$ and $ratio_{res./rower}$.

	$\overline{P}_{residual}$ (N) M (SD)	range	$\overline{P}_{rower}$ (N) M (SD)	range	$ratio_{res./rower}$ M (SD)	range
Reference	23 (4.5)	19 - 33	198 (48.4)	123 - 260	.120 (.013)	.09 - .13
Stroke rate 25	35 (8.5)**	25 - 52	280 (66.5)**	189 - 241	**.126 (.012)****	.10 - .14
Stroke rate 32	53 (9.4)**	43 - 72	339 (80.9)**	278 - 453	**.133 (.008)****	.11 - .14
Early knee extension	21 (4.4)*	17 - 31	178 (44.4)*	118 - 233	.117 (.010)	.09 - .13
Early trunk extension	23 (7.8)	15 - 40	183 (63.8)	109 - 173	**.127 (.009)***	.11 - .14
Low intensity	15 (4.5)**	10 - 25	121 (35.6)**	67 - 169	.121 (.008)	.11 - .13
High intensity	28 (5.4)**	22 - 39	235 (57.9)**	156 - 291	.119 (.011)	.09 - .13
Overall	*28 (13)*	*10 - 72*	*225 (98.8)*	*67 - 453*	*.123 (.011)*	*.09 - .14*

**Differs from reference trial with $p < .05$*
*** Differs from reference trial with $p < .01$*

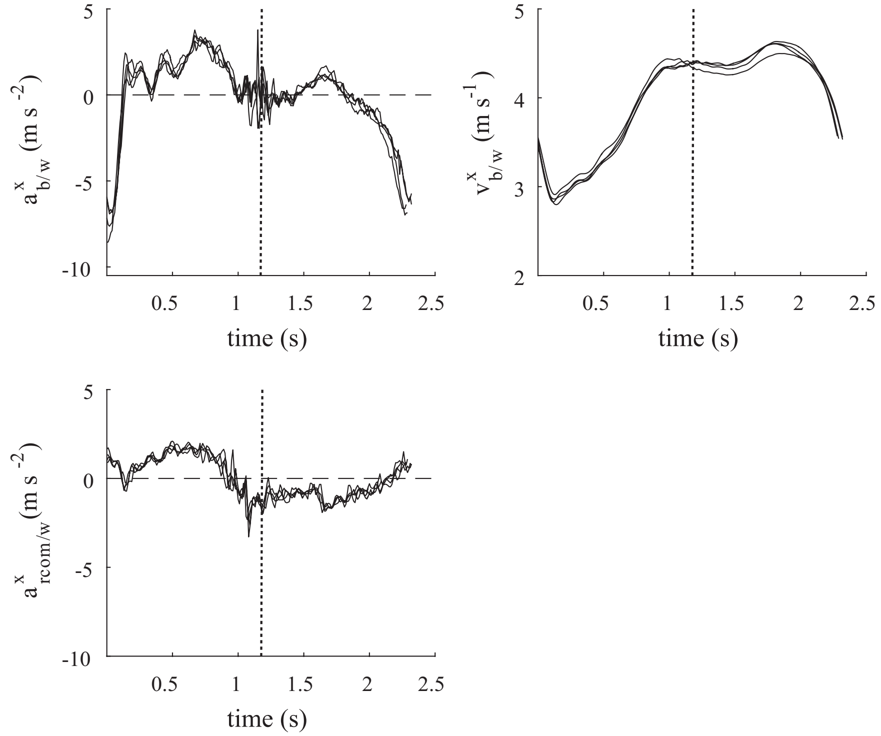

Figure 4.4. Typical examples of boat acceleration in the direction of travel of the boat relative to the world ($a^x_{b/w}$), boat velocity in the direction of travel relative to the world ($v^x_{b/w}$), and the rower's CoM acceleration in travel direction relative to the world ($a^x_{rcom/w}$) of four consecutive stroke cycles of one participant rowing at stroke rate 25. For each stroke cycle, instance of the catch occurs by definition at t = 0 seconds, while the average finish of the stroke phases is indicated with a vertical dashed line.

4.3.4 Variations in $ratio_{res./rower}$ values

To examine the variations in underestimations of true mechanical power output across rowers and rowing conditions, descriptive statistics and a multilevel analysis on $ratio_{res./rower}$ values were conducted. Table 4.4 shows that average $ratio_{res./rower}$ values per rowing manipulation ranged between .117 and .133 with SDs ranging between .008 and .13. These results imply that, depending on rowing conditions, the average mechanical power output of a rower is underestimated with values between 11.7 % and 13.3 % when common proxy calculations are applied, with small variations across rowers. A multilevel analysis revealed that 51.3 % of the total variation in $ratio_{res./rower}$ values was between rowers, while 48.3 % of this variation was within rowers.

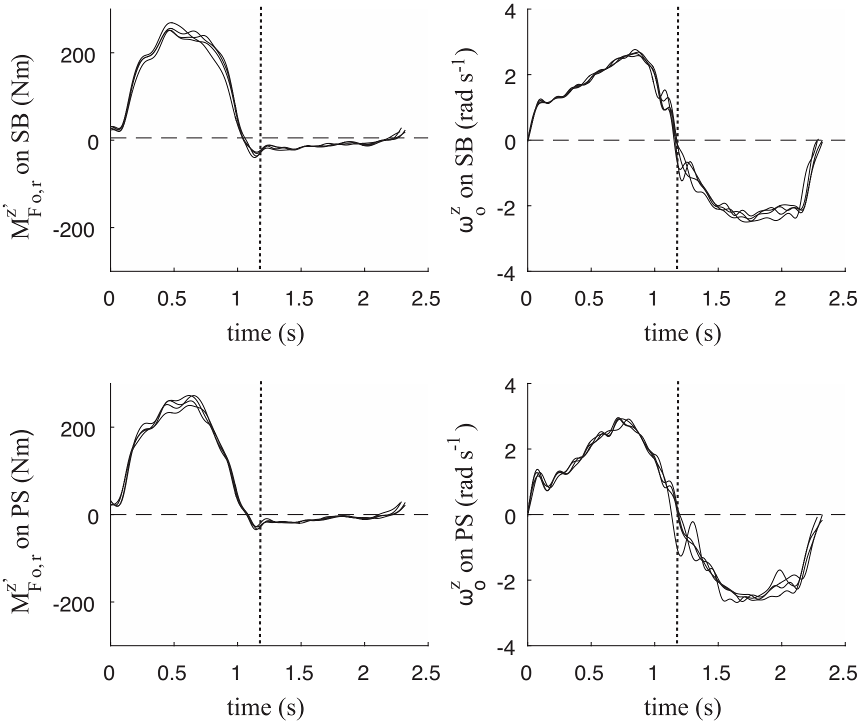

Figure 4.5. Typical examples of $M_{F_{o,r}^{z'}}$ and oar angular velocity ($\omega^{z'}_{o/b}$ of the starboard (S) oar and port side (P) oar of four consecutive stroke cycles of one participant rowing at stroke rate 25. For each stroke cycles, instance of the catch occurs by definition at t = 0 seconds, while the average finish of the stroke phases is indicated with a vertical dashed line.

Variation in $ratio_{res./rower}$ values across participants was not explained by rowers' mass (t(7.03) = 1.83, p = .11).

Variation in $ratio_{res./rower}$ values within rowers was for 43.8 % explained by rowing conditions: a main effect of rowing conditions on $ratio_{res./rower}$ was found (F(46.10) = 7.80, p < .001). Post-hoc analyses revealed that $ratio_{res./rower}$ values were significantly affected by stroke rate and technique, but not by forces applied at the handle of the oar.

$ratio_{res./rower}$ values in all stroke rate conditions differed significantly from each other: the higher the stroke rate, the higher $ratio_{res./rower}$ values (see Table 4.4). This implies that the higher the stroke rate, the more the true power output was underestimated when calculated according to the commonly used proxy described by Equation 4.2.

Regarding technique manipulations, only an early trunk extension seemed to result in slightly higher $ratio_{res./rower}$ values compared to a rower's normal technique (reference condition). No difference in $ratio_{res./rower}$ values were found when participants applied an early knee extension compared to their common technique. This implies that the true power output was underestimated more using common calculation when rowers extend their hips early in the stroke (see Table 4.4).

4.4 Discussion

The difference between the average mechanical power output calculated using the common proxy and the average true power output of a rower equals the mean of a rower's mass multiplied with the rower's CoM acceleration and the boat velocity ($\overline{P}_{residual}$). In this on-water study we quantified this difference and tested the dependency of this difference on rowing situations. Most importantly, we have found that calculating a rower's power output using the common proxy indeed causes an underestimation of the true power output of 12.3 % with relatively small variations between and within rowers.

Part of this variation was explained by rowing conditions, in particular stroke rate and technique. Regarding stroke rate, a relatively larger increase of $\overline{P}_{residual}$ than $\overline{P}_{rower}$ resulted in an increase of the underestimation of the true power output from 12.0 % when rowing at 18 strokes min^{-1} to 13.3 % when rowing at 32 strokes min^{-1}. Regarding technique, an early trunk extension during the stroke reduced $\overline{P}_{rower}$ but not $\overline{P}_{residual}$, compared to normal technique. This resulted in an increase of the underestimation of the true power output from 12.0 % during normal technique to 12.7 % when applying an early trunk extension. However, this result may be considered as marginal, especially because participants applied extreme "errors" in the technique conditions that are not common in daily practice.

Although $\overline{P}_{residual}$ and $\overline{P}_{rower}$ both increased when rower mass increased, the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ did not change. Since statistics were based on only nine rowers, future research including more participants with different masses is required to determine if a rower's mass affects the underestimation of power output.

The average underestimation of power output reported in this study is slightly smaller than the findings reported from experimental data by Kleshnev [49]. This difference may be due to the way true power output was determined. Kleshnev determined power output using forces at the foot stretcher and the oarlocks. Since those forces are high and opposing, this approach is very sensitive to errors in the measurements [38]. In order to reduce these potential errors we replaced foot stretcher forces and determined power output using the common proxy and the power term that is related to the rower's CoM acceleration ($\overline{P}_{residual}$). Since this approach is less vulnerable to significant errors, we expected this approach to provide true values of power output.

Concerning the calculations of $\overline{P}_{residual}$ and $\overline{P}_{rower}$ and the possible effect on our main outcome "the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$", some methodological issues need to be addressed. Firstly, our sample size was rather low. However, we mainly aimed to quantify the the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ under different rowing circumstances. Therefore, we argue that our small but heterogenic sample in combination with seven different rowing conditions provided sufficient data to get insight in the the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ under different rowing circumstances. Secondly, based on previous studies [48, 98], we assumed the point of application of $\vec{F}_{r,o}$ and $\vec{F}_{w,o}$ to be in the middle of the oar grip and the centre of the oar blade (0.05 and 0.2 m) from both outer sides of the oar, respectively (see Figure 4.2). Erroneous estimates of those application points likely influence $\overline{P}_{rower}$ (see Equation 4.11) and, therefore, the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$. Sensitivity analyses, however, showed that changes in point of applications of 80 % to 120 % only marginally affect the average ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ from 0.123 to at most 0.125. Thirdly, in order to calculate both $\overline{P}_{residual}$ and $\overline{P}_{rower}$ we used a GPS to measure the low-frequency variations in boat speed. Previous studies [15, 20, 41], however, showed low validity of velocity data based on GPS over short distances. To increase validity, we averaged GPS speed over the 7–12 steady-state strokes of every trial. To test the effect of possible errors in GPS data on our outcome variable, we conducted sensitivity analyses in which the average speed per trial, measured with GPS, was manipulated with 95 % or 105 % of the measured velocity. The analyses showed that the ratio term was not affected by errors in velocity data measured with GPS.

In order to implement the results of this study, it is worth noting that the results are based on tests conducted in single sculls. The same equation for calculating $\overline{P}_{residual}$ and $\overline{P}_{rower}$ holds true for rowers in crewed boats, but it is currently unknown if the outcome values of both parameters — and more importantly the average ratio value of $\overline{P}_{residual}$ to $\overline{P}_{rower}$ — is similar to the values reported here. The average boat velocity throughout a stroke cycle differs when crew size increases, as well as the boat velocity pattern and probably the CoM acceleration pattern. Testing the effect of crew size and possible interaction of other rowers on the underestimation of the true mechanical power output is an area for future research.

4.5 Conclusions, practical implications and future research

In summary, we have shown that the common proxy to calculate power output results in a substantial underestimation of rower's true power output by 12.3 % on average. Most variation was found within participants and mainly due to stroke rate differences: higher stroke rates resulted in slightly larger underestimations of the true power output. We only evaluated three stroke rate frequencies; future research is required to examine the precise relation between stroke rate frequencies and the ratio of $\overline{P}_{residual}$ to $\overline{P}_{rower}$.

In all cases where a quantitative estimate of the true mechanical power output of a rower is desired, we recommend to multiply the power output calculated using the common method (see also Equation 4.2) by 1.14 (which is equal to 1/(1-the average $ratio_{res./rower}$)). Relevant cases are, for example, a comparison of a rower's mechanical power output between on-water and on-land training sessions, and monitoring or controlling training intensity using innovative real-time feedback.

In cases where a high-accurate estimation of mechanical power output is critical, for example in quantitative research or in crew selection processes focused on the delivered mechanical power output of individual rowers, we suggest to determine $\overline{P}_{residual}$ directly from the rower's CoM acceleration, the mass of the rower and the velocity of the boat (see Equation 4.3). We are aware that — from a practical perspective — using all segment accelerations to determine a rower's CoM acceleration is not feasible. Therefore, further research is required to examine whether CoM acceleration can be accurately determined using a sensor system that is simple enough to be used routinely.

Chapter 5

Real-Time Feedback on Mechanical Power Output: Facilitating Crew Rowers' Compliance With Prescribed Training Intensity

Based on:
Lintmeijer, L.L., Soest, A.J.,Robbers, F.S, Hofmijster, M.J., Beek, P.J. Real-Time Feedback on Mechanical Power Output Facilitates Crew Rowers to Comply With Prescribed Training Intensity . *International Journal of Sports Physiology and Performance* **14:3**, 303:309. Doi: 10.1123/ijspp.2018-0128 (2019).

Athletes require feedback in order to comply with prescribed training programs designed to optimise their performance. In rowing, current feedback parameters on intensity are inaccurate. Mechanical power output is a suitable objective measure for training intensity, but due to movement restrictions related to crew rowing, it is uncertain whether crew rowers are able to adjust their intensity based on power-output feedback. The authors examined whether rowers improve compliance with prescribed power-output targets when visual real-time feedback on power output is provided in addition to commonly used feedback. A total of 16 crew rowers rowed in three training sessions. During the first two sessions, they received commonly used feedback, followed by a session with additional power-output feedback. Targets were set by their coaches before the experiment. Compliance was operationalised as accuracy (absolute difference between target and delivered power output) and consistency (high- and low-frequency variations in delivered power output). Multilevel analyses indicated that accuracy and low-frequency variations improved by, respectively, 65 % ($p > .001$) and 32 % ($p = .024$) when additional feedback was provided. Compliance with power-output targets improved when crew rowers received additional feedback on power output. Two additional observations were made during the study that highlighted the relevance of power-output feedback for practice: (1) there was a marked discrepancy between the prescribed targets and the actually delivered power output by the rowers, and (2) coaches had difficulties perceiving improvements in rowers' compliance with power-output targets.

5.1 Introduction

In endurance sports, physical fitness is essential for performance. To improve fitness, training load should be optimal, that is, one that exceeds the physical capacities of an athlete such that supercompensation occurs, but not to such an extent that it leads to adverse physical effects (e.g. [61]). To support athletes in achieving an optimal training load, coaches prescribe balanced training programs that vary in training volume (duration and frequency of training sessions) and intensity (an athlete's rate of metabolic energy consumption; e.g. [7, 42, 60, 83, 84]). Furthermore, coaches have to ensure that athletes comply with the prescribed training loads.

In rowing, achieving compliance with prescribed intensity is not trivial because feedback on the rate of metabolic energy consumption cannot be routinely provided to the rowers. Therefore, in current practice, derivatives of the rate of metabolic energy consumption, such as boat velocity, stroke rate (number of strokes min^{-1}), and heart rate, are used as indirect measures of training intensity [28, 81, 86, 90]. In addition, coaches use their own subjective observations of rowers' executed intensity to provide intensity feedback.

Unfortunately, the suitability of the previously mentioned parameters as indices for training intensity is limited. After all, stroke rate and velocity reflect the joint effort of all rowers in a crew, rather than the individually experienced intensity. Moreover, these parameters are affected by external factors, such as weather circumstances and water conditions. Heart rate is a more adequate derivative of individual training intensity, but —— due to the delay in heart rate response to physical activity and the limit of maximal heart rate —— the usability of heart rate as a feedback parameter for training intensity is restricted as well, especially for intermittent and high intensity training sessions [1]. Besides, heart rate is also affected by the rower's state [1, 83]. Coaches' observations are subjective and thus may not be accurate either. Therefore, a more suitable and valid feedback parameter is required to assist rowers to attain prescribed levels of training intensity.

From a biophysical perspective, average mechanical power output over one or few stroke cycles (in this chapter shortened to "power output") constitutes a suitable measure to control rowers' compliance with training intensity as it is (1) strongly related to a rower's rate of metabolic energy consumption

[35] and (2) hardly affected by external factors. From a practical perspective, power output represents an interesting feedback parameter, as complementary theoretical and technological advances have made it possible to provide real-time visual feedback on valid power-output values during on-water training sessions [56].

A priori, it is not evident that power-output feedback will help rowers to comply with prescribed training intensities, especially when they row in a crew. Numerous experimental feedback studies have shown that people can change movement patterns based on external visual feedback when they perform an individual perceptual-motor task [62, 63, 79]. Moreover, in real-life individual sport tasks like cycling, the widespread use of power meters suggests that cyclists can change training intensity based on power-output feedback. These indications that athletes are able to change power output based on power-output feedback may be generalised to individual single scull rowers. However, whether the same holds for rowers in crewed boats is not certain because crew rowers have to coordinate their movement patterns with those of the other crew members. This means that stroke rate is determined primarily by the stroke rower (i.e., the one at the stern most position of the boat), while the others are expected to follow. Furthermore, a rower's stroke length is constrained by that of the other rowers. As shown in the "Methods" section, both parameters affect a rower's power output. Therefore, it is by no means evident beforehand that crew rowers will be able to comply with prescribed power-output targets, even in the presence of feedback on actual power output.

Consequently, the aim of the present study was to examine whether compliance with prescribed power-output targets of well-trained crew rowers is enhanced when visual real-time feedback on individual power output is provided. In the "Discussion" section, we reflect on the relevance of introducing feedback on power output in rowing training practice, based on qualitative observations made during the study.

5.2 Methods

5.2.1 Design

Rowers performed three training sessions in crews. To check for daily variations in compliance unrelated to the type of feedback, rowers only received commonly used feedback on intensity (i.e., the stroke rower received visual feedback on stroke rate and boat velocity, whereas the others only received feedback from the coach) during the first two sessions (no additional feedback, nAF1 and nAF2). During the last session, additional visual feedback on power output was provided (additional feedback, AF) to examine the (additional) effect of power-output feedback on rowers' compliance.

Training load was determined by the coaches prior to the experiment: A session consisted of three 2-km trials at "extensive duration" (ED) intensity and one 1.5-km trial at "anaerobic threshold" (AT) intensity. These intensities are frequently used in The Netherlands and correspond to Seiler's classification [77] of "low intensity" and "threshold intensity" training. Power-output targets for ED and AT intensity were specified by the coaches and were based on previous ergometer scores. Compliance with power-output targets was quantified in terms of (1) absolute difference between target power output and delivered power output (accuracy) and (2) high- and low-frequency variations (HF and LF consistency) in delivered power output.

During nAF, stroke rowers received visual feedback on stroke rate and boat velocity, whereas the other rowers only received regular verbal feedback from the coach who cycled alongside the boat. During AF rowers received additional real-time feedback on (1) their average power output over each stroke cycle and (2) a cumulative average of power output from the start of the trial until the last stroke cycle of the trial via android smartphones (see Figure 5.1 for an impression of the feedback).

To limit the influence of confounding variables, we conducted all three sessions at the same time of day within a 1-week time span. The study was approved by the local ethical committee of the Department of Human Movement Sciences of the Vrije Universiteit Amsterdam.

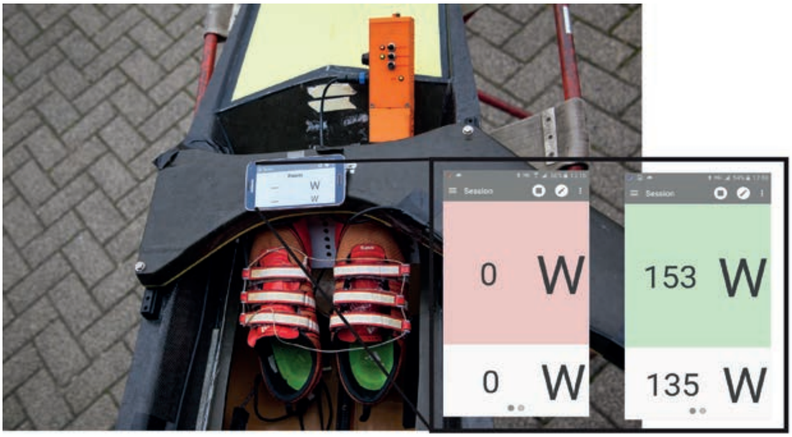

Figure 5.1. (a) Overview of the feedback system mounted on the boat's rigger, and (b) an example of the presented real-time feedback on power output averaged per stroke and per trial.

5.2.2 Participants

In total, four coach teams, consisting of two coaches per team, and 18 well-trained rowers (categorisation based on [67]) participated in the study. The number of training sessions per crew ranged from seven to 12 sessions per week including on-water sessions, ergometer sessions, and others sessions such as strength training and cycling. Data from two rowers were excluded from analyses: one rower reported a large difference in fatigue over training sessions (Δ 15 points on the fatigue scale of the Dutch version of the Profile of Mood States, POMS [92]), whereas another rower perceived his power-output targets as unattainable. Analyses were thus based on a data set of 16 rowers (see Table 5.1 for characteristics).

5.2.3 Protocol and instructions

Prior to the experiment, in-depth interviews with the coaches were held in order to obtain information about their commonly prescribed training intensities during ergometer and on-water training sessions and to inform them about the study. The interviews revealed that most coaches define on-water training intensity for ED and AT in terms of stroke rate and split times of the boat.

Table 5.1. Rower and coach characteristics per boat: (1) a men scull four without coxwain (M4x), (2) a men sweep four without coxwain (M4), (3) a women sweep four with coxwain (W4+), (4) a women scull four with coxwain (W4x+), and (5) a women scull two without coxwain (W2x).

	Gender	Age (y) M (SD)	Experience (y) M (SD)	Level*	Training sessions per week (n) Boat	Ergo	Other	Coach experience (y) Coach 1	Coach 2
M4x	Male	24.7 (2.2)	7.0 (1.8)	Well-trained	9	0	3	5	>20
M4	Male	22.7 (2.5)	2.6 (0.5)	Well-trained	7	1	3	3	8
W4+	Female	24.7 (3.0)	2 (0.8)	Trained	5	2	1	>20	>20
W4x+	Female	24.0 (2.7)	2.3 (0.3)	Trained	5	2	1	>20	>20
W2x	Female	23.4 (1.7)	4.5 (1.4)	Well-trained	3	2	2	2	8

**Categorisation is based on [67].*

Two coaches rationalised on-water training intensity partly on heart rate zones as well. When asked to specify individual training intensity for ED and AT in terms of power-output targets, coaches used information on relevant individual performance parameters obtained during ergometer rowing, such as the average 500 m split time during a 2000 m all-out test, and split times during ED and AT training sessions. Before the first session, rowers were informed about the study's aim and protocol. Coaches and rowers provided informed consent.

At the start of each training session, rowers filled out the fatigue sub-scale of the POMS [92]. Next, they were instructed to stay close to their power-output targets during all trials. Prior to AF, rowers were further instructed that they would be supported with numerical feedback on power output for each stroke cycle as well as colour-coded feedback, that is, the phone's display coloured green when rowers were close to their power-output target and red when they were far removed from this target (see Figure 5.1 for an impression of the feedback). Colour thresholds were based on $\pm$ 1 SD of their delivered power output in the ED and AT intensity trials during nAF.

Power-output targets were printed on a laminated sheet of paper, which was placed beside the smartphone. Sessions started with a warming-up, followed by the trials. Prior to each trial, instructions about the desired intensity were repeated.

