Synchronization in Rowing

Thesis on the effect of crew synchronization on rowing performance

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday April 5, 2018 at 11:00 AM.

Student number:	4078314	
Project duration:	March 24, 2017 – April 5, 2018	
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Abstract

Introduction On all levels of rowing, from the first experience to top level athletes, a general rule is that you have to row together. Rowing together has no clear-cut definition. However, it is known that each rower has his or her own style, which can be registered in movement patterns and force curves. The big question is how to combine these individual styles such that the crew works together in the best way. The Dutch Rowing Federation showed interest in this topic, wanting to know how to adjust the rigging dimensions of the boat to allow the best racing performance. The goal of this thesis is to provide advice on what features of the rowing stroke should be synchronized and whether and how this could be promoted by individualized rigging.

Background The theoretical foundation for this study was a literature study about the current knowledge on the rowing stroke and differences within and between individuals and crews. Questions were asked and answered. The force curve of an individual can be characterized by discrete points based on a force threshold or percentage, by area and by area-derived variables. Variability was discussed for different boat types, ergometers and conditions. A difference was found in the way crew members need to row together in most boats versus the pair. Current used measures on performance and synchronization of rowers were described, and finally a proposal was done for which methods to use in the ongoing of the study.

Method Data was obtained from five female athletes of elite level, doing trials in a quadruple sculls of approximately 30 seconds at 30 SPM and 32 SPM in four different combinations. The strokes were identified and analyzed, based on performance and synchronization measures. Performance was divided into Average Speed and Work per Stroke as primary measures, and Blade Losses, Velocity Fluctuation Losses and their respective and combined efficiencies as secondary performance measures. Synchronization measures were chosen for three fields: kinematics, kinetics and energetics. The picked methods were Mean Standard Deviation of the Phase, Standard Deviation of the Time to Half Impulse and Standard Deviation of the Time to Half Work.

Results The chosen synchronization measures were not completely independent. Low but significant negative correlations were found between Mean Standard Deviation of the Phase and the other two measures ($r = -0.247$ with kinetic synchronization and $r = -0.161$ with energetic synchronization). Standard deviations of time to half impulse and half work were found to be highly similar ($r = 0.970$). An opposite effect was found between kinematic synchronization and the other two. Lower differences in oar phase correlated with lower Average Speed ($r = 0.387$), lower Work per Stroke ($r = 0.363$) and lower blade ($r = 0.206$) and Net Efficiency ($r = 0.202$). This was not in line with the empirical rule that better synchronization leads to better performance. The kinetic and energetic measures did show this effect: Lower standard deviations of time to half impulse and time to half work meant higher average speed ($r = -0.193$) and higher Work per Stroke ($r = -0.574$).

Within performance measures comparison showed that Blade Losses decreased with Average Speed ($r = -0.547$), improving blade and Net Efficiency ($r = 0.648$ and $r = 0.631$ respectively). A higher speed is also related to more Work per Stroke, but less clear ($r = 0.265$). Blade Losses increased ($r = 0.395$), and Blade Efficiency decreased ($r = -0.179$) with Work per Stroke, while Velocity Efficiency increased ($r = 0.167$). The secondary performance measures were closely linked due to their definitions. Interesting was that the two different losses ($r = 0.375$) and efficiencies ($r = 0.386$) were connected too.

Discussion The found ranges and averages of the performance measures were realistic, as they were comparable to literature or otherwise explainable. Time analysis showed that all synchronization measures achieved their goals. Most important implication of the results is that oar phase synchrony should not be pursued, but time to half impulse synchrony instead. A drawback on this measure was

that linear interpolation had to be used to find it (similar for time to half work). The sampling frequency was too low when compared to the ranges of kinetic and energetic synchronization.

Athletes were found to achieve their half impulse moments in a consistent order. Athlete B was found to be consistently early, making the most synchronous trials the ones without her. Athlete B was able to deliver the same range of Work per Stroke as the other rowers, so the results were not influenced by a possibly weaker crew member.

Improving Synchronization To find out whether it is possible to promote synchronization and thus performance by individualizing rigging, the oar angles at the time to half impulse were analyzed. This enabled translation of the time based synchronization into a measure of kinetic similarity. This new measure correlated moderately ($r = 0.624$), meaning it quantifies more or less the same effect. That still more than half of the variance was not explained by the other of the two, was not necessarily a negative thing. The kinetic similarity measure was able to explain performance better ($r = -0.292$ with Average Speed and $r = -0.748$ with Work per Stroke) than the synchronization measure. Also, relatively high consistency was observed.

Conclusion The results in this study have shown how the empirical rule that synchrony leads to better performance can be specified: Simultaneously timed delivery of half impulse improves work generation and boat speed. Similarity of half impulse angles is an even better predictor of performance, and it enables the coach to adjust the rigging such that the timing should improve too. However, this should be tested in a follow-up study.