5.2.4 Instrumentation

All boats were equipped with instrumented oarlocks (Peach Innovations Ltd, Cambridge, United Kingdom). Strain gauges and a reed sensor in the oarlocks measured forces at the oar pin in the movement and transverse direction of the boat and the oar angle in the horizontal plane, respectively. Sensor output was sampled at 100 Hz and stored on an SD card using a custom-made Arduino-based data acquisition system (Vrije Universiteit Amsterdam, The Netherlands; DAQ) mounted on the boat.

Smartphones (Samsung Galaxy S5 or S6; Samsung Engineering Co., Ltd, Seoul, Korea) were placed on the riggers and used as visual feedback devices (see 5.1). They were connected to the DAQ using IOIO-OTG boards (SparkFun Electronics, Boulder, CO) and CSBLUEKEY100 version 2.1 bluetooth dongles (König Electronics, NEDIS BV, 's-Hertogenbosch, Netherlands). A custom-made application provided power-output feedback for each stroke cycle.

5.2.5 Determination of output variables

Compliance with power-output targets was operationalised for each trial in terms of accuracy and HF and LF consistency.

Accuracy was calculated as the absolute difference between average delivered power-output per trial ($\overline{P}_{trial}$) and the power-output target ($\overline{P}_{target}$). To obtain $\overline{P}_{trial}$, we first calculated the work per stroke cycle (Wcycle) as the integral of handle moment ($\vec{M}_{F_{o,r}}$) over handle angular displacement ($\vec{\Phi}_{o/b}$):

$$W_{cylce} = c\int_{\Phi_0}^{\Phi_1}(\vec{M}_{F_o,r})\mathrm{d}\Phi. \tag{5.1}$$

where c is a correction factor of 1.14 that corrects for the error in W_{cylce} caused by the use of a non-inertial frame of reference (see [56] for details). To obtain $\vec{M}_{F_{o,r}}$, we assumed that: (1) the oar is rigid, (2) oar inertia is negligible, and (3) the points of application of the forces on handle and blades are known and fixed (based on [48, 98]).

Subsequently, $\overline{P}_{trial}$ could be calculated as:

$$\overline{P}_{trial} = \frac{\sum_{i=1}^{n} W_{cycle}}{T_{trial}}. \tag{5.2}$$

where T_{trial} is the time duration of the trial in seconds, and n is the number of strokes in the trial.

LF consistency was calculated as the SD of a 20-cycle centred moving average of delivered power output, thus capturing LF fluctuations in power output.

HF consistency captured stroke-to-stroke fluctuations in power output. It was calculated as the SD of the stroke-to-stroke power output for each trial; power output for each stroke was determined as Wcycle divided by the stroke cycle duration.

Lower accuracy values imply smaller systematic errors, and lower HF and LF consistency values imply smaller HF and LF variations in power output. To avoid misinterpretations, note that *lower* values for accuracy, HF and LF consistency will be referred to as *better* compliance values.

Fatigue was measured using the "fatigue" sub-scale of the Dutch POMS [92]. Six symptoms of fatigue, like "exhausted", were measured prior to each training session and rated on a 5-point-Likert scale, ranging from 0 (absolutely not) to 5 (very good).

5.2.6 Data analyses

Data collected with the instrumented oarlocks were analysed using MATLAB 2015b (The MathWorks Inc, Natick, MA). To calculate output variables, stroke starts were determined according to the definition of Lintmeijer et al. [56]. In sweep rowing, a stroke start was defined to occur at the minimum oar angle and in sculling at the average minimum oar angle of the portside and starboard oar. Oar angle was low-pass filtered using a bidirectional fourth-order Butterworth 4 Hz cutoff filter. For every ED and AT intensity trial, the middle 120 and 100 steady-state strokes were selected for analysis, respectively. Selection was based on the boat acceleration pattern and the oar angle signals. For one ED trial, only data of 90 strokes were available for analysis.

5.2.7 Statistical analyses

Statistical analyses were performed using the statistic toolbox of MATLAB 2015b (The MathWorks Inc, Natick, MA). For $\overline{P}_{target}$ and $\overline{P}_{trial}$, means and SDs of ED and AT intensity per boat per training session were provided.

Premodel: Day-to-Day Differences

To check for differences in rowers' fatigue prior to the sessions, a repeated-measured analysis of variance with three factors (i.e., the different training sessions) was conducted on the POMS scores. As for all statistical tests, significance level was set at $p < .05$. Subsequently, using multilevel analyses, possible day-to-day differences in compliance unrelated to type of feedback were examined while taking the hierarchical structure of the data into account; that is, repeated measurements (m) of rowers (r) in boats (b):

$$\begin{aligned}
Accuracy_{mrb} =& \gamma_{000} + \gamma_{100} \cdot nAF_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot nAF_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}, \qquad (5.3a) \\
LFconsistency_{mrb} =& \gamma_{000} + \gamma_{100} \cdot nAF_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot nAF_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}, \qquad (5.3b) \\
HFconsistency_{mrb} =& \gamma_{000} + \gamma_{100} \cdot nAF_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot nAF_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}. \qquad (5.3c)
\end{aligned}$$

Here, γ_{000} is the intercept of the model and γ_{n00} are the regression coefficients. e_{mrb} is the observation error at the measurement level, while u_{0rb} and v_{00b} reflect the variability around the intercept due to rowers and boats, respectively.

Importantly, γ_{100} reflects the difference in compliance with power-output targets between nAF1 and nAF2, whereas γ_{300} reflects an interaction effect of nAF and intensity.

Main Model A: Effect of Additional Feedback

Analyses of the premodel revealed no day-to-day differences in rowers' compliance unrelated to feedback (see "Results" section). Therefore, the effect of additional feedback on rowers' compliance with power-output targets (γ_{100}) was examined by comparing the combined data of the nAF sessions with data from the AF session, using multilevel analyses. In addition, we tested the interaction effect of feedback and intensity (γ_{300}) on compliance with power-output targets:

$$
\begin{aligned}
Accuracy_{mrb} =& \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}, && \text{(5.4a)} \\
LFconsistency_{mrb} =& \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}, && \text{(5.4b)} \\
HFconsistency_{mrb} =& \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} \\
&+ \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} \\
&+ v_{00b} + u_{0rb} + e_{mrb}. && \text{(5.4c)}
\end{aligned}
$$

Local effect sizes were reported when $p < .05$ and calculated analogous to the method described by Selya et al. [78]. According to Cohen's guidelines [14] $f^2 \geq 0.02$, $f^2 \geq 0.15$, and $f^2 \geq 0.35$ represent small, medium, and large effect sizes, respectively.

Main Model B: Differences Between Boats

To examine whether the effect of additional power-output feedback on compliance with power output was similar for all boats, we added random slopes (γ_{100} + γ_{10b}) for boats on the effect of feedback to model A (Equation 5.4).

5.3 Results

5.3.1 Data set

From the data set of 16 rowers, we eliminated data from ED trials from three rowers because those rowers perceived their ED targets as unattainable. In addition, data from seven ED and two AT trials of the AF session (divided over seven rowers) were eliminated because no additional feedback was provided due to technical difficulties (see Table 5.2 for specifications).

5.3.2 Typical Example

Figure 5.2 shows a typical example of one rower rowing at ED and AT intensity when both commonly used and additional feedback was provided. As can be observed, $\overline{P}_{target}$ was higher than $\overline{P}_{trial}$ for all trials. Moreover, accuracy and LF consistency were clearly better in the AF trials relative to the nAF trials.

5.3.3 Prescribed and Executed Intensities

Table 5.2 presents the means and SDs of $\overline{P}_{target}$ and $\overline{P}_{trial}$ per training session per boat. During nAF, rowers' ED intensity targets were higher than the actually delivered power output during ED intensity.

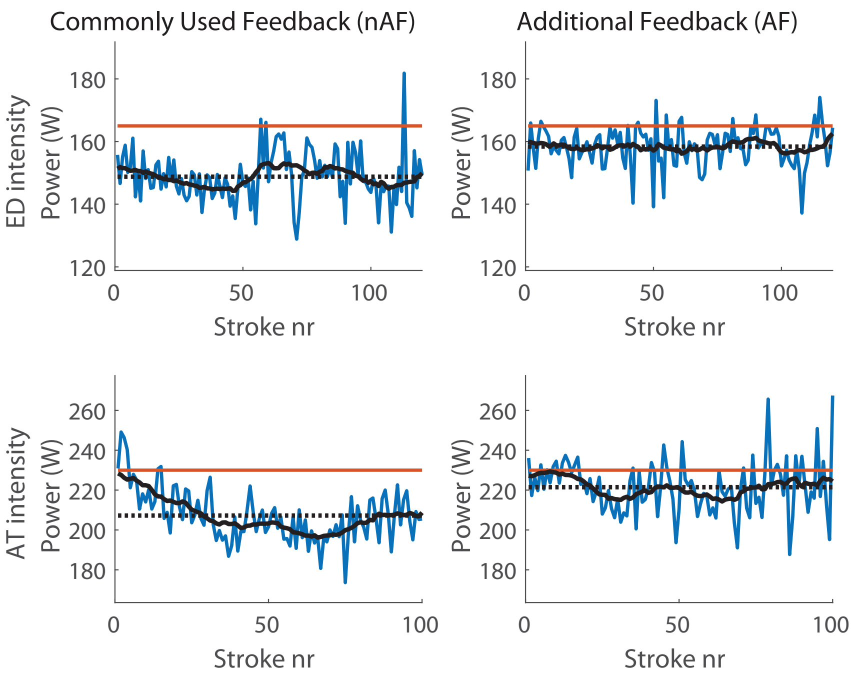

Figure 5.2. A typical example of one rower rowing at "extensive duration" (ED; upper panels) and "anaerobic threshold" (AT; lower panels) intensity with commonly used feedback (nAF; leftmost panels) and additional visual feedback on power output (AF; rightmost panels). All panels present the power-output target ($\overline{P}_{target}$; red line); the average delivered power output per trial ($\overline{P}_{trial}$; black dotted line), the power output per stroke cycle ($\overline{P}_{stroke}$; blue line), and the 20 stroke cycles centred moving average of power output (black line).

5.3.4 Premodel: Day-to-Day Differences

Repeated measures analysis of variance did not reveal differences in POMS scores prior to the training sessions ($M_{nAF1} = 3.59$, $SD_{nAF1} = 2.03$; $M_{nAF2} = 5.00$, $SD_{nAF2} = 3.54$; $M_{AF} = 4.40$, $SD_{AF} = 3.44$; $F(2,28) = 1.467$, $p = .248$), indicating that the 16 rowers did not differ in reported fatigue prior to training sessions.

Multilevel analyses neither revealed a significant difference in accuracy between nAF1 and nAF2, nor a significant nAF-by-intensity interaction effect. Similar results were found for HF and LF consistency (see Table 5.3 for all statistical values). These results indicate that rowers' compliance did not differ between training sessions when only commonly used feedback was provided.

Table 5.2. Means and SDs of the actual delivered power output per trial ($\overline{P}_{trial}$) and the prescribed power-output targets ($\overline{P}_{target}$) for the "extensive duration" (ED) and the "anaerobic threshold" (AT) intensity trials per boat per training session.

	$\overline{\mathbf{P}}_{\mathbf{target}}$		$\overline{\mathbf{P}}_{\mathbf{trial}}$					
			nAF1		**nAF2**		**AF**	
	$\mathbf{n}_{\mathbf{rowers}}$	**M (SD)**	$\mathbf{n}_{\mathbf{trials}}$	**M (SD)**	$\mathbf{n}_{\mathbf{trials}}$	**M (SD)**	$\mathbf{n}_{\mathbf{trials}}$	**M (SD)**
M4x								
ED	4	205 (10)	12a	197 (14)	12a	193 (15)	12a	203 (11)
AT	4	271 (13)	4a	278 (22)	4a	278 (42)	4a	276 (11)
M4								
ED	3	257 (15)	6b	258 (11)	9	239 (18)	8b	261 (9)
AT	3	287 (12)	2b	327 (6)	3	301 (15)	3b	299 (4)
W4+								
ED	2	210 (14)	6	172 (24)	6	178 (24)	4b	196 (11)
AT	3	253 (12)	3	231 (9)	3	245 (11)	2b	242 (10)
W4x+								
ED	3	203 (6)	9	165 (18)	9	167 (12)	8b	192 (13)
AT	4	245 (6)	4	224 (32)	4	220 (23)	3b	237 (18)
W2x								
ED	1	165 (0)	3	139 (8)	3	133 (4)	3	159 (1)
AT	2	240 (14)	2	214 (10)	2	222 (17)	2	229 (11)

- Abbreviations: AF, additional feedback; AT, anaerobic threshold; ED, extensive duration; nAF, no additional feedback.
- Note: During the nAF sessions (nAF1 and nAF2), only commonly used feedback was provided, while rowers received additional visual feedback on power output during the AF session (AF).
- The different boats were: (1) a men scull 4 without coxwain (M4), (2) a men sweep 4 without coxwain (M4), (3) a women sweep 4 with coxwain (W4+), (4) a women scull 4 with coxwain (W4+), and (5) a women scull 2 without coxwain (W2).
- (a) Due to technical problems, during AF, the feedback on power output was based on the power output during the stroke instead of the stroke cycle. Analyses for this boat have been done on the calculated power output during the stroke.
- (b) Note that for some rowers, boats trials are missing due to technological problems with the feedback (AF sessions) or sensors (nAF1; M4).

5.3.5 Main model A: effect of feedback

Tables 5.4 and 5.5 show the effect of additional real-time power-output feedback on rowers' compliance with power-output targets relative to commonly used feedback. A significant main effect of feedback on accuracy was found, but no

Table 5.3. Statistical values obtained from the multilevel analysis on day-to-day differences in compliance (i.e. accuracy, low-frequency consistency and high-frequency consistency) with power-output targets between the training sessions in which commonly used feedback was provided (nAF1 and nAF2).

		value (W)	t (df)	p	Cohen's f^2
Accuracy					
γ_{000}	Intercept	22.95	5.74 (102)	>.001	
γ_{100}	Coefficient Day	4.07	1.3 (102)	.198	
γ_{200}	Coefficient Intensity	.54	.13 (102)	.898	
γ_{300}	Coefficient Interaction	-3.66	-.64 (102)	.525	
Low-frequency consistency					
γ_{000}	Intercept	4.71	8.43 (102)	>.001	
γ_{100}	Coefficient day	.42	.62 (102)	.536	
γ_{200}	Coefficient Intensity	3.12	3.45 (102)	>.001	.11
γ_{300}	Coefficient Interaction	-1.03	-0.82 (102)	.412	
High-frequency consistency					
γ_{000}	Intercept	10.04	12.94 (102)	>.001	
γ_{100}	Coefficient Day	.19	.29 (102)	.771	
γ_{200}	Coefficient Intensity	5.71	6.41 (102)	>.001	.56
γ_{300}	Coefficient Interaction	-1.19	-.99 (102)	.327	

- *Note that the best models were:*
  - $Accuracy_{mrb} = \gamma_{000} + \gamma_{100} \cdot nFA_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot nFA_{mrb} \times Intensity_{mrb} + u_{0rb} + e_{mrb}$
  - $LFconsistency_{mrb} = \gamma_{000} + \gamma_{100} \cdot nFA_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot nFA_{mrb} \times Intensity_{mrb} + v_{00b} + u_{0rb} + e_{mrb}$
  - $HFconsistency_{mrb} = \gamma_{000} + \gamma_{100} \cdot nFA_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot nFA_{mrb} \times Intensity_{mrb} + u_{0rb} + e_{mrb}$

significant feedback by intensity interaction. For both intensities, accuracy was improved by 16 W (65 %) on average when additional power-output feedback was provided compared with the commonly used feedback.

Regarding LF consistency, a significant main effect of feedback and a significant feedback by intensity interaction were found. Post-hoc tests revealed a larger effect of feedback for rowing at AT intensity than ED intensity. For both intensities, LF consistency was improved by 32 % on average when additional feedback was provided.

In addition, no significant main effect of additional feedback was found for HF consistency, only a significant feedback by intensity interaction. Post-hoc tests revealed that additional feedback resulted in better HF consistency during AT intensity, but not during ED intensity.

Table 5.4. Means and SDs for rowers' compliance with power-output targets (i.e. accuracy, low-frequency consistency and high-frequency consistency) during "extensive duration" (ED) and "anaerobic threshold" (AT) intensity trials when only commonly used feedback was provided (nAF) and when *additional* visual feedback on power output was provided (AF). All variables are expressed in watt (W).

	nAF	**AF**	***Total***
	M (SD)	**M (SD)**	***M (SD)***
Accuracy			
ED	25.8 (19.9)	7.9 (9.1)	*20.0 (19.1)*
AT	23.7 (17.0)	10.7 (7.9)	*19.7 (15.9)*
Total	*25.2 (19.0)*	*8.7 (8.8)*	
Low-frequency consistency			
ED	4.9 (2.8)	3.6 (2.1)	*4.5 (2.6)*
AT	7.5 (3.6)	4.1 (1.6)	*6.4 (3.5)*
Total	*5.6 (3.2)*	*3.8 (2.0)*	
High-frequency consistency			
ED	10.2 (3.1)	9.6 (3.1)	*10.0 (3.1)*
AT	15.1 (4.9)	12.1 (3.1)	*14.2 (4.6)*
Total	*11.6 (4.4)*	*10.3 (3.3)*	

5.3.6 Main model B: Differences between boats

The models for accuracy and for LF and HF consistency did not improve when random slopes for boats were added ($\chi^2(1) = 0.55$, p = .458; $\chi^2(1) = 0.13$, p = .718; $\chi^2(1) = 2.11$, P = .146, respectively). This indicates that the effect of additional power-output feedback on compliance with power-output targets was similar across boats.

Table 5.5. Results from the multilevel analysis on the effect of additional visual feedback on power output (AF) on rowers' compliance with power-output targets relative to training sessions with only commonly used feedback (nAF). Bold faced numbers show the important significant values.

		value (W)	**t (df)**	**p**	**Cohen's f^2**
Accuracy					
γ_{000}	Intercept	25.18	7.89 (151)	$>$.001	
γ_{100}	Feedback coefficient	**-15.73**	**-6.47 (151)**	**$>$.001**	**.44**
γ_{200}	Intensity coefficient	-1.55	-.59 (151)	.556	
γ_{300}	Interaction coefficient	1.34	.3 (151)	.767	
Low-frequency consistency					
γ_{000}	Intercept	4.93	12.13 (151)	$>$.001	
γ_{100}	Feedback coefficient	**-1.22**	**-2.28 (151)**	**.024**	**.16**
γ_{200}	Intensity coefficient	2.59	4.61 (151)	$>$.001	0.14
γ_{300}	Interaction coefficient	**-2.19**	**-2.2 (151)**	**.029**	
Low-frequency consistency					
γ_{000}	Intercept	10.19	15.39 (151)	$>$.001	
γ_{100}	Feedback coefficient	-.63	-1.18 (151)	.239	.14
γ_{200}	Intensity coefficient	5.05	8.79 (151)	$>$.001	.62
γ_{300}	Interaction coefficient	**-2.72**	**-2.74 (151)**	**.007**	

-According to Cohen's guidelines [14] , $f^2 \geq 0.02$, $f^2 \geq 0.15$ an $f^2 \geq 0.35$ represent small, medium and large effect sizes, respectively.
- Note that the best models were:

- $Accuracy_{mrb} = \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} + u_{0rb} + e_{mrb}$
- $LFconsistency_{mrb} = \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} + v_{00b} + u_{0rb} + e_{mrb}$
- $HFconsistency_{mrb} = \gamma_{000} + \gamma_{100} \cdot FB_{mrb} + \gamma_{200} \cdot Intensity_{mrb} + \gamma_{300} \cdot FB_{mrb} \times Intensity_{mrb} + u_{0rb} + e_{mrb}$

5.4 Discussion

The main aim of this study was to examine whether additional real-time feedback on power output aids crew rowers to comply with prescribed power-output targets. We found substantial improvements in compliance during AF compared with nAF, in the absence of a statistically significant difference in compliance between the nAF sessions at different days. We therefore conclude that additional feedback on power output facilitates crew rowers to comply with power-output targets, the movement limitations associated with crew rowing notwithstanding.

Compliance with training targets improved in terms of accuracy and LF consistency when additional feedback on power output was provided. Feedback on power output only aids to improve HF consistency for AT intensity and not for ED intensity, perhaps due to a floor effect. However, accuracy and LF consistency are arguably the more relevant compliance parameters, as they provide information on a rower's average power output and on slow fluctuations in power output during a training session, while HF consistency reflects stroke-to-stroke fluctuations resulting mainly from environmental noise (e.g. waves).

The relevance of an objective feedback parameter on intensity is underscored by the fact that during the nAF, the power output of the rowers during ED intensity was (much) lower than their power-output targets that were based on their ergometer scores. This may indicate a discrepancy between coaches' intended intensities for ergometer and on-water rowing and rowers' interpretation of the prescribed intensities. Indeed, some rowers confirmed working "harder" during ergometer sessions than on-water sessions at ED intensity. Likewise, previous studies indicated that athletes' interpretation of training intensities deviates from the intensities prescribed by coaches [9, 25, 39]. Power-output feedback may aid coaches and rowers to converge to the same training intensity and thus improves compliance to the prescribed training programs.

The importance of using power output as a feedback parameter for intensity was also highlighted by a limited number of additional qualitative observations that were made during the study. During the experiment, coaches were asked to observe rowers' compliance with feedback while coaching. In general, coaches in The Netherlands cycle next to the rowing track along with the boat to observe the rowers and provide feedback and instructions from a distance. At the end of each training session, the coaches were asked to rate rowers' compliance using a custom-made scale. However, most coaches mentioned that it was (too) difficult to rate a rower's compliance with training intensity targets due to — among other factors — the lack of objective information on rowers effort during training intensities. In the in-depth interviews of the coaches, they also expressed a strong need for more objective information on rowers' individual delivered training intensity in order to control and monitor rowers' training intensity. Although we realise that these qualitative observations are lacking quantitative substantiation, they suggest that supplying coaches with real-time feedback on power output will most likely assist coaches in monitoring and supporting rowers to comply with the prescribed training intensities.

The present study was conducted in the context of regular training sessions in order to stay close to the actual rowing practice, so that results can be generalised to this practice. Nevertheless, two limitations regarding the generalisability of our results must be mentioned. First, our sample consisted of a rather small group of rowers. More research is needed to determine to what extent rowers with less experience are able to comply with power-output targets. Second, we included only two commonly used training intensities in on-water rowing. Although the feedback provided will be identical for "high-intensity" training sessions (as classified by Seiler [77]), it remains to be determined how effective additional real-time feedback on power output will be during high intensity rowing.

5.5 Conclusion

Rowers require feedback to comply with prescribed training programs designed to optimally improve rowing performance. Unlike the indirect measures that are currently used for this purpose, power output represents a valid index for training intensity that can be provided during on-water rowing. The present results indicate that crew rowers are better able to comply with power-output targets when they receive individual feedback on power output, movement limitations associated with crewed rowing notwithstanding. The relevance of power-output feedback for rowing practice is underscored further by two more qualitative observations suggesting (1) that there is a marked discrepancy between coaches' intended intensities for training sessions and rowers' interpretation of the prescribed intensities and (2) that coaches have difficulties to perceive training intensity of individual rowers.

5.6 Practical Application

With the rapid advent of commercial products enabling the provision of individual visual feedback on power output for a large group of rowers, the present results are highly relevant for rowing training practice. Additional feedback on power output aids rowers to attain preset levels of training intensity and thus better compliance with training programs designed to optimally improve performance. Future research may focus on the effect of compliance with prescribed training intensities on rowing performance defined as the average boat velocity during a 2000 m race. As power-output feedback aids compliance with training intensity in a more complex task such as crew rowing, it is very plausible that these results apply also for more simple tasks such as rowing in a single sculls or cycling.

5.7 Acknowledgement

We are grateful to Richard Casius and Peter Verdijk for their hard and elaborate work on the technologically innovative instrumentation used in the present study.

Chapter 6

The effect of real-time feedback on power losses due to velocity fluctuations in steady-state rowing

Based on:
Lintmeijer, L.L., Hofmijster, M.J. van Soest, A.J., Beek, P.J.. The effect of real-time feedback on velocity fluctuations in steady-state rowing. *BMC Sports Science, Medicine and Rehabilitation* 7(Suppl 1):O5 (2015). DOI:10.1186/2052-1847-7-S1-O5

Rowing performance depends on maximisation of mechanical power delivered by the rower(s) and minimisation of power losses. Though reductions of power losses may increase the average velocity of a boat, traditional feedback methods lack the accuracy to differentiate between small variations in these power losses. Therefore, innovative audiovisual feedback on the power loss due to velocity fluctuations during a stroke cycle has been developed. In this study, the efficacy of this multi-modal feedback — with respect to velocity fluctuations power loss — was compared with the efficacy of traditional feedback by a coach. A cross-over design was conducted in which 10 Dutch rowers participated. Power loss due to fluctuations in boat velocity averaged over each full rowing cycle was transformed into a single numeric parameter indicating the actual average power loss to boat drag, relative to the hypothetical power loss associated with a constant speed based on the average velocity. This parameter (one value per full rowing cycle) was fed back visually in real-time to single scull rowers. In addition, auditory feedback was generated using pitch mapping of the instantaneous power loss due to velocity fluctuations relative to the power loss associated with a constant speed based on the average velocity. On average, descriptive values (Means, SDs, and minimum and maximum values) did not show any reduction of power loss due to velocity fluctuations when multi-modal feedback or traditional coach feedback was provided. This suggests that both forms of feedback were not effective: the feedback seems to be not prescriptive enough to enable rowers to master their power loss due to velocity fluctuations.

6.1 Introduction

Rowing performance can be defined as the average boat velocity during a 2000 m race. It depends on maximisation of mechanical power output delivered by the rower(s) and minimisation of power loss unrelated to average boat velocity [33, 89]. Part of this power loss can be attributed to rowers' movement relative to the boat in combination with their discontinuous push-off. These inherent aspects of rowing cause large fluctuations in boat velocity during a stroke cycle that result in higher energy dissipated by the water drag force than drag energy dissipation at a constant boat velocity equalling the average of the fluctuating boat velocity [33, 74].

In order to reduce the power loss due to velocity fluctuations, rowers need to reduce boat velocity fluctuations by changing their movement relative to the boat and/or their push-off. To this end, accurate feedback that differentiates between small variations in this power loss is desired. In current rowing practice, feedback on this power loss is provided verbally by the coach and based on observations of the movements of the boat and rowers. The accuracy of this feedback can be questioned as the movements of the boat and rowers are observed from a distance, whereas changes in movements related to power loss due to velocity fluctuations may be small. Therefore, more precise and objective feedback may support rowers to minimise their power loss due to velocity fluctuations of the boat.

From a motor-learning perspective, the opportunities to minimise power loss due to velocity fluctuations may be legion and involve many degrees of freedom. This power loss can — most certainly — not be mastered in a single session. Research has shown that — for such complex tasks (qualification is based on [97]) — frequently presented feedback accelerates skill acquisition (see for reviews [79, 97]). Additionally, it has been shown that feedback on the effect of the movement is more beneficial for the acceleration of skill acquisition than feedback on the movement sequence itself (see for reviews [62, 95, 97]). Based on these findings, we developed visual single value feedback on power loss due to velocity fluctuations that is presented after each stroke.

However, one drawback of such single value feedback is that it may not be prescriptive enough to enable athletes to master complex movement sequences [97]. To improve the prescriptiveness of the feedback on power loss due to velocity fluctuations, we complemented the single value feedback with continuous feedback on the instantaneous power dissipation of boat movements relative to the power dissipation during constant speed based on the average velocity. In the view of the complexity of this feedback, it was presented acoustically. The advantage of such auditory feedback is that it can contain a substantial amount of information without overloading the working memory of athletes [79]. Moreover, sound has been suggested to be especially effective in providing information on speed of motion [75, 79].

In this study, we evaluated whether the multi-modal (i.e. the combination of visual and auditory) feedback on power loss due to velocity fluctuations enables rowers to minimise this power loss. Moreover, it was tested whether this feedback is more effective than traditional verbal feedback on this power loss provided by coaches. Subsequently, rowers' evaluation of the multi-modal feedback was examined.

6.2 Methods

6.2.1 Design

Rowers performed four training sessions in single sculls (one man boats) at an extensive duration intensity (see [77] for classifications of training intensities; see Figure 6.1 for a schematic overview). Each training session consisted of one trial without feedback followed by one trial with feedback on power loss due to velocity fluctuations. Each trial, in turn, consisted of two times 3-minutes rowing in opposing direction of travel in order to minimise possible effects of current and wind. In between the trials, rowers familiarised themselves with the feedback. Using a cross-over design, half of the rowers started with two training sessions with traditional verbal feedback from the coach, followed by two training sessions with digital feedback. The other half of the group conducted the training sessions in reversed order.

During the no-feedback and baseline trials coaches were requested not to provide any feedback on the rowing skills of the rowers. During the traditional feedback trials coaches were asked to provide feedback on power loss due to velocity

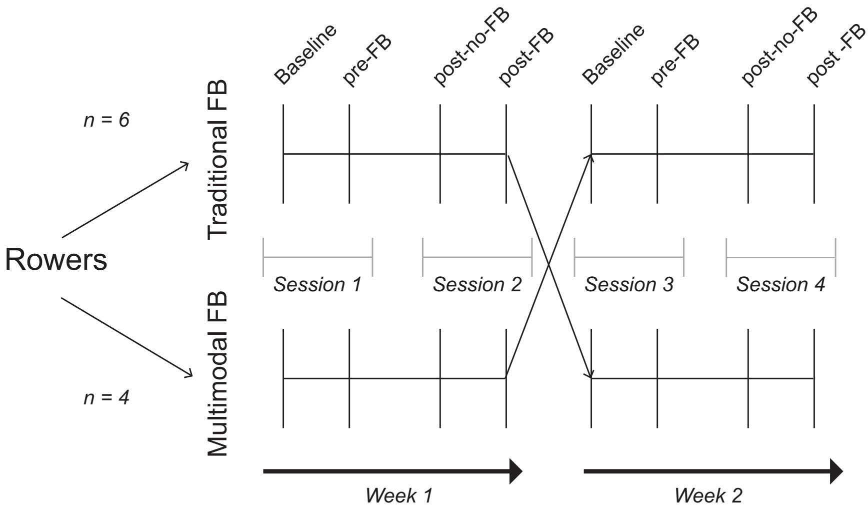

Figure 6.1. Schematic overview of the design of the study. During the baseline trials and the 'post no FB' trials no feedback (FB) on power loss was presented, while during the 'pre FB' and 'post FB' trials either coach or multi-modal feedback on power loss due to velocity fluctuations was provided to the rowers.

fluctuations based on their own experience and observations. During the multimodal feedback trials rowers received visual plus auditory feedback on power loss based on sensor data. The visual feedback consisted of a single value presented after each stroke and indicated the actual average power loss to boat drag relative to the hypothetical power loss associated with a constant speed based on the average velocity. The lower this value, the less power was lost due to velocity fluctuations. The auditory feedback was presented continuously. It was generated using pitch mapping of the instantaneous power loss due to velocity relative to the hypothetical power loss associated with a constant speed that was based on the average velocity of the previous stroke.

All training sessions were conducted in a 2-week time span. To limit the influence of weather circumstances, we aimed to do the rowing sessions under similar weather circumstances in which the wind was not more than 5.3 $m\,s^{-1}$. The study was approved by the local ethical committee of the Department of Human Movement Sciences of the Vrije Universiteit Amsterdam.

Table 6.1. Age, mass, years of experience, and years of experience in single scull for all participants, as well as the corresponding mean values (M) and standard deviations (SD).

Participant number	1	2	3	4	5	6	7	8	9	10	M (SD)
Age (y)	23.0	18.0	19.0	22.0	28.0	24.0	21.0	18.0	18.0	17.0	20.8 (3.3)
Mass (kg)	73.0	71.0	75.0	72.0	70.0	74.0	71.0	66.0	63.0	72.0	70.7 (3.5)
Rowing experience (y)	5.0	2.5	8.0	10.0	8.0	4.0	7.0	2.0	2.0	1.5	5.0 (2.9)
Experience in a single scull (y)	1.0	2.5	6.0	5.0	4.0	2.0	7.0	2.0	2.0	1.0	3.3 (2.0)

6.2.2 Participants

Ten trained and well-trained (categorisation based on [67]) rowers (three male and seven female) participated in this study. Participant characteristics are displayed in Table 6.1.

6.2.3 Protocol and instructions

Prior to the experiment rowers and coaches were informed about the study's aim and protocol, after which the rowers signed an informed consent form. At the start of the training sessions, rowers were instructed to perform their training sessions at an extensive duration intensity, starting with an individual warming up after which the trials would follow. Next, they were instructed to row the trials at a stroke rate of 20 stokes min^{-1}, while aiming to minimise their power loss due to velocity fluctuations. In the first trial of each training session no feedback was provided. In the second trial rowers either received verbal instructions of the coach or multi-modal feedback on power loss due to velocity fluctuations. Instructions about the multi-modal feedback were provided prior to the multi-modal training sessions. Rowers were instructed that a more constant sound and lower visually presented numbers were related to less power loss due to velocity fluctuations. During the training sessions, rowers were allowed to practice and experiment with the multi-modal feedback on power loss. At the end of the last training session rowers filled out an evaluation on the multi-modal feedback.

6.2.4 Instrumentation

Rowers rowed in their own single scull that was equipped with an accelerometer (Peach Innovations Ltd., Cambridge, United Kingdom; 100 Hz sampling frequency) determining the acceleration of the boat. These data were used to capture velocity fluctuations around the low-frequent velocity component (i.e. the mean speed). This low-frequent component was measured using a GPS Tracking system (LOCOSYS, Taipei 121 City, Taiwan; 10 Hz sample frequency). All data were stored at an SD card using a custom-made data acquisition system (Vrije Universiteit, Amsterdam, Netherlands) that was mounted on the boat.

6.2.5 Determination of output variables

Average power loss due to velocity fluctuations ($\overline{P}\Delta v_{stroke}$) can be defined as the difference between average drag-power ($\overline{P}_{drag}$) and the *hypothetical* average drag-power when the boat would have a constant velocity and thus a constant drag ($\overline{P}_{hdrag}$) [17, 36]:

$$\overline{P}\Delta v_{stroke} = \overline{P}_{drag} - \overline{P}_{hdrag}. \tag{6.1}$$

Since:

$$P_{drag} = -k \cdot {v^x_{b/w}}^3, \tag{6.2}$$

,

$\overline{P}\Delta v_{stroke}$ can be written as:

$$\overline{P}\Delta v_{stroke} = -\frac{1}{T} \cdot k \cdot \int_{t_0}^{t_0+T} ({v^x_{b/w}}^3)\mathrm{d}t + k \cdot {\overline{v}^x_{b/w}}^3 \tag{6.3}$$

where $v^{x}_{b/w}$ is the instantaneous velocity of the boat in travel direction in $\mathrm{m\,s^{-1}}$, and $\overline{v}^{x}_{b/w}$ is the average boat velocity in travel direction during a stroke cycle. T is the time duration of a stroke cycle in seconds, and k is a drag constant that depends on the properties of water and boat, such as water density, viscosity, streamline and wetted surface of the boat.

As k is unknown, $\overline{P}\Delta v_{stroke}$ cannot be determined. As an alternative the relative $\overline{P}_{drag}$ to $\overline{P}_{hdrag}$ (i.e. $\overline{P}\Delta v_{stroke}rel$) is calculated as:

$$\overline{P}\Delta v_{stroke}rel = \frac{\frac{1}{T}\cdot\int_{t_0}^{t_0+T}({v^{x}_{b/w}}^{3})\mathrm{d}t}{{\overline{v}^{x}_{b/w}}^{3}} - 1. \tag{6.4}$$

To evaluate whether rowers succeeded in reducing the power loss due to velocity fluctuations, the average power loss per trial was determined according to:

$$\overline{P}\Delta v_{trial}rel = \frac{\sum_{i=1}^{n_{strokes}} \overline{P}\Delta v_{stroke}rel}{n_{strokes}} \tag{6.5}$$

In which $n_{strokes}$ is the number of strokes per trial.

Rowers' evaluation on the multi-modal feedback was obtained using a custom-made questionnaire with questions that could be rated on a 7-point Likert scale or a visual analogue scale (see the supporting information for the specific questions).

6.2.6 Data analyses

Data collected with the accelerometer and GPS were analysed using Matlab 2018a (the Mathworks Inc, Natick, Massachusetts, United States). To calculate $\overline{P}\Delta v_{stroke}rel$, stroke starts were determined using the boat's acceleration signal. The signal was first filtered using a bi-directional fourth-order Butterworth 4 Hz cut-off filter, after which minimum peaks in the signal were selected as catch events (see Figure 6.2 for an example). For every trial, output of 80 strokes (the middle 40 of each part rowed in the two directions) were selected for statistical analyses. To account for steady-state rowing data, strokes were excluded for further data analyses if they had an average velocity of < 2.5 m s^{-1} and/or a stroke rate of < 18 or > 22 strokes min^{-1}. Subsequently, $\overline{P}\Delta v_{stroke}rel$ values of more than 1.5 interquartile above the upper quartile or below the lower quartile of all values per trial (each rowing direction separately) were considered to be outliers and excluded from further analyses. Next, $\overline{P}\Delta v_{trial}rel$ was calculated for each trial.

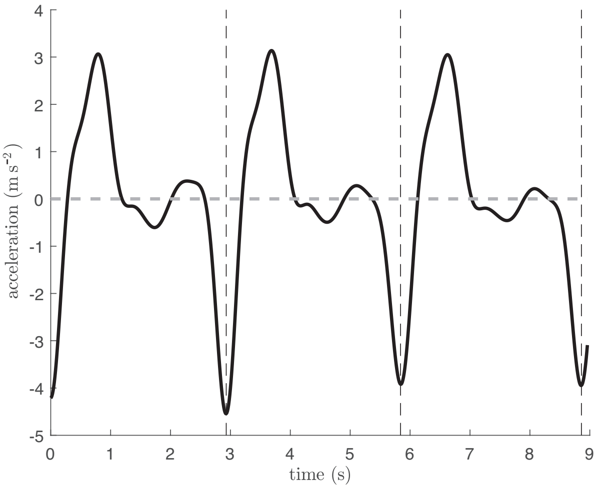

Figure 6.2. Typical example of the filtered (a bi-directional fourth order Butterworth 4 Hz cut-off filter) acceleration pattern of three strokes of a single rower. Stroke starts (see vertical dashed lines) were determined using the minimum peaks in the filtered signal.

6.2.7 Statistical analyses

In view of the limited power of the study only descriptive statistics (i.e. mean, standard deviation and minimum and maximum value) on the effect of feedback conditions on $\overline{P}\Delta v_{trial}rel$ values were calculated.

6.3 Results

6.3.1 Typical examples

Figure 6.3 shows typical examples of $\overline{P}\Delta v_{stroke}rel$ and associated $\overline{P}\Delta v_{trial}rel$ during baseline trials and post-feedback trials with either coach or multi-modal feedback based on sensor data. The typical examples reflect relatively high fluctuations in $\overline{P}\Delta v_{stroke}rel$ within trials, and rather small differences in $\overline{P}\Delta v_{trial}rel$ between trials.

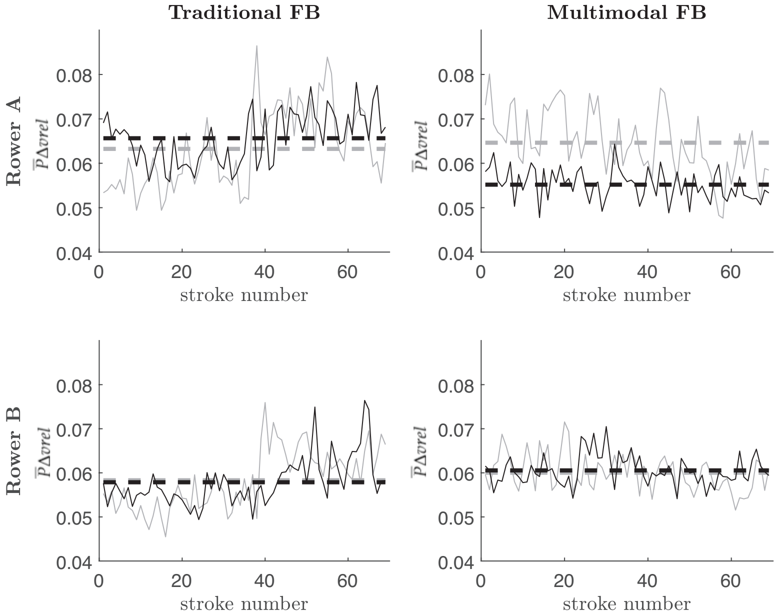

Figure 6.3. Typical example of two rowers for the traditional coach feedback condition and the multi-modal feedback condition. The grey lines present power loss due to velocity fluctuations per stroke ($\overline{P}\Delta v_{stroke}rel$) during baseline trials, while the black lines show $\overline{P}\Delta v_{trial}rel$ during post-FB trials. Power loss due to velocity fluctuations averaged over a trial ($\overline{P}\Delta v_{trial}rel$) for the baseline trials and the post-FB trials are presented using dashed grey and black lines, respectively.

6.3.2 The effect of feedback on power loss to drag

Overall, descriptive statistics reflected no effect of coach and multi-modal feedback on power loss due to velocity fluctuations (see Table 6.2). Neither verbal feedback of the coach, nor multi-modal feedback did appear to aid rowers to reduce their power loss due to velocity fluctuations.

Table 6.2. Mean values (M), standard deviations (SD), minimum values (min), and maximum values (max) of the change in power loss due to velocity fluctuations over test trials (pre-FB, post-no-FB and post-FB) relative to the power loss during baseline conditions.

	$\Delta\ \overline{P}\Delta v_{trial}rel$		$\Delta\ \overline{P}\Delta v_{trial}rel$ (%)	
	M (SD)	**range**	**M (SD)**	**range**
Coach FB				
pre-FB	.0004 (.0031)	-.0058 - .0052	.7 (4.68)	-8.1 - 8.1
post-no-FB	-.0015 (.0041)	-.0118 - .0023	-2.1 (5.90)	-16.5 - 4.0
post-FB	-.0004 (.0048)	-.0113 - .0069	-.3 (7.17)	-15.8 - 11.4
multi-modal FB				
pre-FB	-.0002 (.0019)	-.0028 - .0040	-.4 (3.12)	-5.2 - 6.3
post-no-FB	-.0006 (.0036)	-.0067 - .0042	-.9 (5.87)	-10.4 - 7.0
post-FB	.0003 (.0050)	-.0096 - .0076	.3 (8.10)	-14.8 - 11.9

A more detailed exploration of the individual data (see Figure 6.4) revealed that three rowers reduced their power loss when provided with multi-modal feedback but not with coach feedback. For two rowers the opposite effect was observed.

6.3.3 Evaluation of the feedback

Descriptive statistics suggest that, overall, coach feedback was slightly better evaluated than multi-modal feedback. Nevertheless, rowers still used the multi-modal feedback to reduce power loss due to velocity fluctuations. They indicated that especially the visual part of the feedback, motivated them to decrease the power loss. This visual feedback was better evaluated than the auditory feedback (see supporting information for details).

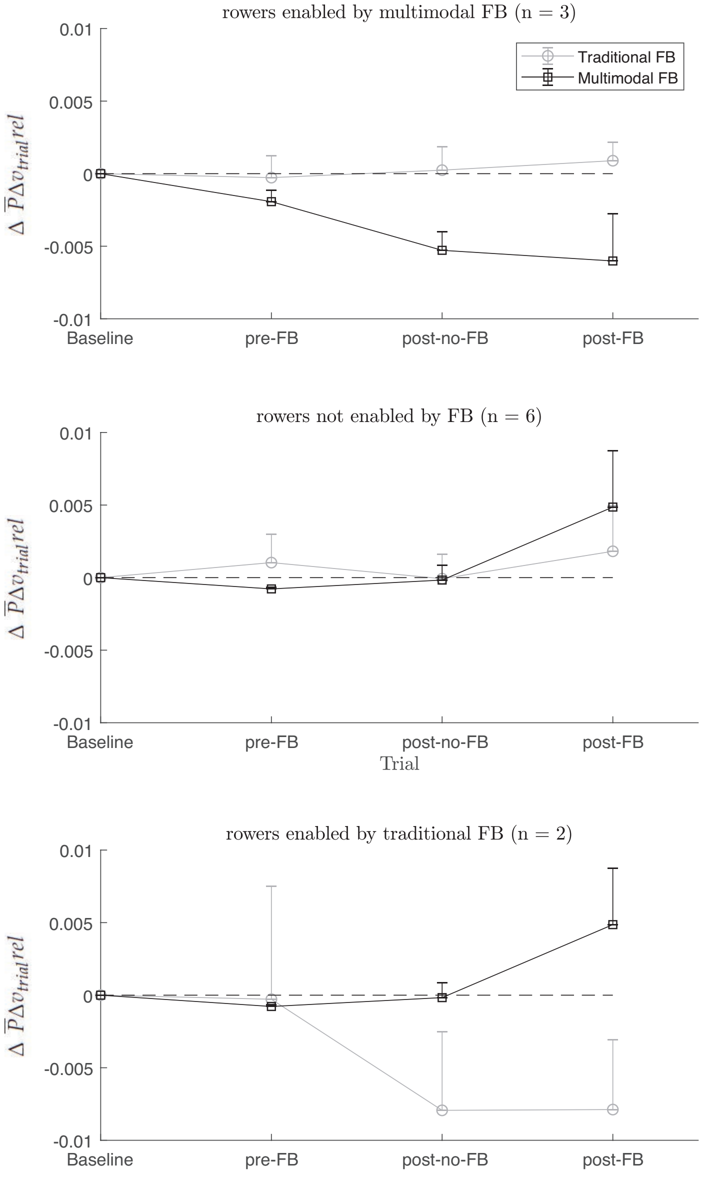

Figure 6.4. The change in $\overline{P}\Delta v_{trial}rel$ over all trails relative to power loss due to velocity fluctuations during baseline ($\Delta\ \overline{P}\Delta v_{trial}rel$) for three different groups of rowers. The first panel shows the average of $\Delta\ \overline{P}\Delta v_{trial}rel$ per trial for rowers that seem to reduce $\overline{P}\Delta v_{trial}rel$ by multi-modal feedback on power loss (black line). The second panel shows the average of $\Delta\ \overline{P}\Delta v_{trial}rel$ per trial for rowers that reduce $\overline{P}\Delta v_{trial}rel$ using traditional coach feedback (grey line). And the third panel shows the average $\Delta\ \overline{P}\Delta v_{trial}rel$ per trial for rowers who did not reduce their power losses during the experiment.

Exploration of individual data (see supporting information) revealed that the three rowers who succeeded in reducing power loss in the presence of multi-modal feedback, believed that the multi-modal feedback corresponded better with their own feeling of power loss than rowers who did not succeed to reduce their power loss using the multi-modal feedback. Additionally, the same three rowers were more motivated by the auditory feedback than the rowers who did not benefit from the multi-modal feedback. Rowers who only benefited from verbal feedback of the coach and not from the multi-modal feedback indicated that the multi-modal feedback correspond less well with their own feeling of power loss than the other rowers.

6.4 Discussion

In principle, rowing performance can be improved by reducing power loss due to velocity fluctuations. To this end, accurate feedback on this power loss is desired. In the current study, it was evaluated whether multi-modal feedback on power loss due to velocity fluctuations was more effective in reducing this power loss than traditional verbal feedback by the coach. The results of this study suggest that, at a group level, neither coach feedback nor multi-modal feedback on power loss aided rowers to reduce power loss. However, at the individual level, the results indicated that three rowers succeeded in reducing power loss in the presence of multi-modal feedback. These rowers believed that the multi-modal feedback correspond better with their own feeling of power loss than other rowers. Additionally, they felt more motivated by the multi-modal feedback to reduce their power loss than the other rowers.

The present findings suggest that the feedback was for most rowers not informative enough to reduce their power loss due to velocity fluctuations. This might have been due to a combination of reasons. Firstly, rowers might have been unable to instinctively understand the relation between their movement pattern and the feedback since the skill to master power loss due to velocity fluctuations requires a specific pattern of movement coordination that involves multiple degrees of freedom. Secondly, the feedback may have been too noisy. Power loss due to velocity fluctuations is relatively small and it strongly depends on shell velocity, which in turn is also affected by small changes in weather circumstances such as wind flaws and water currents. Due to this noise, rowers might have been unable to detect small variations in power loss that are related to a rower's variation in movement sequence. Thirdly, small measurement errors of the GPS may have resulted in erroneous values of the visual feedback, since the feedback highly depends on GPS data.

To understand why the multi-modal feedback did not support rowers to reduce their power loss due to velocity fluctuations, a controlled experiment is required in which the effect of small differences in weather circumstances can be excluded and the effect of different forms of feedback (both uni-modal and multi-modal) can be tested. However, such a controlled experiment will have very low ecological validity and will not provide information on the effectiveness of feedback on power loss due to velocity fluctuations in rowing practice.

6.5 Conclusion

Although power loss due to velocity fluctuations is an important variable to analyse and understand rowing performance, the results of this study suggest that the variable — as it is presented in this study — cannot be used as an effective feedback variable in practice to reduce power loss. To understand why the presented feedback on power loss was generally ineffective, controlled lab experiments are required.

6.6 Supplementary materials

Evaluation of the multi-modal feedback

Table 6.3. Rowers' evaluation of the multi-modal feedback

	All participants		**Enabled by multi-modal FB**		**Enabled by coach FB**	
	n	**M (SD)**	**n**	**M (SD)**	**n**	**M (SD)**
Coach FB						
Did the feedback correspond with you feeling? (1 = not at all and 7 = totally)	10	5.5 (1.2)	3	5.7 (.6)	2	6.0 (.0)
Did the feedback motivate you to reduce power loss? (1 = not at all and 7 = totally)	10	5.8 (.6)	3	5.7 (.6)	2	6.0 (.0)
On a scale from 0 to 10, how much did you like the feedback?	10	7.7 (1.2)	3	7.7 (1.2)	2	9.0 (.0)
Visual FB						
Did you use the feedback to reduce power loss? (1 = never and 7 = always)	10	5.4 (.8)	3	5.3 (.6)	2	5.5 (2.1)
Did the feedback correspond with you feeling? (1 = not at all and 7 = totally)	10	4.2 (1.1)	3	5.7 (.6)	2	3.5 (3.5)
Did the feedback motivate you to reduce power loss? (1 = not at all and 7 = totally)	10	5.7 (0.8)	3	6.3 (.6)	2	.0 (.0)
On a scale from 0 to 10, how much did you like the feedback?	10	7.0 (1.6)	3	6.3 (.6)	2	6.0 (.0)
Auditory FB						
Did you use the feedback to reduce power loss? (1= never and 7 = always)	10	4.1 (1.8)	3	5.0 (2.0)	2	5.0 (1.4)
Did the feedback correspond with you feeling? (1 = not at all and 7 = totally)	10	4.4 (1.7)	3	5.7 (.6)	2	4.5 (2.1)
Did the feedback motivate you to reduce power loss? (1 = not at all and 7 = totally)	10	4.0 (1.7)	3	5.3 (1.2)	2	4.5 (.7)
On a scale from 0 to 10, how much did you like the feedback?	10	5.1 (2.3)	3	4.7 (3.6)	2	6.1 (2.9)

Chapter 7

Towards determination of power loss at a rowing blade: validation of a new method to estimate blade force characteristics

Based on:
Lintmeijer, L.L., Onneweer, J.P.T., Hofmijster, M.J., Wijgergangs, W.A., de Koning, H., Clairbois, B., Westerweel, J., Grift, E.J., Tummers, M.J., van Soest, A.J. Towards determination of power loss at a rowing blade: validation of a new method to estimate blade force characteristics. *PLOS One* **14(5)**: e0215674. DOI.org/10.1371/journal.pone.0215674 (2019).

To analyse on-water rowing performance, a valid determination of the power loss due to the generation of propulsion is required. This power loss can be calculated as the dot product of the net water force vector ($\vec{F}_{w,o}$) and the time derivative of the position vector of the point at the blade where $\vec{F}_{w,o}$ is applied ($\vec{r}_{PoA/w}$). In this article we presented a method that allows for accurate determination of both parameters using a closed system with three rotational equations of motion for three different locations of the oar. Additionally, the output of the method has been validated. An oar was instrumented with three pairs of strain gauges measuring local strain. Force was applied at different locations of the blade, while the oar was fixed at the oarlock and the end of the handle. A force transducer and Optotrak measured the force vector and the deflection of the oar. These data were considered to be accurate and used to calibrate the measured strain for bending moments, the deflection of the oar and the angle of the blade relative to its unloaded position. Additionally, those data were used to validate the output values of the presented method plus associated instantaneous power output. Good correspondence was found between the estimated perpendicular force and its reference (ICC= .999), while the parallel force could not be obtained (ICC = .000). The position of the PoA relative to the blade could be accurately obtained when the perpendicular force $\geq$ 5.3 N (ICC = .927). Instantaneous power-output values associated with the perpendicular force could be obtained with reasonable accuracy (ICC . = .747). The results suggest that the power loss due to the perpendicular water force component can be accurately obtained, while an additional method is required to obtain the power losses due to the parallel force.

7.1 Introduction

For an accurate determination of the average power lost to the generation of propulsion per stroke cycle ($\overline{\mathrm{P}}_{blade}$; see List of Symbols for a list of all abbreviations), valid information about the net water force vector at the blade of the oar ($\vec{F}_{w,o}$) and its associated point of application (PoA) are essential since:

$$\overline{\mathrm{P}}_{blade} = \frac{1}{T}\int_{t_0}^{t_0+T} (\vec{F}_{w,o} \cdot \dot{\vec{r}}_{PoA/w})\mathrm{d}t \tag{7.1}$$

where T is the time duration of a stroke cycle and $\dot{\vec{r}}_{PoA/w}$ is the time derivative of the position vector (i.e. the velocity vector) of the point of the blade where $\vec{F}_{w,o}$ is applied relative to an earth-bound frame of reference ($\vec{r}_{PoA/w}$). Determination of $\vec{F}_{w,o}$, $\vec{r}_{PoA/w}$ and its time derivative is not trivial due to the (1) deflection of the oar and (2) a constantly changing force distribution at the blade resulting in an unknown and time-variant point of application of the water force. In previous studies [2, 3, 8, 10, 12, 36, 74, 98], power loss due to the generation of propulsion has been estimated assuming the oar to be rigid and the PoA of the water force vector to be in the middle of the blade. Additionally, the force component parallel to the blade has been typically neglected. These assumptions are not only unrealistic [46, 55], but do also affect calculated values of $\overline{\mathrm{P}}_{blade}$ significantly [36].

In the first part of this article we present a novel cost-effective method to obtain $\vec{F}_{w,o}$ and $\vec{r}_{PoA/w}$ that does not rely on the above mentioned assumptions. Additionally, we evaluate whether the method provides an accurate quantification of $\vec{F}_{w,o}$ and $\vec{r}_{PoA/w}$ in a simulated rowing situation. After showing that both parameters can be determined accurately, an indication of the extent in which $\overline{\mathrm{P}}_{blade}$ can be accurately determined in on-water rowing is provided.

In the presented method we make use of pairs of light-weight strain gauges that are attached at location *i* at the oar shaft and measure the local bending strain at location *i*. This local strain is a function of the local bending moment and the material properties of the oar shaft [30]. It is straightforward to show that — in concept — this bending moment contains information regarding the net force applied near a free end of the oar and its point of application by analysing the rotational equation of motion for a free body running from location i to the free end of the oar. Consider, as an example, the schematic representation of an oar in an xy-plane in Figure 7.1. Taking point A as the pivot point of free body 1 and measuring the bending moment at point A, the following rotational equation of motion for free body 1 is obtained:

$$\vec{M}_{2,1} + \vec{M}_{F_{ex}} = \vec{M}_{2,1} + \vec{r}_{PoA/A} \times \vec{F}_{ex} = \vec{I}_{1/A}\ddot{\vec{\phi}}_1, \tag{7.2}$$

where $\vec{M}_{2,1}$ and $\vec{M}_{F_{ex}}$ are the bending moment vectors measured at location A and the unknown moment vector due to a net external force vector, respectively. $\vec{F}_{ex}$ is the unknown external force applied at the free end of the oar and $\vec{r}_{PoA/A}$ is the unknown point of the oar at which $\vec{F}_{ex}$ is applied relative to point A. $I_{1/A}$ is the inertia of free body 1 and $\ddot{\vec{\phi}}_1$ the oar angular acceleration of the free body.

As the right hand term of the Equation 7.2 is relatively small, it can be neglected and a quasi-static approach can be applied, which results in:

$$\vec{M}_{2,1} = -\vec{r}_{PoA/A} \times \vec{F}_{ex}. \tag{7.3}$$

If oar deflection would be neglected, Equation 7.3 can be further simplified into:

$$M^z_{2,1} = -r^x_{PoA/A} \cdot F^y_{ex}. \tag{7.4}$$

Equation 7.4 thus provides information on the product of the unknown $r^x_{PoA/A}$ and F^y_{ex}. Note that the moment only has a z-component since the z-component of the force vector is negligible. When a second bending moment at another location such as at location B (see Figure 7.1C) is measured, a second rotational equation of motion can be formulated with the very same two unknowns:

$$M_{3,2}^{z} = -(r_{PoA/A}^{x} + r_{A/B}^{x})F_{ex}^{y}. \tag{7.5}$$

In which $M_{3,2}^{z}$ is the measured internal moment in point B and $r_{A/B}^{x}$ the known x-component of the position vector of point B relative to point A.

Interestingly, Equation 7.4 and 7.5 are independent and — although the relation between the two unknowns is nonlinear — this system of two equations has a unique solution:

$$F_{ex}^{y} = \frac{M_{2,1}^{z} - M_{3,2}^{z}}{r_{A/B}^{x}}, \tag{7.6a}$$

$$r_{PoA/A}^{x} = -\frac{M_{2,1}^{z} \cdot r_{A/B}^{x}}{M_{2,1}^{z} - M_{3,2}^{z}}. \tag{7.6b}$$

As explained above, Equation 7.6 is obtained when the oar is assumed to be rigid. When the oar is assumed to be deformable, additional unknown parameters appear. For every extra unknown parameter related to the applied external force vector and the $\vec{r}_{PoA/A}$, an extra pair of strain gauges and and extra free body with a related rotational equation of motion with the exact same parameters is prerequisite in order to obtain a system of equations that has a unique solution.

Thus the essence of our method is that we can calculate the values of *n* unknown parameters related to an applied external force vector and the $\vec{r}_{PoA/A}$, using a system of *n* independent but nonlinear rotational equations of motions for *n* free bodies with known bending moments. Moreover, any redundant measurement and related rotational equation of motion $(n+1)$ will result in an overdetermined system that can be solved using a least square method.

As outlined above, in theory, the presented method allows for an estimation of the unknown force vector and the position vector of the location of the PoA relative to a known location at the oar. To determine power loss due to the

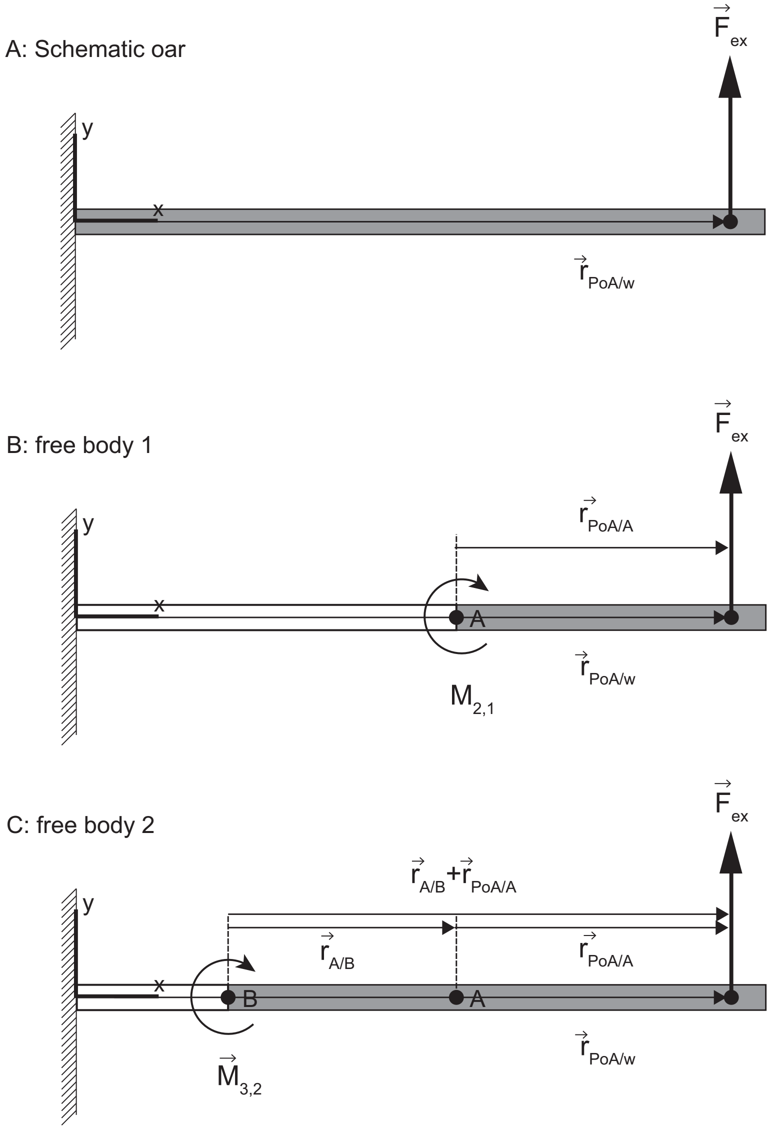

Figure 7.1. Schematic diagram of an non-deformable oar with a net external force ($\vec{F}_{ex}$) applied at the free end of the oar and the position of the location at the blade at which the external force is applied at that moment in time ($\vec{r}_{PoA/w}$) (panel A). In panel B and C the free bodies 1 and 2 are presented.

generation of propulsion according to Equation 7.1, these variables have to be combined with knowledge on the position and velocity of the oar in a world-bound frame of reference. However, in practice, the accuracy of the estimation of the force vector and its PoA remains to be shown. In contrast to our simple example discussed above, it is unrealistic to assume the oar shaft to be rigid [55]. This means that the pairs of strain gauges do not only have to provide information on bending moments, but also on the deflection of the oar. As of yet, the linearity of the relation between deflection of the oar and the local strain measured at location *i* of the tool is unknown. Moreover, in rowing the propulsion force consists of an unknown perpendicular and parallel force component relative to the orientation of the blade ($F_{w,o}^{y'}$ and $F_{w,o}^{x'}$, respectively; see Figure 7.2C in the material and methods section). As $F_{w,o}^{y'}$ and its moment-arms are much larger than $F_{w,o}^{x'}$ and its moment-arms, cross-talk may interfere with the determination of the parallel component. For sure, the parallel force cannot be determined if the oar is not bending, since it will result in zero lever-arms of $F_{w,o}^{x'}$.

In an experimental study we therefore aim to evaluate whether the presented method can be used to obtain an accurate quantification of the net propulsion force vector applied at the blade of a rowing oar and the location of its PoA. More specifically, we will first confirm that strain gauges attached at different locations of the rowing oar allow for an accurate determination of M_i^zs and the deflection of the oar. Additionally, we will examine whether the method provides an accurate quantification of both the perpendicular and parallel component of $\vec{F}_{w,o}$ and $\vec{r}_{PoA/w}$. Subsequently, we will examine the extent to which the power output associated with the bending of the oar can be determined accurately.

7.2 Methods

7.2.1 Setup and instrumentation

A horizontal-plane experiment was conducted in a laboratory. One sweep oar (Big Blade; Concept2 Inc, Morrisville, USA) was instrumented with three pairs of strain gauges (HBM 1-DY41-6/350) measuring the local strain (2000 Hz) at three locations of the oar (see Figure 7.2 for the experimental setup and an overview of the frames of reference). The oar was supported at the oarlock and the end of the handle mimicking the oarlock and the rower's hands. The part of the oar between the supports was assumed to be rigid, which means that the oar can be approached as a cantilever beam with one load applied at the free end. As can be seen from Figure 7.2A, the net propulsion force vector ($\vec{F}_{w,o}$) was simulated by pulling with varying force on a rope attached to the blade at different locations mimicking the $\vec{r}_{PoA/w}$ of the $\vec{F}_{w,o}$. The resultant force was measured using a force transducer (Futek LSB350, 500lbs, Futek, Irvine, USA; sample frequency of 2000 Hz). The direction of the force vector and the deflection of the oar were determined using 20 opto-electronic markers (Optotrak 3020, NDI, Ontario, Canada; sample frequency of 100 Hz) mounted at the oar, the oar blade, and the force transducer (see Figure 7.2B for the exact locations of the markers). Data obtained with Optotrak and the force transducer were considered to be the most accurate and used for (1) calibration of the output of the strain gauges, and (2) validation of the output variables of the presented method (see below). All sensor signals were recorded using two bridge modules (NL-9237, National Instruments, Austin,USA). In order to synchronise the signals an additional analogue input channel was used to measure the start signal of the Optotrak system.

The experiment consisted of 12 trials in which time-varying forces (ranging between zero and 400 N; based on estimated forces in on-water rowing studies [36]) were quasi randomly applied at the four different positions located at 0.225, 0.327, 0.423, and 0.520 m from the beginning of the blade. The angle of the resultant force ranged between zero and 2.6 rad relative to the x-axis of the earth bound frame of reference (see Figure 7.2B). Trials with an even number were used to calibrate the output of the strain gauges (from now on referred to as 'calibration trials'), while trials with an uneven number (from now on called 'validation trials') were used to validate the obtained $\vec{F}_{w,o}$, $\vec{r}_{PoA/w}$, and the instantaneous power output associated with the deflection of the oar (P_{defl}; see below).

7.2.2 Calibration of strain gauges

In order to calculate $\vec{F}_{w,o}$, $\vec{r}_{PoA/w}$, and P_{defl}, output of the strain gauges first had to be calibrated for (1) internal bending moments, (2) the deflection of the oar relative to its neutral position and (3) the orientation of the blade relative to an earth bound frame of reference ($M^z_{sg\,i}$, $\Delta^y_{oar_{sg}\,i}$, and $\Phi_{b/w_{sg}}$; see Figure 7.2). Note that the calculated internal bending moments only have a z-component since the analyses were restricted to forces and motions in the horizontal plane. Furthermore, deflection of the oar was only determined in y-direction, assuming

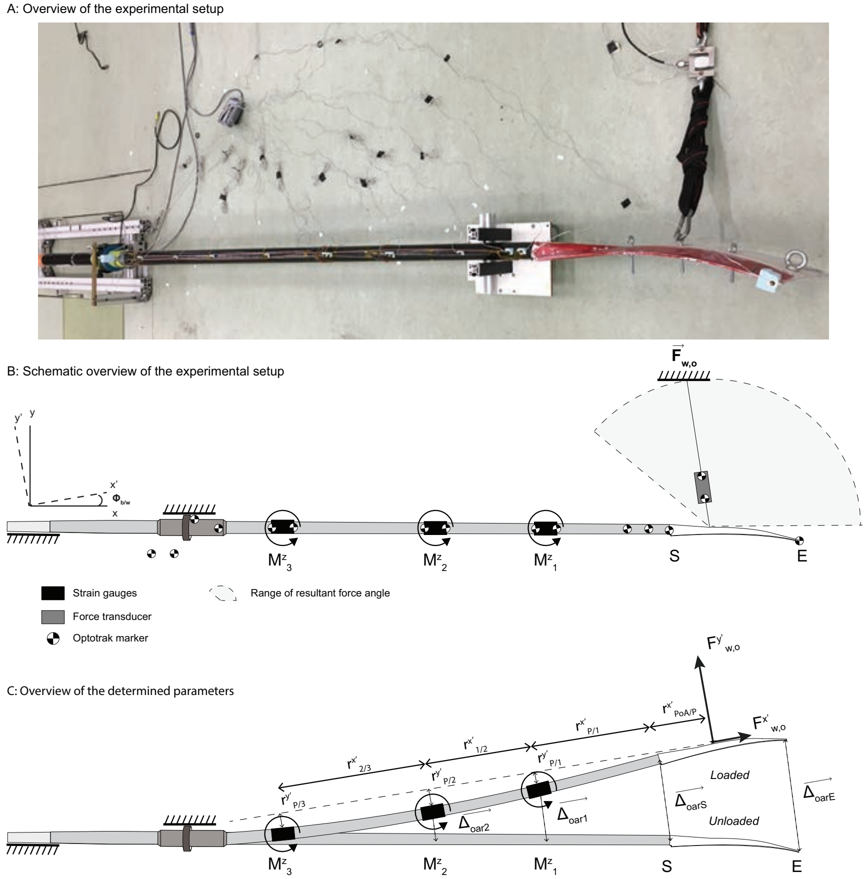

Figure 7.2. (A) An overview of the experimental setup, (B) the related schematic overview of the experimental setup in a horizontal plane, and (B) a schematic representation of the bended oar relative to its neutral position with the relevant determined parameters.The xy-frame of reference represents an earth-bound frame of reference in which the positive x-axis points towards the blade of the oar in an unloaded position. The x'y'-frame of reference represents the blade-bound frame of reference in which the positive x'-axis points towards the end of the blade. $\Phi_{b/w}$ is the angle of the blade in loaded position relative to the blade in neutral position. M_1^z, M_2^z, and M_3^z refer to the three bending moments measured at location 1,2, and 3 of the oar respectively. S and E are the beginning and the end of the blade respectively. $\vec{F}_{w,o}$ is the external force vector applied at the blade, while $F_{w,o}^{y'}$ and $F_{w,o}^{x'}$ are the perpendicular and parallel force components, respectively. $\Delta o\vec{a}r_1$, $\Delta o\vec{a}r_2$, $\Delta o\vec{a}r_S$, and $\Delta o\vec{a}r_E$ are the position vectors of location 1,2, S, and E in the loaded situation relative to their location in the unloaded position. Note that $\Delta o\vec{a}r_3$ is not depicted in this figure since it is very small. The $r_i^{x'}$s and $r_i^{y'}$s represent the x' and y'-components of the known and measured moment-arms in a blade-bound frame of reference. $r_{PoA/S}^{x'}$ is the x'-component of the position vector of the location of the PoA with respect to the beginning of the blade.

deflection of the oar in x-direction to be negligible small. The deflection of the oar was calibrated for five locations at the oar: i.e. the locations where the strain gauges were attached, and the beginning and end of the blade (point S and E, respectively).

Using the data from the calibration trials, a linear relation was fitted between the output signals of every pair of strain gauges attached at location *i* and the related applied internal bending moments at location *i*. As the deflection of the oar at locations *i*, S, and E depends on the deflection of the previous locations, data of all strain gauges were used as inputs to calibrate the deflection of the oar. A similar method was used to calibrate $\Phi_{b/w}$.

7.2.3 Determination of $F^{y'}_{w,o}$, $F^{x'}_{w,o}$, $r^{x'}_{PoA/w}$, and P_{defl}

Determination of the estimated values

Assuming (1) the blade to be rigid under all circumstances, (2) the product of the inertia and oar angular acceleration to be negligible small, and (3) the x'- components of the moment-arms in a blade-bound frame of reference to be identical to the x-components of the moment-arms in an earth bound frame of reference, $F^{x'}_{w,o_{sg}}$, $F^{y'}_{w,o_{sg}}$, and $r^{x'}_{PoA/w_{sg}}$ could be calculated using the approach outlined in the introduction. In this case, a closed system with three unknown parameters and three independent equations was constructed:

$$M_1 = (r^{x'}_{S/1} + r^{x'}_{PoA/S})F^{y'} - r^{y'}_{S/1}F^{x'}, \tag{7.7a}$$

$$M_2 = (r^{x'}_{2/1} + r^{x'}_{S/1} + r^{x'}_{PoA/S})F^{y'} - r^{y'}_{S/2}F^{x'}, \tag{7.7b}$$

$$M_3 = (r^{x'}_{2/3} + r^{x'}_{1/2} + r^{x'}_{S/1} + r^{x'}_{PoA/S})F^{y'} - r^{y'}_{S/3}F^{x'}. \tag{7.7c}$$

In which $r^{x'}_i$s are assumed to be equal to the associated r^x_is and $r^{y'}_i$s are calculated as:

$$r^{y'}_i = \Delta^y_{oar_{sg}} \cdot \cos(\Phi_{b/w_{sg}}) - r^x_i \cdot \sin(\Phi_{b/w_{sg}}) \tag{7.8}$$

$r^{x'}_{PoA/w_{sg}}$ is calculated as the sum of $r^{x'}_{S/w_{sg}}$ and $r^{x'}_{PoA/S_{sg}}$.

The associated instantaneous power ($P_{defl_{sg}}$) was calculated as the dot product of $\vec{F}_{w,o_{sg}}$ and $\dot{\vec{r}}_{PoA/w_{sg}}$. To determine $\dot{\vec{r}}_{PoA/w_{sg}}$, $\vec{r}_{PoA/w_{sg}}$ was differentiated and rotated to the blade orientated frame of reference (see Equation 1 and 2 in the "Supporting Information" for an elaboration).

Determination of the reference values

Reference values for $\vec{F}_{w,o_{sg}}$ and $\dot{\vec{r}}_{PoA/w_{sg}}$, (i.e. $F^{x'}_{w,o_{ref}}$, $F^{y'}_{w,o_{ref}}$, and $\dot{\vec{r}}_{PoA/w_{ref}}$, respectively) were calculated using Optotrak and force transducer data. The reference value of $r^{x'}_{PoA/w_{sg}}$ (i.e. $r^{x'}_{PoA/w_{ref}}$) was obtained using a ruler. Reference power-output values (i.e. $P_{defl_{ref}}$) were calculated as the dot product of $\vec{F}_{w,o_{ref}}$ and $\dot{\vec{r}}_{PoA/w_{ref}}$.

7.2.4 Data analyses

Data analyses were performed using Matlab 2017a (the Mathworks Inc, Matick, Massachusetts, United States). Data collected with the strain gauges and force transducer, both measured with 2000 Hz, were down-sampled to 100 Hz in order to match the sample frequency of the Optotrak.

Nine percent of the Optotrak data was missing. Cases with missing Optotrak data were excluded for further analysis. Additionally, cases in which the applied parallel force was lower than -30 N or higher than 20 N were excluded for further analyses since these values were considered to be unrealistic for rowing practice (based on findings of [36]). These exclusions resulted in a data set of six calibration trials consisting of 22445 samples and six validation trials consisting of 18432 samples.

7.2.5 Statistical validation of the obtained results

Statistical analyses were performed using Matlab 2017a (the Mathworks Inc, Matick, Massachusetts, United States). First, the validity of the obtained gains for $M^{z}_{sg}i$, $\Delta^{y}_{oar_{sg}}i$, and $\Phi_{b/w_{sg}}$ was checked. Subsequently, the correspondence between $F^{y'}_{w,o_{sg}}$, $F^{x'}_{w,o_{sg}}$, $r^{x'}_{PoA/w_{sg}}$ and their related reference values was quantified using intraclass correlation coefficients (ICC(3.1)) [53], since this reflects deviation from the identity line. ICC values between .75 and .90 were interpreted as reasonably good, while ICC values higher than .90 were assumed to be good (based on [70] in [53]). In addition, the standard error of the estimate (SEE) was calculated to provide dispersion of the prediction. $P_{defl_{sg}}$ and $P_{defl_{ref}}$ were compared to provide an indication of the maximum accuracy with which $P_{defl_{sg}}$ may be estimated during on-water rowing.

7.3 Results

7.3.1 Typical examples

In Figure 7.3 typical examples of an estimated bending moment and the orientation of the blade plus their references are shown for one validation trial in order to provide an indication of the accuracy of the estimated values. Likewise, the estimated displacement of the beginning of the blade in y-direction and its reference are depicted. These examples imply that output of the strain gauges can be calibrated for bending moments, the deflection of the oar, and the orientation of the blade relative to the earth-bound frame of reference (see Table in S2 Table for correspondence values).

In Figure 7.4, typical examples of the estimated $F^{y'}_{w,o_{sg}}$, $F^{x'}_{w,o_{sg}}$, and $r^{x'}_{PoA/w_{sg}}$ and their references are presented for the same validation trial. These typical examples show that $F^{y'}_{w,o_{sg}}$ is very similar to $F^{y'}_{w,o_{ref}}$, while $F^{x'}_{w,o_{sg}}$ is very different from $F^{x'}_{w,o_{ref}}$. $r^{x'}_{PoA/w_{sg}}$seems to be fairly similar to $r^{x'}_{PoA/w_{ref}}$ when there is a force applied at the oar.

7.3.2 Accuracy of $\Phi_{b/w_{sg}}$, $\vec{F}_{w,o_{sg}}$, and $r^{x'}_{PoA/w_{sg}}$

Overall, correspondence values between $F^{y'}_{w,o_{sg}}$ and $F^{y'}_{w,o_{ref}}$ were very good, while there was no agreement between (1) $F^{x'}_{w,o_{sg}}$ and $F^{x'}_{w,o_{ref}}$, and (2) $r^{x'}_{PoA/w_{sg}}$ and $r^{x'}_{PoA/w_{ref}}$ (see Table 7.1 for all correspondence values).

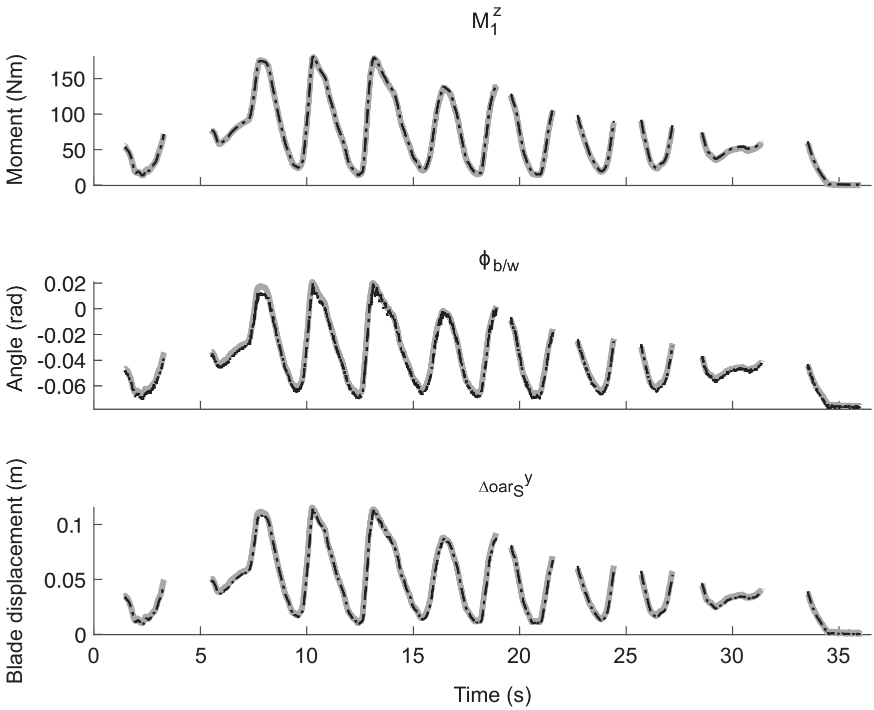

Figure 7.3. Typical examples of the (1) bending moment at one location of the oar M_1^z, (2) the orientation of the blade relative to an earth-bound frame of reference ($\Phi_{b/w}$), and (3) the displacement of the beginning of the blade in y-direction for one validation trial ($\Delta_{oar_S}^y$). Reference values are depicted using a bold grey line, while the values estimated using strain gauges are illustrated as dashed black lines. Note that the missing data refers to data in which the parallel force is lower than -30 N or higher than 20 N.

However, a detailed exploration of the data revealed that correspondence values between $r_{PoA/w_{sg}}^{x'}$ and $r_{PoA/w_{ref}}^{x'}$ were related to the deflection of the oar. As can be seen in Table 7.1 correspondence between $r_{PoA/w_{sg}}^{x'}$ and $r_{PoA/w_{ref}}^{x'}$ was good (ICC $\geq$ .900) when the beginning of the blade was displaced with more than 0.58 cm, which was related to a perpendicular force of 6.0 N. SEE was still relatively high but decreased when the oar was bending more. SEE was smaller than 1.5 cm when the displacement of the beginning of the blade was more than 2.6 cm, which corresponds with a perpendicular force of higher than 42.6 N.

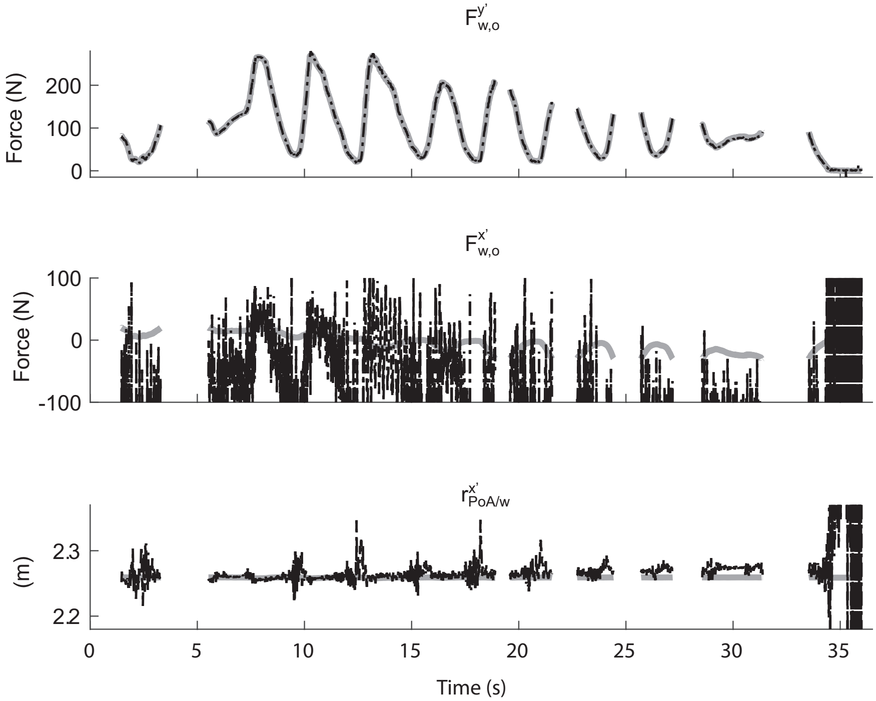

Figure 7.4. Typical examples of (1) the perpendicular force component ($F^{y'}_{w,o}$), (2) the parallel force component ($F^{x'}_{w,o}$), and (3) the x'-component of the location of the point of application $r^{x'}_{PoA/w_{sg}}$. The bold grey lines represent the reference values obtained using Optotrak and the force transducer, while the black dashed lines are the values obtained using the presented method. Note that the missing data is data in which the parallel force is lower than -30 N or higher than 20 N.

7.3.3 Accuracy of $P_{defl_{sg}}$

As $F^{x'}_{w,o_{sg}}$ could not be determined accurately, instantaneous power output associated with $F^{x'}_{w,o_{sg}}$ could not be determined. Correspondence between the estimated instantaneous power output associated with $F^{y'}_{w,o_{sg}}$ using the strain gauges and its reference value was reasonably accurate (ICC = .747, SEE = 14.15; see Figure 7.5).

Table 7.1. Correspondence values (i.e. Intraclass Correlation; ICC; and the Standard Error of the Estimate; SEE) between estimated force components and the x'-component of the position vector of the location of the point of application (i.e. $F^{y'}_{w,o_{sg}}$, $F^{x'}_{w,o_{sg}}$,$r^{x'}_{PoA/w_{sg}}$, respectively) on the one hand, and their reference values on the other hand for the (1) whole data set and a data set that only includes samples of which the displacement of the beginning of the blade was more than (2) 0.58 cm and (3) 2.6 cm

	ICC	SEE
$\boldsymbol{F^{y'}_{w,o_{sg}}}$		
all data	.999	3.8 N
$\Delta^{y}_{oar_{refp}} \geq .0058$ m	.999	4.0 N
$\Delta^{y}_{oar_{refp}} \geq .0262$ m	.998	4.6 N
$\boldsymbol{F^{x'}_{w,o_{sg}}}$		
all data	.000	67503 N
$\Delta^{y}_{oar_{refp}} \geq .0058$ m	.021	279.2 N
$\Delta^{y}_{oar_{refp}} \geq .0262$ m	.238	83.7 N
$\boldsymbol{r^{x'}_{PoA/w_{sg}}}$		
all data	.000	15.29 m
$\Delta^{y}_{oar_{refp}} \geq .0058$ m	.927	.047 m
$\Delta^{y}_{oar_{refp}} \geq .0262$ m	.992	.015 m

7.4 Discussion

In this article we presented a method in which we used the bending oar moments measured with strain gauges to determine the net propulsion force vector and its $\vec{r}_{PoA/w}$ in rowing. Additionally, we validated the accuracy of the obtained force vector and its $\vec{r}_{PoA/w}$ for a simulated rowing situation. We confirmed that output of the strain gauges attached at a rowing oar shaft can be accurately calibrated for (1) internal bending moments, (2), the deflection of the oar, and (3) the orientation of the blade relative to an earth-bound frame of reference. Most importantly, we found that the perpendicular component of the propulsion force vector ($F^{y'}_{w,o}$) could be validly obtained. Moreover, we found that $\vec{r}_{PoA/w}$ could be accurately determined when the beginning of the blade was displaced with more than .58 cm in y-direction, which corresponds to a perpendicular force of 6.0 N for this particular oar. Additionally, we found that an increase in the perpendicular force, resulted in a more accurate determination of $\vec{r}_{PoA/w}$. Subsequently, we have shown that the power output associated

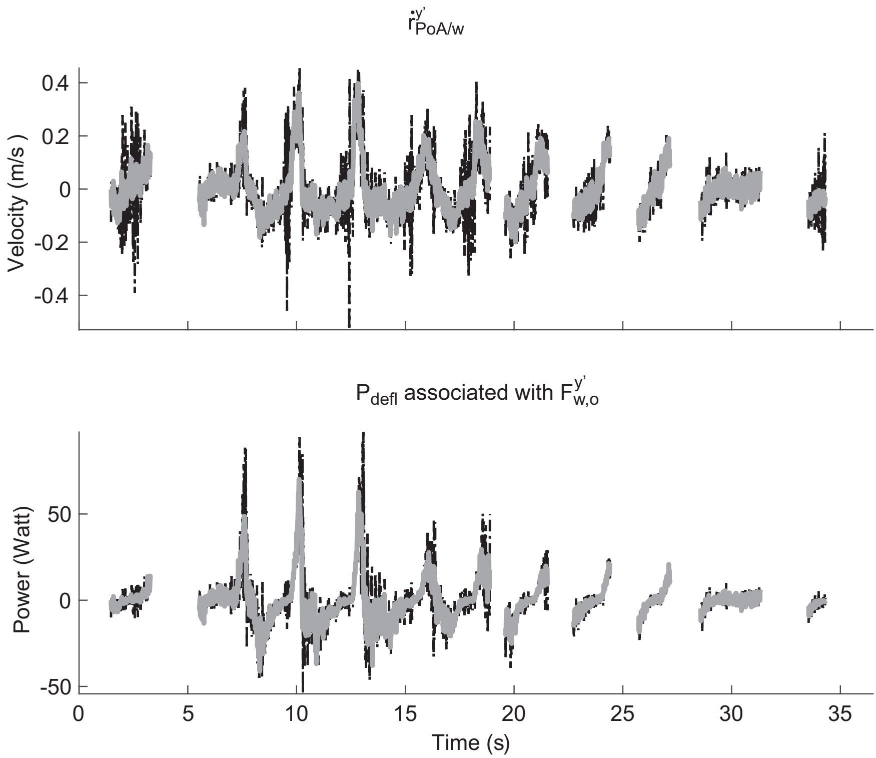

Figure 7.5. Typical examples of (a) the velocity in y'-direction of the location of the blade where the point of application is located ($\dot{r}^{y'}_{PoA/w_{sg}}$), and (b) the component of P_{defl} associated with the perpendicular force. The bold grey lines represent the reference values obtained using Optotrak and the force transducer, while the black dashed lines are the values obtained using the presented method. Note that the missing data is data in which the parallel force is lower than -30 N and higher than 20 N.

with the perpendicular force resulting in bending of the oar could be determined with reasonable accuracy. The parallel force component could not be estimated.

Using a different measuring setup, Hofmijster and colleagues [36], were — in contrast to us — able to estimate the parallel net water force component. They cut the oar and mounted a custom-built oar shaft with two strain gauges each in an angle of 45 degrees relative to the length of the oar. This custom-made oar shaft was designed to be sensitive for strain caused by the parallel force, but added considerable mass to the oar. Moreover, this was a one-off setup. In the context of a light-weight and practical method, we measured local strain by using pairs of strain gauges that were mounted directly at the oar shaft itself. In the current study, the strain of the oar shaft caused by the parallel force might have been too small to be distinguished from noise. Additionally, cross-talk due to strain caused by the perpendicular force may have interfered with the determination of the parallel force as well. In pilot studies we have aimed to obtain the parallel force by measuring the compression and extension of the oar with strain gauges. However, the parallel forces could still not be obtained using that method due to the combination of high stiffness of the shaft and low parallel forces resulting in very small deformations of the oar shaft in x'-direction. As the parallel force does result in additional power loss [36], future studies should keep on searching for a practical method that allows for an accurate estimation of the parallel force component.

However, the presented method is — to our knowledge — the first method that allows for a better estimation of the time-dependent variation in $\vec{r}_{PoA/w}$ in on-water rowing as opposed to previous studies in which it was commonly assumed that the PoA is fixed in the centre of the blade [2, 3, 8, 10, 12, 36, 74, 98]. This improvement in determination is expected to result in a more accurate determination of power loss at the blade during on-water rowing relative to previous estimations as (1) the $\vec{r}_{PoA/w}$ fluctuates during the stroke [46], and (2) the actual $\vec{r}_{PoA/w}$ highly influences calculated values of power loss at the blade [36].

Some limitations related to the setup or the experiment are worth mentioning. Firstly, trials with time-varying forces have been used to calibrate the strain gauges. These forces were applied manually by pulling a rope that was attached to the blade of the oar. In hindsight, a static controlled calibration might have been preferred for calibration, since gains for linear fits also depend on the distribution of the input variables. For example, since the forces were manually applied during the trials relatively many samples reflect a bending moment of 0 N m and only a few samples are related to a max bending moment. This may have influenced the gains for calibration. However, sensitivity tests in which the distribution of the input variables has been equalised did not reveal different agreement values for the estimated water force vector and the $\vec{r}_{PoA/w}$. Secondly, in this experiment the point of application was fixed at the blade during the trials, while this is assumed to vary during the stroke in on-water rowing. However, as the same system of equations will hold true for a time-varying point of application, we do not have doubts about the generalisation of our results with respect to the determination of the location of the point of application.

With respect to the generalisation of our results to rowing practice a few concerns are worth mentioning. Firstly, we evaluated the presented method for one type of oar with specific stiffness properties. Although the same system of equations holds true for different rowing oars, force thresholds and maybe even displacement thresholds for which the method provides valid insight in $\vec{r}_{PoA/w}$ may differ. A calibration and quick validation of the presented method for different oars is thus highly recommended. Secondly, it should be noted that the current calculated power-output values associated with the perpendicular force are expected to be much smaller than the power-output values associated with the perpendicular water force component in real on-water rowing, as the perpendicular velocity of the location at the blade at which the $\vec{F}_{w,o}$ is applied ($\dot{r}^{y'}_{PoA/w}$) will be larger in on-water rowing. In this experiment, $\dot{r}^{y'}_{PoA/w}$ was only due to the bending of the oar, while in on-water rowing $\dot{r}^{y'}_{PoA/w}$ consists of three components that are all different from zero: (1) a velocity component that is due to the velocity of the boat, (2) a velocity component that is due to the rotation of the (rigid) oar relative to the boat, and (3) a velocity component that is due to the bending of the oar (see also the appendix on the calculations of $\dot{r}^{y'}_{PoA/w}$). To determine the total instantaneous power loss due to the generation of propulsion in on-water rowing and thus $\overline{\mathrm{P}}_{blade}$, the velocity components related to the boat velocity and the oar angular velocity need to be taken into account as well.

This study mainly focused on rowing. In passing, we note that the essence of the presented method — using strain gauges to measure bending moments and a system of equations to determine the unknown parameters related to external forces and the position of the PoA — may well be suited to be used for accurate quantifications of force vector components and the associated position of the PoA in other (sport) applications, such as kayaking and different ball sports. For example, the application of the presented method may be interesting for obtaining (bio)mechanical information in ball sports where athletes hit a ball with a racket or bat.

7.5 Conclusion and relevance

The aim of this study was to describe and evaluate a method that allows for an accurate determination of the power loss due to the generation of propulsion in rowing. As mentioned in the introduction, an accurate quantification of the water force vector, the $\vec{r}_{PoA/w}$, and its time-derivative are crucial for obtaining insight in that power loss. Despite the fact that the parallel force component relative to the blade could not be obtained, we are the first who developed a cost-effective practical method that allows for the determination of a perpendicular force component in combination with its time-varying $\vec{r}_{PoA/w}$ in on-water rowing practice. The presented method is therefore a promising option to gain more insight in the power losses due to the generation of propulsion during on-water rowing.

7.6 Supporting information

Determination of $\dot{\vec{r}}_{PoA/w_{sg}}$

Determination of the time-derivative of the point of the blade where the water force vector is applied ($\dot{\vec{r}}_{PoA/w_{sg}}$). The expression of $\vec{r}_{PoA_{sg}}$ in an earth-bound frame of reference is:

$$
\begin{aligned}
\vec{r}_{PoA/w_{sg}}(t) =& \vec{r}_{d/w} + |\vec{r}_{S1/d}| \cdot \begin{pmatrix} \cos(\Phi_{d/w}) \\ \sin(\Phi_{d/w}) \end{pmatrix} \\
& + \Delta^{y}_{oar_{sg_S}} \cdot \begin{pmatrix} -\sin(\Phi_{d/w}) \\ \cos(\Phi_{d/w}) \end{pmatrix} \\
& + |\vec{r}_{PoA/S_{sg}}| \cdot \begin{pmatrix} \cos(\Phi_{d/w} + \Phi_{b/d_{sg}}) \\ \sin(\Phi_{d/w} + \Phi_{b/d_{sg}}) \end{pmatrix}.
\end{aligned}
\tag{7.9}
$$

where $\vec{r}_{d/w}$ is the position vector of the oar pin in an earth-bound frame of reference. While in real rowing this information may be provided by a GPS, in our experiment the origin of the frames of references is at the oar pin and the $\vec{r}_{d/w}$ is thus zero. $\vec{r}_{S1/d}$ is the position vector of the beginning of the blade in the unloaded position. Calculation of $\vec{r}_{S/d}$ is based on the angle of the oar pin relative to the earth-bound frame of reference and the distance of the beginning of the blade from the oar. $\Delta^{y}_{oar_{sg_S}}$ is the position of the beginning of the blade in the loaded situation relative to the position of the beginning of the blade in the unloaded situation. Calculation of $\vec{r}_{PoA/S_{sg}}$ is based on $|r_{PoA/S_{sg}}|$ and $\Phi_{b/w_{sg}}$, both determined using the presented method.

Therefore, $\dot{\vec{r}}_{PoA/w_{sg}}$ is:

$$
\begin{aligned}
\dot{\vec{r}}_{PoA/w_{sg}} =& \dot{\vec{r}}_{d/w} + |\vec{r}_{S/d}| \cdot \dot{\Phi}_{d/w} \cdot \begin{pmatrix} -\sin(\Phi_{d/w}) \\ \cos(\Phi_{d/w}) \end{pmatrix} \\
& + \Delta \dot{oar}^{y}_{sg_S} \cdot \begin{pmatrix} -\sin(\Phi_{d/w}) \\ \cos(\Phi_{d/w}) \end{pmatrix} \\
& + \Delta oar^{y}_{sg_S} \cdot \dot{\Phi}_{d/w} \cdot \begin{pmatrix} -\cos(\Phi_{d/w}) \\ -\sin(\Phi_{d/w}) \end{pmatrix} \\
& + |\dot{r}_{PoA/S_{sg}}| \cdot \begin{pmatrix} \cos(\Phi_{d/w} + \Phi_{b/d_{sg}}) \\ \sin(\Phi_{d/w} + \Phi_{b/d_{sg}}) \end{pmatrix} \\
& + |r_{PoA/S_{sg}}| \cdot (\dot{\Phi}_{d/w} + \dot{\Phi}_{b/d_{sg}}) \cdot \begin{pmatrix} -\sin(\Phi_{d/w} + \Phi_{b/d_{sg}}) \\ \cos(\Phi_{d/w} + \Phi_{b/d_{sg}}) \end{pmatrix}.
\end{aligned}
\tag{7.10}
$$

Correspondence values for input variables

Table 7.2. Correspondence values (i.e. Intraclass Correlation; ICC; and the Standard Error of the Estimate; SEE) between on the one hand the estimated bending moments ($M^z_{sg\,i}$), the displacement of the oar ($\Delta^y_{oar_{sg}\,i}$), and the angle of the blade relative to its neutral position ($\Phi_{b/w_{sg}}$), and the other hand the related reference values ($M^z_{ref\,i}$, $\Delta^y_{oar_{ref}\,i}$, and $\Phi_{b/w_{ref}}$, respectively).

	ICC	SEE
$M^z{}_1$	1.000	3.48 N m
$M^z{}_2$	1.000	1.77 N m
$M^z{}_3$	1.000	1.42 N m
$\Delta^y_{oar\,1}$	.991	.0003 m
$\Delta^y_{oar\,2}$	.998	.0012 m
$\Delta^y_{oar\,3}$	.998	.0015 m
$\Delta^y_{oar\,S}$	.998	.0022 m
$\Delta^y_{oar\,E}$	.998	.0034 m
$\Phi_{b/w}$	.998	.0025 rad


1
7
9
6

Chapter 8

Epilogue

Motivated by the intention to contribute to the understanding and improvement of rowing performance, innovative tools for rowing practice have been developed and evaluated. In this chapter, an evaluation is provided of (1) the main findings of this thesis, (2) its contribution to the sport science community, and (3) its implications for rowing practice. Furthermore, some future steps in rowing research are discussed.

8.1 Introduction

The overarching aim of this thesis was to supply rowing practice with innovative tools that contribute to the understanding and improvement of rowing performance (i.e. the average boat velocity over a race distance). To this end, the power balance for rowing [33, 89] was derived in order to identify performance determining factors. From this balance, it follows that (1) a rower's power output averaged over a stroke cycle, and (2) power losses associated with boat velocity fluctuations and (3) the generation of propulsion constitute three key variables for analysing and understanding rowing performance.

In this thesis, studies were conducted to evaluate whether these three power variables can be used as *effective* feedback variables to improve rowing performance. As stated in the introduction (**Chapter 1**), feedback on key variables can be qualified as *effective* when (1) they can be determined accurately, and (2) allow athletes to adjust behaviour related to the feedback variable [69]. In **Chapter 2-7** it was examined whether feedback on the power variables meets those requirements. In this chapter, the main findings of this thesis are discussed and future research directions are indicated. Moreover, a reflection on the scientific contribution of this work and the implementation of its findings in rowing practice are discussed.

8.2 An evaluation of the main findings

8.2.1 Determination of power variables in rowing

To examine whether the power variables in rowing can be determined accurately, commonly used methods to calculate power output and power losses in rowing were evaluated after which improved methods were provided and tested (**Chapter 2-4, 7**). An objective derivative of the power loss due to velocity fluctuations could already be determined rather accurately prior at the start of this thesis [33], but this was not the case for a rower's average delivered power per stroke cycle and the power loss at the blade due to the generation of propulsion. Previous methods to determine these last two variables were demonstrated to be based on unrealistic assumptions resulting in inaccurate values of these variables (e.g. [2, 3, 5, 12, 19, 26, 31, 36, 51, 64–66, 71, 74]). With respect to the average power output of a rower, it was shown in **Chapter 2-4** that this power variable cannot be determined from oar forces and oar movements alone: the most commonly used method to date (e.g. [2, 3, 5, 19, 26, 32, 51, 64–66, 71, 74]). Instead, the product of acceleration of a rower's centre of mass, the boat velocity and the mass of the rower should be quantified as well. Neglecting this last term results in a substantial underestimation of a rower's true power output of 12.3 % on average with small variations between rowers and rowing conditions, such as the number of strokes min^{-1} (i.e. stroke rate). As regards the power loss due to the generation of propulsion, it was argued in **Chapter 7** that previous methods aiming to determine this power term (e.g. [12, 36, 65]) incorrectly assumed (1) the net water force vector to be always perpendicular to the blade, (2) the point of application (PoA) of the net water force vector to be fixed in the middle of the blade, and/or (3) the oar to be rigid. In this chapter a method was presented and evaluated that does not rely on the last two assumptions. Using this method the perpendicular force component factor, as well as the actual PoA can be obtained accurately.

As regards the method to obtain power loss at the blade (**Chapter 7**), two critical notes need to be highlighted. Firstly, the presented method was only validated in lab. Although the simulated water force in the lab will be similar to actual water force, the simulated blade velocity is smaller than in real on-water rowing. This also means that power loss at the blade in real-rowing will be different than in the lab. It is therefore recommended to validate the method in situations in which more realistic kinematics and kinetics of the blade movement are imposed, for example by using a robot that prescribes the movements of the blade through a towing tank (see as an example [27]). Secondly, and more critical, it is worth mentioning that this method still not allows for an accurate determination of the net water force component that is in parallel direction of the blade. This means that about 20 % of the total power loss due to the generation of propulsion can still not be obtained [36]. In order to get more insight into the parallel force the data retrieved from this experiment might be analysed using a so-called neural network technique. This statistical machine learning technique is often used for finding complex non-linear relations between input and output variables. Alternatively, a new (set of) sensor(s) that is more prone to changes in parallel forces could be developed.

8.2.2 The effectiveness of feedback on power variables

To examine whether power variables can be used as effective feedback variables to adjust behaviour related to these power variables, it was evaluated whether feedback on average power output and power loss due to velocity fluctuations enables rowers to adopt their performance according to (pre-)set targets related to these variables (**Chapter 5-6**). The results of the first study (**Chapter 5**) confirmed that feedback on a rower's average power output indeed aids rowers to comply much better with power-output targets imposed by the coaches compared to more traditional feedback variables such as boat velocity and stroke rate. Since power output is strongly related to metabolic energy consumption, this finding implies that feedback on power output allows for better control of training intensity and, presumably, — in the long run — improve rowers' physical capacities and rowing performance. In contrast, the results of the second feedback study (**Chapter 6**) suggested that feedback on power loss due to velocity fluctuations does not aid rowers to reduce their power loss: only one third of the rowers who participated in the study were able to reduce their power loss.

The different results found in **Chapter 5** and **6** may be explained by the different instructions provided to the rowers in both experiments. In **Chapter 5** rowers were instructed to comply with very specific power-output targets, while in **Chapter 6** the goal was much less specified: rowers were only instructed to "do their best" to reduce their power loss as much as possible. Research has shown that the effect of feedback is moderated by the specificity of the goals [52, 58]: specific goals direct attention, mobilise effort and motivate people to reach goals, while non-specific goals do not. Another explanation is that the tasks in both experiments (i.e. adjusting power output versus adjusting power losses) differ in complexity. Average power output can be altered by either changing the force applied at the oar or the stroke rate. The skill to master power loss due to velocity fluctuations, in contrast, requires a pattern of movement coordination involving multiple degrees of freedom. Complex tasks require more effort and information processing on the part of the learner [94]. In the case of reducing power loss due to velocity fluctuations, rowers might require more time to alter their technique to reduce the power loss than the amount of time that was provided in the feedback study of **Chapter 6**. Alternatively, the power loss feedback provided in this study might not have been specific enough in relation to the complexity of the task.

This last suggestion raises the question on what level of rowing performance feedback need to be provided in order to optimally improve performance. Actions and goals can be organised hierarchically, whereby goals of the self are at the top of the hierarchy, followed by motivational and physical goals and actions [52, 87]. Translated to rowing, a rower's self-esteem will be at the highest level. This self-esteem may depend on the goal to become an Olympic rower, followed by the goal and action to improve rowing performance. This goal again can be subdivided hierarchically in more specific goals and actions as the goal/action to (1) improve boat velocity, (2) to improve the power variables related to boat velocity, and (3) to improve the kinetics and kinematics related to the power variables. In general, it is stated that feedback should not engage on the most lowest actions as those actions are often executed automatically. Directing attention towards automatic movements is likely to interrupt those movements [87]. Moreover, it costs more cognitive resources and drifts attention from the motivational actions [52], resulting in an impairment of performance. However, when the feedback is engaged on high level goals and actions, the feedback may not contain enough information for learners to adjust the key movement patterns on a lower level [94]. On what level of hierarchy feedback need to be provided in order to optimally improve performance also depends on characteristics of the learner, such as his/her level of skill competence or self-efficacy (e.g. [52]). From the "optimising performance through intrinsic motivation (OPTIMAL) theory" [96] it follows that motivational and attentional factors may influence the effect of a feedback variable on performance, in particular (1) the learner's future expectation on performance, (2) his/her autonomy to learn a skill, and (3) his/her locus of attention (external versus internal focus). Using a biomechanical and pragmatic approach, it was argued in this thesis that feedback on power output aids rowers to improve performance more than feedback on boat velocity. However, it was beyond the scope of the research aim to explicitly examine whether feedback provided on the level of power output is *most* effective to improve performance compared to feedback on other levels. There was also no attention paid on rowers' individual characteristics that may moderate the effect of feedback variable on rowing performance. Therefore, systematic research with a strong theoretical framework on motor learning is required.

8.3 Future research

8.3.1 Research directions to improve the understanding of rowing performance

In this thesis methods were presented that allow for an accurate quantification of the energetics of rowing in order to improve understanding of rowing performance and the difference in performance between rowers and boats. However, this thesis does by no means provide a complete understanding of rowing performance. For example, no attention was paid to the psychological aspects of performance. Also, more aspects of the mechanics and energetics of rowing that likely influence rowing performance are still not well understood.

First, consider the power loss due to the generation of propulsion. The dedicated method developed in the present thesis allows for a better estimation of this power loss (**Chapter 7**), but it hardly provides insight into the causes of this power loss and the associated processes. To this end, a better understanding of the hydrodynamics around the blade is required. New technological advances such as particle image velocimetry and robots mimicking the movement of the blade [27] allow for detailed measurements of the characteristics of the water flow around the blade in the lab. Insight into the water flow is required to better understand the relationship between power loss due the generation of propulsion on the one hand, and a rower's propulsion technique, blade shapes, and oar gearing on the other hand.

Second, consider the relation between rowing energetics and *inter*personal movement coordination. As explicitly stated in **Chapter 1**, this thesis focused on the improvement of physical power and *intra*personal movement aspects of rowing, leaving interpersonal movement coordination aside. However, this inherent aspect of crew rowing has been assumed to be a critical determinant of rowing performance as well, even though the exact relation with performance is poorly understood. Research has shown that improved synchronisation of interpersonal movements may be detrimental for rowing performance, as it results in an increase of velocity fluctuations and the associated power loss [17, 33]. However, other experimental results suggest that improved synchronisation do also support rowers to increase their average power output, as synchronisation leads to minimised boat perturbations [16] and higher subjective pain threshold

[13, 85]. The net effect of synchronisation of interpersonal movement on average boat velocity is thus still unclear. This net effect may be examined using the power balance for rowing as a framework, as it will provide insight into the effect of synchronisation in crew rowing on the average power output delivered by the rowers, the power loss due to boat velocity fluctuations, and the boat velocity.

8.3.2 Research directions to improve rowing performance

Inspired by the power balance of rowing [33, 89], it was examined in this thesis whether feedback on the power variables enables rowers to improve performance. However, as mentioned before, it was not tested whether feedback that applies on this level of hierarchy is the most optimal to improve performance. Moreover, possible moderating effects of characteristics of the learners (the rowers) were not examined either. Besides these content related aspects, this thesis did also not explicitly examine the effect of the presentation of the feedback provided. From motor learning studies, it is known that the modality of the feedback, as well as its frequency and timing affect skill acquisition (see reviews from [69, 95, 97]). For example, it has been suggested that auditory feedback is more effective for time-depending coordination tasks, while visual feedback is more beneficial for spatial depending tasks [79]. The frequency should be limited to a certain extent that it still accelerates skill acquisition without athletes getting (too) dependent on the feedback [69, 95, 97]. Systematic research that is based on a firm conceptual framework is required to understand what kind of feedback is most optimal to improve performance in applied sport settings, such as rowing practice.

Such systematic research is facilitated by the rapid development of technology in sports. Also in this project, an innovative feedback tool for rowing practice has been developed that allows for graphically and numerically real-time feedback on multiple biophysical feedback variables (**Appendix**). As of yet, this tool can only be used for research purposes. A next step is to improve the tool and make it user-friendly and available for the rowing community. Additionally, a software application (Smartview) was developed that allows for visual feedback on sports parameters in general. For this project the parameters were specified for rowing. However, since the application can deal with multiple sensors, it allows for visual feedback in other sports and rehabilitation disciplines as well.

8.3.3 Directions for collaboration between practice and research

The current development of technology leads to an exponential growth of available (sensor) data in sports practice. This growth may not only help to increase insight into sports performance, but may also encourage collaborations between sports scientists and practitioners. Both groups initially share a common goal: gaining more insight into sport performance. The scientist, however, is in general more interested in *why and how* a certain performance is reached, while the practitioner is more interested in the practical usability of the knowledge to improve athletes' performance. This difference in emphasis leads to different research approaches. The scientists would preferably start with theoretical models followed by time-consuming systematic research designs to understand performance on group level. The practitioner prefers a quicker approach that helps her/him to improve *individual* performance of outstanding talents. (S)he might be less interested in the average effects of a certain intervention. As of yet, these different interests and time-frames can lead to compromises in studies to satisfy all interests, while at the same time unintentionally falling short on both. With the upcoming technology, sports federations and clubs have more options to collect and store large amounts of data to monitor the development of individual performances. At the same time, such systematic data collection can cover important information for sport scientists to understand performance. These new options for data collection could encourage scientists and practitioners to collaborate more closely as both slightly different interests are covered by one same database.

8.4 Contributions to science

The work reported in this thesis contributes to sport science in two regards. First of all, the methods developed to accurately determine key performance variables in rowing have added to the understanding of this sport. Secondly, the adopted multidisciplinary approach sets an example for the applied sports feedback literature in general. Previous studies on the effectiveness of augmented feedback in sports were often conducted from either a biomechanical or a motor learning perspective [69]. Generally speaking, biomechanical studies have focused predominantly on the development of new technology and/or the determination of key performance variables, but with a limited eye for the effect of the feedback provided on skill acquisition (e.g. [29, 47, 59, 68, 80]). Conversely, the majority of the motor learning studies have addressed the effect of multiple aspects of feedback (e.g. content, frequency, timing and focus of attention) on skill acquisition, but most conclusions were drawn from laboratory studies involving artificial tasks [69, 97]. As a result, the conclusions of these studies cannot be readily generalised to more complex tasks in applied sport settings. In the present work a biomechanical approach was combined with a motor learning approach. The biomechanical approach was followed to identify performance variables and to develop methods and tools to accurately quantify these variables and provide feedback on them. Subsequently, a motor learning approach was adopted to evaluate whether providing feedback on those variables was effective in attaining preset training goals. Such a combined approach provides a better understanding as to how to efficiently improve sports performance.

8.5 Practical implementations

This thesis started with the statement that, despite extensive research on rowing, coaches and rowers lack relevant information and tools to effectively improve performance. To fill this gap, this work aimed to supply rowing practice with innovative tools that contribute to the understanding and improvement of rowing performance. To this end, the work reported was conducted in close collaboration with rowing practice, in particular the Dutch Rowing Federation. Below, the practical implementation of the most important outcome of this work is discussed: the use of accurate power-output feedback in order to control training intensity.

This work has shown that feedback on power output aids rowers to comply with training intensity. Besides this main finding a marked discrepancy was observed between the prescribed targets by coaches and the actually delivered power output by the rowers. Moreover, coaches had difficulties perceiving improvements in rowers' compliance with power-output targets (**Chapter 5**). These findings underscore the importance of implementing power output in practice. Practically — and owing to rapid technological advances — it has already become possible to provide real-time feedback on power output in practice (e.g. the Em-Power Oarlock; Nielsen Kellerman, Boothwyn, PA). However, most — if not all

— commercial systems that allow for power-output feedback base their power output calculations on oar forces and oar motion alone. As demonstrated, this method is incorrect and leads to a substantial underestimation of true power-output values. Rowers' compliance with such erroneous values of power output may lead to higher performed training intensities than intended and eventually to higher risks of overtraining. Therefore, a correction of the commonly used method is required in order to provide better estimates of rowers' true average power-output values.

Based on the findings of **Chapter 4**, it was proposed to obtain power-output values using the commonly used method multiplied by a factor of 1.14 (see the discussion of **Chapter 4** for an elaborated explanation). Note that (1) this method does not take the small variations in underestimations of power-output values between rowers and rowing conditions such as stroke rate into account, and (2) that the factor 1.14 is based on results obtained from single scull rowing. From this, it follows that this "simple" rectification of the commonly used method can be used to provide feedback on power-output values to control training intensity, but that a comparison of power-output values between rowers should be made with caution.

To enable such comparisons, it is advised to determine average power-output values using the correct method provided in **Chapter 2**, instead of the commonly used method. This means that power-output values need to be determined using the oar forces and oar motions *plus* the product of the mass of a rower, his/her centre of mass (CoM) acceleration and the boat velocity. To capture the CoM acceleration of a rower, 13 inertial sensors were used in **Chapter 3** and **4**. Since this setup is too cumbersome for daily use, a follow-up study[1] (of which the results remain to be reported) was done to examine whether the number of inertial sensors could be reduced without compromising on the accuracy of the obtained CoM acceleration to an unacceptable degree. A so-called 'brute-force method' was used to analyse the data obtained in **Chapter 3**. This means that regression analyses were conducted with all possible combinations of the 13 different horizontal body segment accelerations captured with the inertial sensors. Preliminary results suggest that two adequately positioned inertial sensors suffice to estimate a rower's CoM acceleration rather accurately (see Table 8.1). More analyses are needed to examine the impact on the accuracy of obtained power-output values using only two or three sensors. When this

[1] This work has been done in collaboration with and Msc. Loois and ir. Bouhassani, working at the applied university of Amsterdam.

method is proven to be accurate, it could be implemented in practice so as to obtain "true" power-output values.

Table 8.1. The different number of sensors placed at different body segments to determine a rower's centre of mass acceleration in rowing direction. Rsquared represents the explained variance.

Number of sensors	Sensor placement	Rsquared (%)
1	Thorax	94.1
2	Thorax and one forearm	96.8
3	Thorax, pelvis and one upperarm	97.9
4	Thorax, pelvis, head, and one forearm	98.8
13 (all)	(see **Chapter 3**)	99.2

8.6 Conclusion

The overarching aim of this thesis was to provide rowing practice with innovative tools that contribute to the understanding and improvement of rowing performance. To this end, concepts and methods from biomechanics and motor learning studies were combined. At first, the power balance for rowing was derived on the basis of which the average power output and power losses of a rower were identified as key performance variables. Methods were developed that allow for improved estimations of those power variables. Subsequently, feedback studies were conducted to evaluate whether the power variables enable rowers to adjust those variables. Results confirm that average power-output feedback enables rowers to better comply with power-output targets. As such, feedback on power output thus seems useful to control rowers power output during training sessions and —in the long run— improve their physical capacities and rowing performance. We therefore recommend rowing practice and science to implement a valid method to determine average power output and to control training intensity using feedback on power output. To further understand rowing performance, we encourage research to provide more insight into the understanding of the power loss around the blades and the role of interpersonal movement coordination on rowing performance. Additionally, in order to effectively improve performance, future feedback studies should focus on what feedback leads to the most optimal improvement of rowing performance; for example, by comparing feedback variables and presentations applied at different hierarchical levels. These fundamental and controlled studies may be supplemented by new technology that allow for large amounts of sensor data collected during daily training sessions and stored in large databases.

8.7 Take home messages

1. A rower's average power output cannot be calculated from oar forces and oar motion alone. The product of the rower's centre of mass, his/her centre of mass acceleration and the boat velocity should also be taken into account.
2. Calculating a rower's average power output from oar forces and oar motion alone results in an underestimation of the true average power output by 12.3 %.
3. Large horizontal centre of mass accelerations can be determined very accurately by using inertial sensors placed at 13 body segments and Zatsiorsky's standard distribution of mass model [99].
4. Real-time feedback on power-output values results in improved compliance of rowers with a prescribed training intensity.
5. Real-time feedback and coach feedback on power loss due to velocity fluctuations do not seem to aid rowers in reducing this power loss.
6. Power loss due to the generation of propulsion can be estimated rather accurately by using three pairs of strain gauges attached at the shaft of an oar.

Appendix

The development of an innovative tool for real-time feedback in rowing

Introduction

In order to provide real-time feedback on valid power output (**Chapter 5**) and power loss due to velocity fluctuations (**Chapter 6**), a tool has been developed that allows for visual real-time feedback for rowers and coaches during on-water rowing. In this appendix, an overview of the system and its functionality is provided. Additionally, an evaluation of the tool is provided in the light of its functionality and practical use.

Overview and functionality of the system

The system consists of two parts: (1) the Rowing Coach Cockpit (RCC) hardware that collects the data using several sensors and transfers them to an Android phone or tablet and (2) "Smartview" software that enables feedback to rowers and coaches.

The Rowing Coach Cockpit

The RCC consists of three components (see Figure A.1 for a schematic overview): (1) the sensors that collect the data, (2) the central unit that receives the data and (3) the sender that transfers the data to display devices.

1. Most of the sensors used for the RCC are part of the PowerLine Rowing Instrumentation system (Peach Innovations Ltd., Cambridge, UK). This system consists of either one (sweep rowing) or two (scull rowing) instrumented oarlocks per rower that measure forces applied at the oarlock and oar angle in the horizontal plane using force transducers and a reed sensor. The system comes with an inertial sensor that measures the acceleration of the boat in the travel direction, as well as yaw, pitch and roll angles of the boat. All these data are collected at 100 Hz. A GPS sensor (LOCOSYS, Taipei City, Taiwan; 10 Hz sample frequency) measures the location of the boat (in global coordinates) and its velocity at 10 Hz.

2. The central unit is a waterproof custom made data acquisition system (Vrije Universiteit Amsterdam, The Netherlands) that consists of a Seeeduino ADK Main Board (Seeed Studio, Shenzen, China), an SD-card shield to save the collected data, a RS-485 that sends the data to the sender, and the aforementioned GPS sensor. Moreover, the central unit is equipped with a Lithium Ion battery that powers the Powerline system, the central unit and the sender for about 3-3.5 hours. The system is operated using three switches: (1) a power switch, (2) a record switch, and (3) a switch to put markers in the data.
3. The data sender is a small water proof box containing a Rasperry Pi 2 model B (Raspberry PI foundatio, Cambridgeshire, UK) that transfers the collected data over wifi (using a TP-Link TL-WN722N dongle; TP-Link Technologies Co., Ltd; Shenzen, China) to display-devices in and close to the boat.

The "Smartview" software

Smartview is a collection of Android libraries that supports the integration, analysis and presentation of multiple sensor data using smartphones, tablets or smartglasses. Due to its generic design, it can also be applied in other sports using different sensor input. Smartview consists of three parts: (1) a sport specific library to integrate and analyse the data, (2) a library to manage and present the data, and (3) a library that supports mirroring the presented data to smartglasses via Bluetooth (see Figure A.2 for a schematic overview).

1. The sport specific library contains modules that are used to integrate and analyse multiple sensor data in order to determine sport specific variables. In the case of rowing, the data from the RCC and a heart rate monitor is integrated and analysed to determine (rowing specific) feedback variables such as catch and finish angles, power output, maximum forces, that have been provided by the Dutch Rowing Federation.
2. The Smartview application allows for the presentation of sport specific variables to athletes and coaches. The application is flexible in different ways. Firstly, coaches and athletes can choose themselves what variables need to be presented per training session using the 'manage template' function (see Figure A.3). Secondly, they can choose whether they would

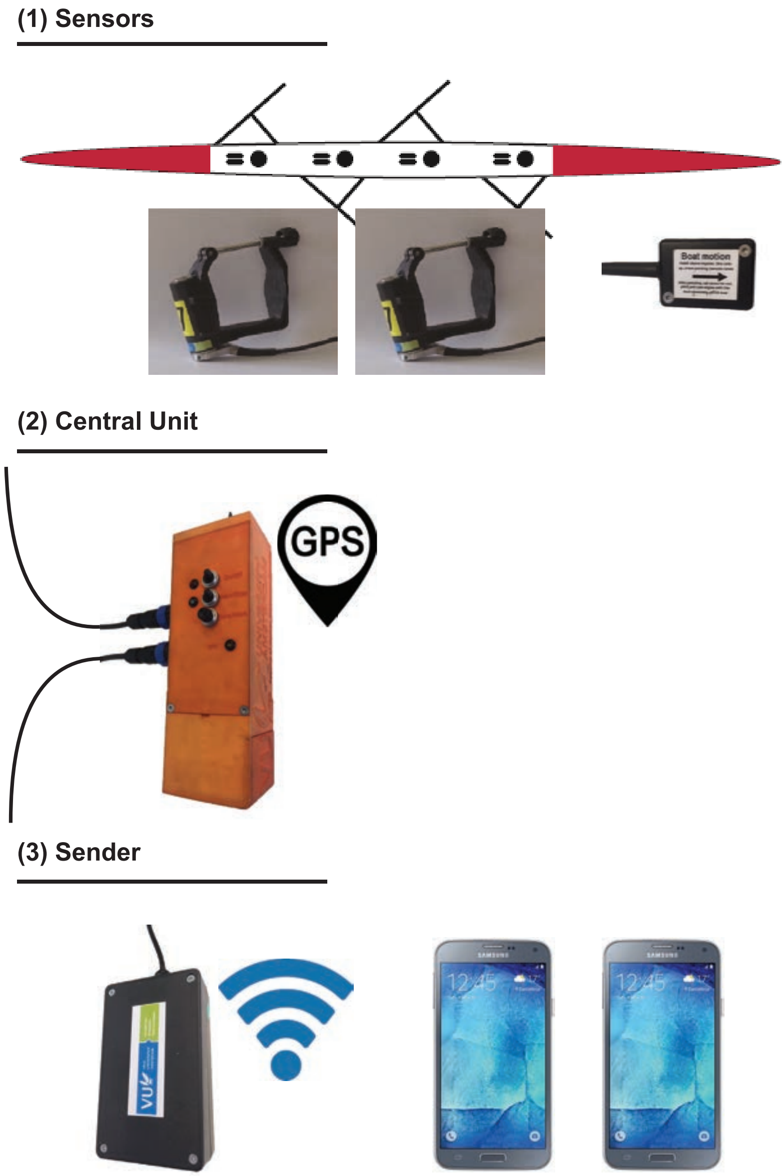

Figure A.1. A schematic overview of the Rowing Coach Cockpit. (1) the sensors consists of the PowerLine Rowing Instrumentation. (2) the central unit saves the collected data from the sensors on an SD-card and sends it to the sender. The GPS (LOCOSYS, Taipei City, Taiwan; 10 Hz sample frequency) is included in the central unit. (3) The sender is a Rasperry PI (Raspberry PI foundatio, Cambridgeshire, UK) that sends the 100 Hz data to tablets and smartphones using a WiFi protocol.

like variables to be presented numerically or graphically. Thirdly, individually based thresholds can be set per variable in order to guide athletes towards their goals. In the case of rowing, rowers and coaches can choose multiple feedback variables that can be presented numerically of graphically. The variables can be based either on data from their own instrumented oarlock(s) or on data from other oarlocks in the boat (see Figure A.3 the variables). This way, coaches and rowers are able to monitor multiple rowers in the same boat at one feedback screen.

3. Using Smartview, analysed data can be sent via Bluetooth to smartglasses.

Figure A.2. A schematic overview of the Smartview software platform with its (1) sport specific libraries that can be used to integrate and analyse multiple sensors data. (2) The Smartview application that allows for presentation of sport specific feedback variables and (3) the possibility to connect with a smart glass.

Evaluation

The RCC plus smartview software is a tool that can be used for research purposes. To evaluate whether the feedback tool has potential to be used as a commercial tool, attention on its benefits and drawbacks is drawn.

The first benefit of the tool is that it allows for valid feedback for both sweep *and* scull rowing. Most currently used feedback tools base their scull rowing feedback on *one* instrumented oarlock, while it is well-known that the kinematics and kinetics of the portside oar can be different from the kinetics and kinematics of the starboard oar (e.g. [93]). The RCC plus smartview software determines feedback variables based on data from both an instrumented portside and starboard oar. Secondly, the RCC saves the 100 Hz data collected at all oars using an SD-card. This way, the system does not only allow for online one single value feedback per stroke cycle, but also for an offline evaluation of rowers' stroke characteristics, such as the force-angle curve. Additionally, these offline data provide insight in the (synchronisation of) interpersonal movement coordination, since the 100 Hz data of the separate oarlocks are measured and saved synchronously. Thirdly, the smartview software allows for personalised feedback on different levels: coaches and rowers can change (1) the number of variables visible in one feedback screen, (2) what variables are presented, and (3) how they are presented. Fourthly and very relevant for this thesis and beyond, the RCC provides a valid determination of a rower's average power output as its algorithm is based on the results of **Chapter 4**.

Due to its benefits, the RCC plus Smartview system seems an interesting tool for commercial purposes instead of only a research tool. However, it does require some further improvements before it can be commercialised and implemented into practice. The first issue that needs to be improved is the data transfer from the RCC to the Smartview software. During the first years of development, sensor data collected by the central unit were sent to Android smartphones via cables and IOIO-OTG boards (SparkFun Electronics, Boulder, CO, USA). Although this system was reliable, it was bulky and the setup of the system was time-consuming. Moreover, the cables were too sensitive for water drops. At first instance, Bluetooth connections (CSBLUEKEY100 v. 2.1 Bluetooth dongles, König Electronic, Germany) from the IOIO-OTG boards to the smartphones seemed promising in order to reduce the water problems. However, the data transmission via Bluetooth was much less reliable resulting in connection difficulties and data loss. Most missing data in **Chapter 5** was due to incorrect and unreliable data transfer from the IOIO's to the smartphones. Another disadvantage of this Bluetooth was that it only allowed one to one data transmission over a few meters. Therefore, coaches could not be provided with real-time feedback on their rowing crew. Due to the multiple problems with Bluetooth, a wifi setup has been chosen. For now, the system can provide feedback to one to four rowers in a boat plus one coach being close to the boat. However, as of yet, it seems difficult to provide a crew of 8 rowers with feedback. Several solutions have been tried but none of them have been systematically tested yet. These systematic tests and an improvement of the wifi protocol are crucial before launching the system commercially.

The second issue that needs to be resolved before the system can become commercial is the usability of the system. Firstly, the RCC system is rather bulky. For example, due to its organic development process it consists of a Seeeduino and a Raspberry PI, while these two systems can most possibly be integrated into one. Secondly, the system makes use of water-proof smartphones with touch screens as feedback displays. On the one hand, smartphones are really user-friendly as everyone has one and knows how to operate it. On the other hand, smartphones with touch screens are sensitive to water drops and hardly visible when the sun is out. Therefore, I would recommend custom-made displays such as the Nielsen Kellerman displays (Speedcoach, NKsports, Boothwyn, PA) in order to present rowing feedback.

Conclusion

In close collaboration with the Dutch Rowing Federation, an innovative feedback tool has been developed. The system provides valid real-time feedback for both sweep and scull rowing. Data from rowing specific sensors are collected by a central unit that saves the data on a SD-card for offline evaluation of a training session. Simultaneously, data are sent to feedback displays such as tablets and smartphones over wifi using a Rasperry Pi. This data is then integrated, analysed and presented to coaches and rowers by the Smartview software application. To implement the feedback system in the daily rowing practice, it is recommended to improve (1) the data transfer between the RCC and Smartview and (2) the usability of the system.

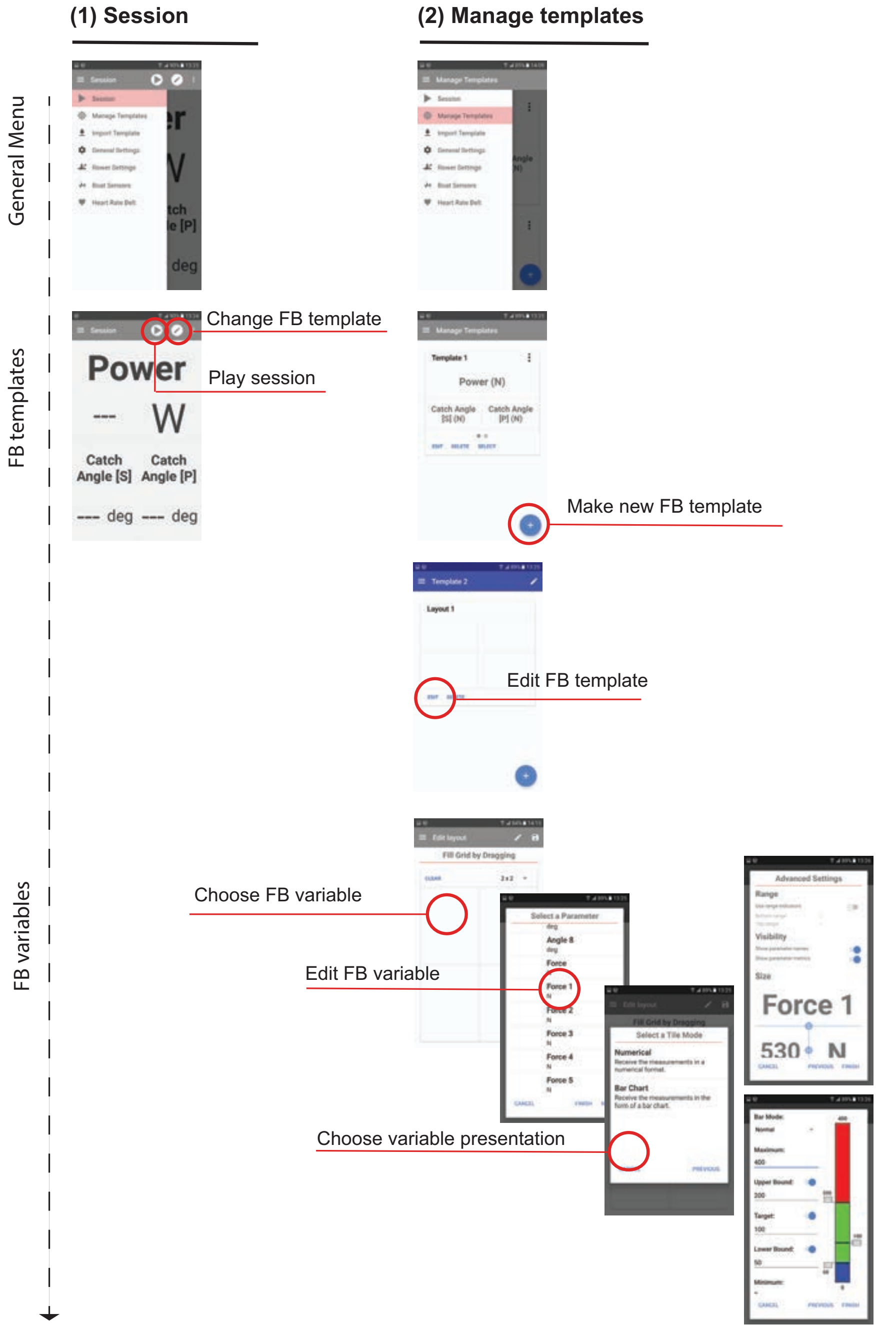

Figure A.3. A schematic overview of two functions in the Smartview application. (1) In the "session" function athletes and coaches can choose self-made templates in order to present feedback during a training session. (2) In the "manage templates" function athletes and coaches can create their own feedback template with different variables that can all be presented digital or graphical. For all variables individual thresholds can be set (see advanced settings and bar mode).

Summary

As in other sports, rowing races are often decided within very small margins. Rowing performance can be quantified as the average boat velocity over a given race distance and is determined by a combination of rowers' physical power and rowing technique[1]. Rowers and coaches continuously search for opportunities and methods to improve performance. The work reported in this thesis aimed to contribute to this search by developing and evaluating tools for understanding and improving rowing performance.

To better understand rowing performance from a biomechanical point of view, the power balance for rowing [33, 89] was used. This balance provides insight into the relation between the physical capacities and intrapersonal movement coordination of rowers and their effect on rowing performance. More in particular, it follows from this balance that a rower's average power output and power losses associated with boat velocity fluctuations and the generation of propulsion are performance determining variables. Average power output is strongly related to metabolic energy consumption [37], and therefore an objective measure for the physical capacities of a rower. It thus forms and interesting variable to control training intensity and — in the long term — improve the physical capacity of a rower. Power losses are most certainly related to rowing technique and therewith potentially useful feedback variables for improving rowing technique.

To improve average power output and reduce power losses rowers require 'effective' feedback on these power variables. As stated in the introduction (**Chapter 1**), feedback on key variables can be qualified as effective as (1) the feedback variables can be determined accurately and (2) feedback on those variables enables athletes to adjust them [69]. To meet the first requirement, methods

[1] Rowing technique encompasses both *intra*personal movement coordination and, in the case of crew boats, *inter*personal movement coordination as well.

that allow for accurate estimations of the power variables were developed and evaluated (**Chapter 2-4, 7**). Subsequently, in the view of the second requirement, it was evaluated whether feedback on power variables enables rowers to adjust these variables (**Chapter 5-6**). To provide the feedback during training sessions and feedback studies, a custom-made feedback tool was developed (**Appendix**).

As regards power output, a new method to accurately determine this power variable was developed. As of yet, a rower's average power output was calculated by using oar forces and oar movements alone (e.g. [1–3, 6, 8, 9, 14, 17–19, 21, 22]), of which the calculation of the product of the moment around the oar and the oar angular velocity has been used the most (e.g. [1, 3, 6, 21]; referred to as the commonly used method). In **Chapter 2**, Newtonian mechanics was applied to demonstrate that this commonly used method is incomplete and therefore invalid. For a valid determination of a rower's average power output the average of the product of a rower's mass, the boat velocity, and the acceleration of a rower's centre of mass (CoM) need to be taken into account as well. The first two parameters can be measured rather accurately using one or two sensors, but this is not the case for the determination of the CoM acceleration. A validation study (**see Chapter 3**) showed that a rower's CoM acceleration can be accurately determined using inertial sensors measuring the acceleration of 13 body segments and Zatsiorsky's standard mass distribution model [5, 26].

Subsequently, in an on-water rowing experiment (**Chapter 4**), it was shown that the difference between average power output values determined using the commonly used method and the 'correct' method is substantial. When power output values are determined using the commonly used method, the values are underestimated by 12.3 % on average, with only marginal variations between rowers and rowing conditions such as the number of strokes min^{-1} (stroke rate). These results imply that the commonly used method needs to be corrected in order to provide accurate feedback on power output. An alternative would be to use the more encompassing measurement method introduced in **Chapter 2** and **3**, but this is less feasible in daily rowing practice.

An on-water feedback study was conducted to examine whether power output feedback enables rowers to adjust their power output (**Chapter 5**). Based on previous results from motor learning studies (e.g. [15, 16, 23, 25]), and the successful use of power output feedback in cycling, it was expected that rowers in single sculls (one man boats) were able to adjust their power output based on feedback on power output. However, it was uncertain whether the same would hold for rowers in crew boats since their movements are confined by the movements of other crew members. The results obtained confirmed that crew rowers can improve their compliance with power output feedback substantially when they receive additional feedback on power output compared to only traditional feedback, such as feedback on boat velocity and the number of strokes $\min^{-1}$. This implies that feedback on power output can be used to control power output and thus training regimens aimed at improving physical capacities and rowing performance.

It can be appreciated from the power balance of rowing that average power output is not the sole determining factor of rowing performance. Performance also depends on power losses unrelated to average boat velocity. Although the power loss due to velocity fluctuations could already be determined with relative ease [33], it was uncertain whether feedback on this power loss enables rowers to reduce the loss. The results of a study involving audio-visual feedback on power losses resulting from velocity fluctuations (**Chapter 6**) suggested that, in general, this is not the case. Based on these results, it was concluded that this type of feedback is not useful to reduce power loss due to velocity fluctuations and thus improve rowing performance.

A larger portion (i.e. > 20 %; [2, 34, 36, 51]) of a rower's average power output is lost due to the generation of propulsion. Since this power loss could not be determined accurately at the start of this thesis, an alternative method has been developed to estimate this type of power loss more accurately (**Chapter 7**). The method in question consists of three pairs of strain gauges allowing for an accurate determination of local bending moments. A system of three associated moment equations allows for the determination of the water force component perpendicular to the blade and its point of application. The smaller but relevant parallel force component should in the future be determined with a different method. Additional research is required to examine whether rowers are able to reduce the power loss associated with the generation of propulsion when provided with feedback about this power loss.

In conclusion, this thesis aimed to develop and evaluate tools that contribute to the understanding and improvement of rowing performance. A mechanical analysis indicated that mechanical power output and power losses are important determinants of rowing performance. It was demonstrated that both variables can be determined rather accurately. Feedback on power loss due to velocity fluctuations however seemed to be ineffective, but rowers clearly benefited from feedback on average power output to control their power output. The most important implication of these findings for rowing practice is that the implementation of accurate online feedback about a rower's power output during training will help to control training intensity. In the long run, a better control of training intensity will likely help rowers to improve their physical capacities and rowing performance.

Dutch Summary (Samenvatting)

Net als bij andere cyclische sporten zoals schaatsen, zwemmen en wielrennen, is het doel van roeien om als snelste van start naar finish te komen. Daarom kan een roeiprestatie worden gedefinieerd als de gemiddelde snelheid van een boot over een bepaalde raceafstand. Deze gemiddelde snelheid wordt voornamelijk bepaald door een combinatie van de fysieke capaciteiten en de bewegingsuitvoering van de roeiers[2]. Om roeiprestaties te verbeteren zijn coaches en roeiers voortdurend op zoek naar nieuwe manieren om deze capaciteiten te optimaliseren. Het doel van deze dissertatie was om een bijdrage te leveren aan deze zoektocht. De focus lag daarbij op het ontwikkelen en evalueren van methoden en technieken die bijdragen aan enerzijds het *inzichtelijk maken* van de roeiprestatie en anderzijds *het verbeteren* van de prestatie.

Om roeiprestaties beter inzichtelijk te maken is er gebruik gemaakt van de 'vermogensbalans voor roeien' [34, 89]. Dit biomechanisch model geeft inzicht in de relaties tussen de fysieke capaciteiten van roeiers, hun bewegingsuitvoering en de roeiprestatie (de gemiddelde snelheid van de boot). Specifiek laat deze balans zien dat de roeiprestatie afhangt van (1) het geleverde vermogen van een roeier gemiddeld over een haalcyclus.[3] en (2) de vermogensverliezen die enerzijds ontstaan door snelheidsfluctuaties van de boot tijdens de haalcyclus en anderzijds door het in beweging zetten van water tijdens de afzet. Omdat het gemiddeld geleverde vermogen van een roeier sterk gerelateerd is aan de metabole energieconsumptie van de roeier [37], is mechanisch geleverd

[2]De technische capaciteiten omvatten zowel de bewegingsuitvoering van een roeier zelf als ook, in het geval van meermansboten, de bewegingsuitvoering tussen roeiers.

[3]Een haalcyclus bestaat uit een haal waarin de roeier met zijn/haar riem afzet tegen het water en een herstelfase waarin de roeier naar voren beweegt en het blad niet in het water heeft: zie ook introductie.

vermogen een objectieve maat voor de fysieke capaciteiten van de roeier. Daarmee is het ook een interessante variabele om de trainingsintensiteit van een roeier te controleren en — op lange termijn — de fysieke capaciteiten van een roeier te vergroten. De mate van vermogensverliezen tijdens een roeicyclus is onder andere afhankelijk van de bewegingsuitvoering van een roeier en is daarmee mogelijk een interessante feedbackvariabele om deze vermogensverliezen te verminderen.

Om daadwerkelijk het geleverde vermogen van een roeier te vergroten en de vermogensverliezen te verkleinen moet feedback over deze variabelen *effectief* zijn. Zoals in de inleiding aangegeven, kan feedback als *effectief* worden gekwalificeerd wanneer (1) de feedbackvariabele accuraat kan worden gemeten en (2) wanneer de variabele de atleet in staat stelt om aanpassingen aan de variabele te doen op basis van feedback over de variabele [69]. Om aan de eerste voorwaarde te voldoen, zijn er in deze dissertatie nieuwe methoden ontwikkeld en geëvalueerd die het mogelijk maken om de specifieke vermogensvariabelen (gemiddeld geleverd vermogen van een roeier over een haalcyclus en vermogensverliezen) accuraat te kwantificeren (**Hoofdstuk 2-4,7**). Vervolgens, en in lijn met de tweede voorwaarde, is onderzocht of roeiers in staat zijn om de vermogensvariabelen aan te passen op basis van directe feedback over de vermogensvariabelen (**Hoofdstuk 5-6**). De directe feedback is gegenereerd door een zelf ontwikkeld feedbacksysteem (**Appendix**).

Met betrekking tot het geleverde mechanische vermogen van een roeier, is er eerst een methode ontwikkeld om dit vermogen accuraat te bepalen. Tot nog toe werd dit vermogen bepaald aan de hand van de krachten op een roeiriem en de beweging van de roeiriem (e.g. [2, 3, 5, 19, 26, 32, 51, 64–66, 71, 74]). Een veel gebruikte methode is het berekenen van het product van het moment rondom een riem en de bijhorende hoekversnelling (e.g. [2, 5, 19, 71]): de zogenoemde 'standaard' methode. In **Hoofdstuk 2** is, met behulp van de klassieke wetten van Newton, aangetoond dat deze standaard methode niet volledig is. Voor een valide bepaling van het vermogen is een aanvulling nodig die gelijk is aan het product van de massa van de roeier, de snelheid van de boot, en de versnelling van een roeier's lichaamszwaartepunt, gemiddeld over één complete haalcyclus; de zogeheten 'nieuwe methode'. De eerste twee variabelen zijn met behulp van één of twee sensoren accuraat te bepalen, maar voor de versnelling van het lichaamszwaartepunt van een roeier geldt dat niet. In een validatiestudie (**Hoofdstuk 3**) is geconcludeerd dat dit lichaamszwaartepunt wel heel nauwkeurig kan worden bepaald met behulp van 13 inertiële sensoren die elk de versnelling van een lichaamssegment van een roeier meten in combinatie met een model van Zatsiorsky waarin een verdeling van de massa van een persoon over zijn/haar lichaamssegmenten wordt bepaald [18, 99].

Vervolgens is in een experimenteel onderzoek aangetoond dat er een groot verschil is in de gemiddelde vermogenswaarden van een roeier bepaald met de standaard methode en de vermogenswaarden berekend met de nieuwe methode (**Hoofdstuk 4**). Concreet: de standaard methode onderschat het daadwerkelijk geleverde vermogen van een roeier met gemiddeld 12.3 %, waarbij er slechts marginale verschillen in onderschatting zijn tussen roeiers en verschillende roeicondities zoals het aantal slagen per minuut waarmee een roeier roeit. Deze resultaten impliceren dat de standaard methode moet worden gecorrigeerd zodat feedback over het gemiddeld vermogen van een roeier accuraat kan worden bepaald.

In **Hoofdstuk 5** is aangetoond dat, in lijn met de tweede voorwaarde, accurate directe feedback over het geleverde vermogen roeiers in meermansboten in staat stelt om veel beter te voldoen aan een — door de coach opgelegd — vermogen dan traditionele feedback zoals de snelheid van de boot en het slagtempo. Op basis van resultaten van eerdere leerstudies (e.g. [62, 63, 79, 97]) en het toenemende gebruik van vermogensmeters in het wielrennen, werd a priori al verwacht dat een roeier in een skiff (een eenmansboot) in staat is om zijn of haar geleverde vermogen aan te passen op basis van feedback over vermogen. Het was echter onduidelijk of dit ook gold voor roeiers in meermansboten omdat zij hun bewegingen moeten aanpassen aan de bewegingen van de andere roeiers in de boot. Nu is gebleken dat zelfs roeiers met beperkte bewegingsvrijheid baat hebben bij feedback over vermogen, kan worden geconcludeerd dat vermogensfeedback helpt om trainingsintensiteit te controleren.

De vermogensbalans laat echter zien dat niet alleen het gemiddeld geleverde vermogen een belangrijke variabele is om roeiprestatie te verklaren. De roeiprestatie hangt ook af van vermogensverliezen die niet zijn gerelateerd aan de gemiddelde snelheid van de boot. Het vermogensverlies door snelheidsfluctuaties van de boot kan relatief eenvoudig worden berekend [17, 33]. A priori aan dit onderzoek was het echter onzeker of feedback over dit vermogensverlies roeiers in staat stelt dit vermogensverlies ook te reduceren. Resultaten van een feedbackstudie (**Hoofdstuk 6**) waarin roeiers directe audio-visuele feedback kregen over het vermogensverlies door snelheidsfluctuaties van de boot suggereren dat deze vorm van feedback niet effectief is. Daarom is de voorlopige conclusie dat deze vorm van feedback niet kan worden gebruikt om vermogensverlies door snelheidsfluctuaties van de boot te verminderen en dus roeiprestaties te verbeteren.

Een groter deel van het gemiddeld vermogen van een roeier gaat echter verloren doordat de roeier water in beweging zet tijdens de afzet. Geschat wordt dat dit meer dan 20 % van het totaal door de roeier geleverde vermogen is [2, 34, 36, 51]. Deze schatting is echter niet nauwkeurig door een aantal irrealistische aannames. Zo wordt in eerdere modellen aangenomen (1) dat het water alleen kracht levert op het blad in loodrechte richting van het blad, (2) dat het aangrijpingspunt van de waterkracht gefixeerd is in het midden van het blad, en (3) dat de riem niet buigt tijdens het roeien. In **Hoofdstuk 7** van deze dissertatie is een nieuw model gepresenteerd dat niet afhangt van de laatste twee aannames. De methode bestaat uit drie paren rekstroken op de schacht van de riem die elk het lokale buigmoment van de riem meten. Met een stelsel van drie bijhorende momentsvergelijkingen kan de loodrechte krachtcomponent en het bijhorende aangrijpingspunt goed worden teruggeschat. De kleinere maar relevante parallele krachtcomponent kan met deze methode echter niet accuraat worden herleid. Daarvoor is een andere methode nodig. Ook zal toekomstig onderzoek moeten aantonen of roeiers in staat zijn om op basis van feedback over vermogensverlies rondom het blad dit vermogensverlies te reduceren en roeiprestatie te verbeteren.

Kortom, het doel van deze dissertatie was het ontwikkelen en evalueren van methoden en technieken die bijdragen aan enerzijds het beter inzichtelijk maken van de roeiprestatie en anderzijds het verbeteren van deze prestatie. Uit een mechanische analyse bleek dat het mechanisch geleverde vermogen van een roeier en de — niet aan de snelheid van de boot gerelateerde — vermogensverliezen belangrijke determinanten zijn voor de roeiprestatie. In deze thesis werd aangetoond dat alle variabelen accuraat kunnen worden bepaald. Daarnaast werd aangetoond dat feedback over vermogensverlies door snelheidsfluctuaties niet effectief is, maar dat roeiers *wel* veel baat hebben bij accurate feedback over hun geleverd vermogen. De meest belangrijke implicatie voor de roeipraktijk die volgt uit deze resultaten is dat accurate feedback over geleverd vermogen van een roeier roeiers veel beter helpt om hun trainingsintensiteit te controleren dan feedback over bootsnelheid en slagtempo. Betere controle van trainingsintensiteit helpt roeiers -op de lange termijn- naar alle waarschijnlijkheid beter hun fysieke capaciteiten te vergroten en hun roeiprestaties te verbeteren.

Bibliography

1. Achten, J. & Jeukendrup, A. E. Heart Rate Monitoring. *Sports Medicine* **33,** 517–538 (2003).
2. Affeld, K., Schichl, K. & Ziemann, A. Assessment of rowing efficiency. *Int J Sports Med* **14 Suppl 1,** 39–41 (1993).
3. Alexander, F. The Theory of rowing. *Proceedings of the University of Durham Philosophical Society,* 160–179 (1925).
4. Baudouin, A. & Hawkins, D. A biomechanical review of factors affecting rowing performance. *Br J Sports Med* **36,** 396–402 (2002).
5. Baudouin, A. & Hawkins, D. Investigation of biomechanical factors affecting rowing performance. *J Biomech* **37,** 969–976 (2004).
6. Bernard, T. *et al.* Distribution of power output during the cycling stage of a triathlon world cup. *Medicine and Science in Sports and Exercise* **41,** 1296–1302 (2009).
7. Borresen, J. & Lambert, M. I. The quantification of training load, the training response and the effect on performance. *Sports Med* **39,** 779–795 (2009).
8. Brearley, M. B., de Mestre, N. J. & Watson, D. R. Modelling the rowing stroke in racing shells. *Mathematical Gazette* **82,** 389–404 (1998).
9. Brink, M. S., Frencken, W. G. P., Jordet, G. & Lemmink, K. A.P. M. Coaches' and players' perceptions of training dose: Not a perfect match. *International Journal of Sports Physiology and Performance* **9,** 497–502 (2014).
10. Cabrera, D., Ruina, A. & Kleshnev, V. A simple 1+ dimensional model of rowing mimics observed forces and motions. *Hum Mov Sci* **25,** 192–220 (2006).

11. Caplan, N. & Gardner, T. Modeling the Influence of Crew Movement on Boat Velocity Fluctuations during the Rowing Stroke. *International Journal of Sports Science and Engineering* **1,** 165–176 (2007).

12. Celentano, F., Cortili, G., Di Prampero, P. E. & Cerretelli, P. Mechanical aspects of rowing. *J Appl Physiol* **36,** 642–647 (1974).

13. Cohen, E. E. A., Ejsmond-Frey, R., Knight, N. & Dunbar, R. I. M. Rowers' high: behavioural synchrony is correlated with elevated pain thresholds. *Biology Letters* **6,** 106–108 (2010).

14. Cohen, J. *Statistical power analysis for behavioral sciences* (Lawrence Erlbaum Associates Inc., Hillsdale, NJ, 1988).

15. Coutts, A. J. & Duffield, R. Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of science and medicine in sport* **13,** 133–5 (2010).

16. Cuijpers, L. S. *et al.* Rocking the boat: does perfect rowing crew synchronization reduce detrimental boat movements? *Scandinavian Journal Of Medicine & Science In Sports,* 1–8 (2016).

17. De Brouwer, A. J., de Poel, H. J. & Hofmijster, M. J. Don't Rock the Boat: How Antiphase Crew Coordination Affects Rowing. *PLoS ONE* **8,** 1–7 (2013).

18. De Leva, P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics* **29,** 1223–1230 (1996).

19. Doyle, M. M., Lyttle, A. & Elliott, B. Comparison of force-related performance indicators between heavyweight and lightweight rowers. *Sports biomechanics* **9,** 178–192 (2010).

20. Duffield, R., Reid, M., Baker, J. & Spratford, W. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *Journal of science and medicine in sport / Sports Medicine Australia* **13,** 523–5 (2010).

21. Euler, E. *A compleat theory of the construction and properties of vessels, with practical conclusions for the management of of ships, made easy to navigators. (H. Watson, trans.)* (London, UK, 1790).

22. Faber, G. S., Chang, C. C., Kingma, I., Dennerlein, J. T. & van Dieen, J. H. Estimating 3D L5/S1 moments and ground reaction forces during trunk bending using a full-body ambulatory inertial motion capture system. *Journal of Biomechanics* **49,** 904–912 (2016).

23. Faber, G. S., Chang, C. C., Rizun, P. & Dennerlein, J. T. A novel method for assessing the 3-D orientation accuracy of inertial/magnetic sensors. *Journal of Biomechanics* **46,** 2745–2751 (2013).

24. Fiskerstrand, A. & Seiler, K. S. Training and performance characteristics among Norwegian International Rowers 1970-2001. *Scandinavian Journal of Medicine and Science in Sports* **14,** 303–310 (2004).

25. Foster, C., Heimann, K. M., Esten, P. L., Brice, G. & Porcari, J. P. Differences in perceptions of training by coaches and athletes. *S Afri J Sports Med* **8,** 3–7 (2001).

26. Fukunaga, T., Matsuo, A., Yamamoto, K. & Asami, T. Mechanical efficiency in rowing. *European Journal of Applied Physiology and Occupational Physiology* **55,** 471–475 (1986).

27. Grift, E., Balaji, N., Tummers, M. & Westerweel, J. *Optimal drag in an accelerating rowing blade* in *71st annual meeting of the APS division of fluid dynamics* (the American Physical Society, 2018).

28. Guellich, A., Seiler, S. & Emrich, E. Training Methods and Intensity Distribution of Young World Class Rowers. *International Journal of Sport Physiology and Performance* **4,** 448–460 (2009).

29. Harfield, P., Halkon, B., Mitchell, S., Phillips, I. & May, A. A novel, real-time biomechanical feedback system for use in rowing. *Procedia Engineering* **72,** 126–131 (2014).

30. Hibbeler, R. *Mechanics of materials* 10th (Pearson, New York, 2017).

31. Hill, H & Fahrig, S. The impact of fluctuations in boat velocity during the rowing cycle on race time. *Scand J Med Sci Sports* **19,** 585–594 (2009).

32. Hill, H. Dynamics of coordination within elite rowing crews: evidence from force pattern analysis. *Journal of Sports Sciences* **20,** 101–117 (2002).

33. Hofmijster, M. J. *Mechanics and Energetics of Rowing* PhD thesis (Vrije Universiteit Amsterdam, Amsterdam, 2010).

34. Hofmijster, M. J., Landman, E. H., Smith, R. M. & van Soest, A. J. Effect of stroke rate on the distribution of net mechanical power in rowing. *J Sports Sci* **25,** 403–411 (2007).

35. Hofmijster, M. J., van Soest, A. J. & de Koning, J. J. Gross efficiency during rowing is not affected by stroke rate. *Med Sci Sports Exerc* **41,** 1088–1095 (2009).

36. Hofmijster, M. J., de Koning, J. J. & van Soest, A. J. Estimation of the energy loss at the blades in rowing: common assumptions revisited. *J Sports Sci* **28,** 1093–1102 (2010).

37. Hofmijster, M. J., van Soest, A. J. & De Koning, J. J. Rowing skill affects power loss on a modified rowing ergometer. *Medicine and Science in Sports and Exercise* **40,** 1101–1110 (2008).

38. Hofmijster, M. J., Lintmeijer, L. L., Beek, P. J. & Van Soest, A. J. Mechanical power output in rowing should not be determined from oar forces and oar motion alone. *Journal of Sports Sciences* **36** (2018).

39. Hopkins, W. G. & Stewart, A. M. Swimmers' compliance with training prescription. *The American College of Sports Medicine* **29,** 1389–1392 (1997).

40. Ishiko, T. Biomechanics of rowing. *Medicine and sport* **6,** 249–252 (1971).

41. Janssen, I. & Sachlikidis, A. Validity and reliability of intra-stroke kayak velocity and acceleration using a GPS-based accelerometer. *Sports biomechanics* **9,** 47–56 (2010).

42. Jeukendrup, A. & Diemen, A. V. Heart rate monitoring during training and competition in cyclists. *Journal of Sports Sciences* **16,** 91–99 (1998).

43. Jeukendrup, A. E., Craig, N. P. & Hawley, J. A. The bioenergetics of world class cycling. *Journal of Science and Medicine in Sport* **3,** 414–433 (2000).

44. Jurimae, J., Maestu, J., Purge, P. & Jurimae, T. Changes in stress and recovery after heavy training in rowers. *J Sci Med Sport* **7,** 335–339 (2004).

45. Kingma, I., Bosch, T., Bruins, L. & van Dieën, J. H. Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading. *Ergonomics* **47,** 1365–1385 (2004).

46. Kinoshita, T., Miyashita, M., Kobayashi, H. & Hino, T. in *Bio-mechanisms of Swimming and Flying* (eds Kato, N. & Kamimura, S.) 345–359 (Springer Japan, Tokyo, 2008).

47. Kirby, R. Development of a real-time performance measurement and feedback system for alpine skiers. *Leisure/ Loisir* **2,** 43–52 (2009).

48. Kleshnev, V. Estimation of Biomechanical Parameters and Propulsive Efficiency of Rowing. *Australian Institute of Sport* (1998).

49. Kleshnev, V. in *International research in sports biomechanics* (ed Hong, Y) 224–230 (Routledge, London, UK, 2002).

50. Kleshnev, V. Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. *Journal of sports engineering and technology* **233,** 10 (2010).

51. Kleshnev, V. Propulsive Efficiency of Rowing. *17th International Symposium on Biomechanics in Sports,* 3–6 (1999).

52. Kluger, A. & DeNisi, A. Kluger deNisi - feedback and performance. *Psychological Bulletin* **119,** 254–284 (1996).

53. Koo, T. K. & Li, M. Y. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine* **15,** 155–163 (2016).

54. Lamb, D. H. A kinematic comparison of ergometer and on-water rowing. *Am J Sports Med* **17,** 367–373 (1989).

55. Laschowski, B., Hopkins, C. C., de Bruyn, J. R. & Nolte, V. Modelling the deflection of rowing oar shafts. *Sports Biomechanics* **16,** 76–86 (2017).

56. Lintmeijer, L. L., Hofmijster, M. J., Schulte Fischedick, G. A., Zijlstra, P. J. & Van Soest, A. J. Improved determination of mechanical power output in rowing: Experimental results. *Journal of Sports Sciences* **36,** 2138–2146 (2018).

57. Lintmeijer, L. L. *et al.* An accurate estimation of the horizontal acceleration of a rower' s centre of mass using inertial sensors : a validation. *European Journal of Sport Science* **18,** 1–7 (2018).

58. Locke, E., Shaw, K., Saari, L. & Latham, G. Goal Setting and task performance: 1969-1980. *Psychological bulletin* **90,** 125–152 (1981).

59. Loschner, C. & Smith, R. *The relationship between seat movement and boat acceleration* in *17th International Symposium on Biomechanics in Sports* (1999), 89–92.

60. Mäestu, J., Jürimäe, J. & Jürimäe, T. Monitoring of performance and training in rowing. *Sports Medicine* **35,** 597–617 (2005).

61. Meeusen, R. *et al.* Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science* **13,** 1–24 (2012).

62. Newell, K. M. Motor Skill Acquisition. *Annual Review of Psychology* **42,** 213–237 (1991).

63. Newell, K. M. & Walter, C. B. Kinematic and kinetic parameters as information feedback in motor skill acquisition. *Journal of Motor Behavior,* 235–254 (1981).

64. Nolte, V. *Die Effektivität des Ruderschlages* (Bartels & Wernitz, Berlin, 1984).

65. Nolte, V. Shorter oars are more effective. *Journal of Applied Biomechanics* **25,** 1–8 (2009).

66. Nozaki, D., Kawakami, Y., Fukunaga, T. & Mechanical, M. M. Mechanical efficiency of rowing a single scull. **251,** 251–253 (1993).

67. Pauw, K. D. *et al.* Guidelines to classify subject groups in sport- science research. *International Journal of Sports Physiology and Performance* **8,** 111–122 (2013).

68. Perez, P. Effects of three feedback conditions on aerobic swimming. *Journal of sports sciences and medicine* **8,** 6 (2009).

69. Phillips, E., Farrow, D., Ball, K. & Helmer, R. Harnessing and understanding feedback technology in applied settings. *Sports Medicine* **43,** 919–925 (2013).

70. Portney, L. G. & Watkins, M. P. *Foundations of clinical research: Applications to practice.* (Prentice Hall, Upper Saddle River, NJ, 2000).

71. Renfree, A., Martin, L., Richards, A. & St Clair Gibson, A. All for one and one for all! Disparity between overall crew's and individual rower's pacing strategies during rowing. *International journal of sports physiology and performance* **7,** 298–300 (2012).

72. Roetenberg, D., Luinge, H. & Slycke, P. *Xsens MVN : Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors* tech. rep. (Xsens Technology B.V., 2013).

73. Salmon, A. W., Schmidt, R. A. & Walter, C. B. Knowledge of Results and Motor Learning: A Review and Critical Reappraisal. *Psychological bulletin* **95,** 355–386 (1984).

74. Sanderson, B. & Martindale, W. Towards optimizing rowing technique. *Med Sci Sports Exerc* **18,** 454–468 (1986).

75. Schaffert, N., Gehret, R. & Mattes, K. Modeling the Rowing Stroke Cycle Acoustically. *Journal of the Audio Engineering Society* **60,** 551–560 (2012).

76. Schmidt, R. A. & Wrisberg, C. A. *Motor control and performance: a behavioral emphasis.* 2nd (Human Kinetics, Champaign, IL, 2000).

77. Seiler, S. What is Best Practice for Training Intensity and Duration Distribution in Endurance Athletes? *BRIEF REVIEW International Journal of Sports Physiology and Performance* **5,** 276–291 (2010).

78. Selya, A. S., Rose, J. S., Dierker, L. C., Hedeker, D. & Mermelstein, R. J. A practical guide to calculating Cohen's f 2, a measure of local effect size, from PROC MIXED. *Frontiers in Psychology* **3,** 1–6 (2012).

79. Sigrist, R., Rauter, G., Riener, R. & Wolf, P. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin and Review* **20,** 21–53 (2013).

80. Smith, R. M. & Loschner, C. Biomechanics feedback for rowing. *Journal of Sports Sciences* **20,** 9 (2002).

81. Smith, T. B. & Hopkins, W. G. Measures of Rowing Performance. *Sports Medicine* **42,** 16 (2012).

82. Smith, T. B. *Monitoring Performance of Elite Rowers* PhD thesis (Auckland University of Technology, 2011).

83. Soligard, T. *et al.* How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of illness. *British Journal of Sports Medicine* **50,** 1030–1041 (2016).

84. Steinacker, J. M. & Secher, N. H. Advances in physiology and biomechanics of rowing. *Int J Sports Med* **14 Suppl 1,** 1–2 (1993).

85. Sullivan, P. & Rickers, K. The effect of behavioral synchrony in groups of teammates and strangers. *International Journal of Sport and Exercise Psychology* **11,** 286–291 (2013).

86. Tran, J., Rice, A. J., Main, L. C. & Gastin, P. B. Convergent validity of a novel method for quantifying rowing training loads. *Journal of sports sciences* **33,** 1–9 (2014).

87. Vallacher, R. R. & Wegner, D. M. Action Identification and Human Behavior. *Psychological Review* **94,** 3–15 (1987).

88. Van Beijsterveldt, A.-M., de Jong, M., Lemmink, K. & Stubbe, J. Training load and health problems in freshman rowers. *BMC Sports Science, Medicine and Rehabilitation* **7,** O1 (2015).

89. Van Ingen Schenau, G. J. & Cavanagh, P. R. Power equations in endurance sports. *J Biomech* **23,** 865–881 (1990).

90. Vogler, A. J., Rice, A. J. & Gore, C. J. Physiological responses to ergometer and on-water incremental rowing tests. *International Journal of Sports Physiology and Performance* **5,** 342–358 (2010).

91. Von Zitzewitz, J. *et al.* Real-time rowing simulator with multimodal feedback. *Sports Technology* **1,** 257–266 (2008).

92. Wald, F. & Mellenbergh, G. De verkorte versie van de Nederlandse vertaling van de Profile of Mood States (POMS) [The shortened version of the Dutch translation of the Profile of Mood States (POMS)]. *Nederlands Tijdschrift voor de Psychologie en haar Grensgebieden* **45,** 86–90 (1990).

93. Warmenhoven, J. *et al.* Force coordination strategies in on-water single sculling: Are asymmetries related to better rowing performance? *Scandinavian Journal of Medicine and Science in Sports* **28,** 1379–1388 (2018).

94. Wulf, G & Shea, C. H. Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review* **9,** 27 (2002).

95. Wulf, G & Shea, C. H. in *Skill acquisition in sport: research, theory and practice.* 2nd, 121–144 (Routledge, London, UK, 2005).

96. Wulf, G. & Lewthwaite, R. Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin and Review* **23,** 1382–1414 (2016).

97. Wulf, G., McConnel, N., Gärtner, M. & Schwarz, A. Enhancing the learning of sport skills through external-focus feedback. *Journal of Motor Behavior* **34,** 171–182 (2002).

98. Zatsiorsky, V. M. & Yakunin, N. Mechanics and Biomechanics of Rowing : A Review. *International Journal of Sport Biomechanics* **7,** 229–281 (1991).

99. Zatsiorsky, V. *Kinetics of human motion* (Human Kinetics, Champaign, IL, 2002).

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List of publications

Journal articles

Articles in peer reviewed journals

Lintmeijer, L.L., Onneweer, J.P.T., Hofmijster, M.J., Wijgergangs, W.A., de Koning, H., Clairbois, B., Westerweel, J., Grift, E.J., Tummers, M.J., van Soest, A.J. Towards determination of power loss at a rowing blade: validation of a new method to estimate blade force characteristics. *PLOS One* **14(5)**: e0215674. DOI.org/10.1371/journal.pone.0215674 (2019).

Lintmeijer, L.L., Soest, A.J.,Robbers, F.S, Hofmijster, M.J., Beek, P.J. Real-Time Feedback on Mechanical Power Output Facilitates Crew Rowers to Comply With Prescribed Training Intensity . *International Journal of Sports Physiology and Performance* **14:3**, 303:309.
Doi: 10.1123/ijspp.2018-0128 (2019).

Lintmeijer, L.L., Faber, G.S., Kruk, H.R., van Soest, A.J., Hofmijster, M.J. An accurate estimation of the horizontal acceleration of a rower's centre of mass using inertial sensors: a validation. European Journal of Sport Science, **18:7**, 940-946. DOI: 10.1080/17461391.2018.1465126 (2018).

Lintmeijer, L.L., Hofmijster, M. J., Schulte Fischedick, G. A., Zijlstra, P. J., & van Soest, A. J. An improved determination of mechanical power output in rowing: experimental results. Journal of Sports Science, **36**, 2138-2146. DOI:10.1080/02640414.2017.1367821 (2018).

Hofmijster, A.J., **Lintmeijer, L.L.**, Beek, P.J., van Soest, A.J. Mechanical power output should not be determined from oar forces and oar motion alone. Journal of Sports Science, **36**, 2147-2153.
DOI:10.1080/02640414.2018.1439346 (2018)

Houtveen, J.H., van Broeckhuysen-Kloth, S., **Lintmeijer, L.L.**, Geenen, R. Intensive multidisciplinairy treatment of severe somatoform disorder: a prospective evaluation. Journal of Nervous & Mental Diseases, **203(2)**, 141-148. Doi: 10.1097/NMD.0000000000000250 (2015).

Houtveen, H.H., **Lintmeijer, L.L.**, van Broeckhuysen, S. The clinical effectiveness of a long-term multidisciplinary integrative psychological treatment with a focus on body-related mentalisation of patients with somatoform disorder. Journal of Psychosomatic Research, **74(6)**, 547. DOI 10.1016/j.jpsychores.2013.03.042 (2013).

Articles in non-peer reviewed journals

Lintmeijer, L.L., Houweling, J., Grift, E.J., Beek, P.J. (2016). Optimaal door het water:op zoek naar de ideale techniek voor roeien en zwemmen. Sportgericht,**3**, 12-17.

International conference proceedings

Lintmeijer, L.L. Determination and use of power output in rowing practice. Rowers conference, *(invited] speaker)*,Dorney Lake, London, UK (2019).

Lintmeijer, L.L., Beek, P.J., Hofmijster, M.J., Huiberts, S. Row your beat: the development of an innovative auditory feedback platform for rowing performance. 23rd Congress of the European College of Sports Sciences, *oral presentation*,Dublin, Ireland (2018).

Lintmeijer L.L., Hofmijster, M.J., Robbers, F.S., Soest, A.J. "Knoek", Beek, P.J. Feedback on power output improved compliance to intended on-water training intensity. The 16th Congress of the International Society of Biomechanics, *oral presentation*, Brisbane, Australia (2017).

Lintmeijer L.L., Hofmijster, M.J., Robbers, F.S., Soest, A.J. "Knoek", Beek, P.J. Feedback on power output improved compliance to intended on-water training intensity. International Society of Biomechanics in Sports conference, *oral presentation*, Cologne, Germany (2017).

Lintmeijer, L.L. Mechanical power output in periodic motions. Dynamic Walking Conference, *(invited) oral presentation*, Marieland, Finland (2017).

Lintmeijer, L.L., Hofmijster, M.J., Beek, P.J., Schulte Fischedick, G.A., Zijlstra, P.J., Soest, A.J. Rower's on-water power output is commonly underestimated. 21nd Congress of the European College of Sports Sciences, *oral presentation*, Vienna, Austria (2016).

Lintmeijer, L.L., Hofmijster, M.J., van Soest, A.J., Beek, P.J. The effect of real-time feedback on velocity fluctuations in steady-state rowing. BMC Sports Science, Medicine and Rehabilitation, 7(suppl 1):O5, *oral presentation*.

Lintmeijer, L.L., Hofmijster, M.J., Soest, A.J. The effect of real-time feedback on velocity fluctuations in steady-state rowing. 19th Congress of the European College of Sports Sciences, *oral presentation by Scholtens*, Amsterdam, Netherlands (2014).

Scholtens, E.J., **Lintmeijer, L.L.**, Soest, A.J., Hofmijster, M.J.Real-time visual feedback about oar force and position helps to adapt rowing technique. 19th Congress of the European College of Sports Sciences, *oral presentation by Scholtens*, Amsterdam, Netherlands (2014).

Klerks, I.C., **Lintmeijer, L.L.**, Paradies, G.L. Verhoeven, L.A., van den Bos, K. (2009). Jaarboek Sociale Psychologie 2008. Groningen: ASPO congres, *oral presentation*.

Lotte Lintmeijer was born on September 21, 1986 in Utrecht, The Netherlands. In 2005 she started her bachelor “Psychology” in Utrecht. During her bachelor she followed an honours track in Social Psychology. With her broad interest in international social issues, psychology and research, she decided to follow a minor in “International Development Studies” ,including a second bachelor thesis on the communication between children and parents in rural Southern India. Her interest for methods and statistics let her decide to do a research master on “Social and Health Psychology”.

During her studies she was a “full-time” stear and coach at a student rowing club. This is where her interest in the relation between human’s physical and mental performance has arisen. She did her master thesis on the effects of sports on anxiety and depression under the supervision of dr. Jan Houtveen. As a side job, she analysed the clininal effectiveness of long-term treatment on the quality of life of patients with severe somatoform disorder at Altrecht, Utrecht. After her master, she worked on research on unexplained physical complaints at the University of Birmingham, England

In November 2013, Lotte started her PhD project on optimisation of propulsion in rowing and swimming, of which the rowing part is described in this thesis. The project was a collaboration of the the TU Delft, TU Eindhoven, Vrije Universiteit Amsterdam, and the Dutch rowing and swimming federation (KNRB and KNZB, respectively). It was funded by the Netherlands Organization of Scientific Research (NWO). During the project Lotte collaborated with several commercial parties and (applied) Universities. The project gave her the opportunity to improve her mathematical skills, while learning more about biomechanics and programming. She currently works as a data scientist and analyst, with a focus on sports and health.

Amsterdam Movement Sciences

Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.