Preface

Dear reader,

Before you lies the result of my graduation project on synchronization of athletes in rowing. This thesis presents an extensive data analysis to find out the details of 'rowing together', which crews of all levels are told by their coaches, and to give practical advise on how to improve on this. I've written this thesis in fulfillment of the graduation requirements of my study Mechanical Engineering at Delft University of Technology, following the BioMechanical Design track and the Sports Engineering specialization. The project was started up at the end of March 2017 and I engaged in researching and writing this dissertation until March 2018.

The project was executed in collaboration with the Dutch Rowing Federation (KNRB), where I did my internship, and the Vrije Universiteit Amsterdam (VU). Having a great interest in rowing and the physics behind it, I started out looking for possibilities in rowing simulators. I then found out my fellow graduate student Janneke Voordouw did an internship on this subject, and also wanted to continue with it. During the shaping of the project, simulation became modelling, and modelling became data analysis.

The goal was to help Eelco Meenhorst, coach of the men quadruple sculls (M4x), by advising on the rigging dimensions of the boat. During the meetings with him and prof. Mathijs Hofmijster (who coordinates the rowing research taking place at the KNRB) the word synchronization was commonly used. It was discussed that it's not yet evident in what way rowers should 'row together', because even top level athletes are still different from each other, and how the rigging dimensions should be adjusted for this.

The investigation of this mechanism was a long road into the unknown. Little research had been done on this phenomenon specifically, so the process of specifying measures of synchronization was extensive. With this research I deem to have made a fundamental step in uncovering the mechanisms behind 'rowing together'. My supervisor, Arend Schwab, was always there to push me in the right direction and elucidate the connection between the mathematical description and the real world. He also helped me in the integration of this report by pointing out the missing 'pieces of the puzzle'.

I would like to thank Arend for his guidance and support during the process. I would also like to thank Eelco for the fine cooperation and his efforts to supply me with data, and Mathijs for making this collaboration possible and his readiness to take a critical look at my findings. I would like to thank Daan Bregman for the diplomacy in setting up the collaboration between the universities.

To Janneke, you were an extremely valuable colleague. I enjoyed our cooperation, the fluid shaping of the process, determining who tackles which problem, and your unstoppable interest and discipline. Next, I would like to thank the other colleagues in the bicycle lab and my friends at D.S.R. Proteus Eretes for all the great opportunities to spar with them about my research. And finally to my parents, thank you for the unconditional support and trust. Because of it I was able to work steadily on towards a perfected and complete report.

J.H. Doeksen
Delft, March 2018

Contents

Glossary

Average Speed Average speed of the boat during a stroke, represented by $\dot{x}$. This is a measure of crew performance. iii, iv, xv, xvi, 27, 28, 31, 39, 43, 45, 43, 46, 48, 55, 57, 58, 59, 61, 63, 66, 69

Blade Efficiency The ratio of energy not lost at the blades and the energy generated at the handles, also noted as η_{blade} iii, 27, 32, 39, 43, 48, 50, 52, 57, 59

Blade Losses Energy lost at all blades that are considered, by the perpendicular blade force. The axial forces and losses are not considered as they could not be derived in the used setup. Represented by W_{blades}. iii, xv, 27, 28, 30, 31, 37, 39, 48, 50, 51, 52, 53, 59, 69

catch The instant during a rowing stroke that the blade enters the water. xv, 5, 6, 7, 8, 9, 14, 15, 25, 37, 45, 46, 52, 55, 61, 73

double Boat type with two athletes handling two oars each (sculling). 11, 52

drive The part of the rowing stroke when the blade is submerged and the rower pulls the oar. xv, 5, 7, 8, 9, 11, 14, 15, 25, 29, 30, 31, 35, 45, 46, 53, 55

finish The instant during a rowing stroke that the blade exits the water. xv, 1, 5, 6, 7, 8, 9, 14, 15, 22, 25, 31, 52

interstroke interval Refer to recovery time. This is ambiguous because stroke refers only to the drive in this case. 8

KNRB Abbreviation of Koninklijke Nederlandsche Roeibond, which is the Dutch rowing federation. v, 2, 19, 69

Mean Standard Deviation of the Phase Mean Standard Deviation of the Phase, a number representing how much a crew moves their handles in sync during the entire stroke. Also referred to as kinematic synchronization, and presented by symbol $\bar{\sigma}_{phase}$. iii, 33, 41, 43, 52, 57, 73

Net Efficiency The ratio of energy not lost at the blades or as additional drag due to velocity fluctuations, and energy generated at the handles. Also noted as η_{net}. iii, 13, 17, 27, 32, 39, 43, 48, 50, 59, 63, 66

pace Pace is the number of strokes that could be made in one minute, if all those strokes were like the stroke of interest. 39, 52, 54, 59, 70

pair Boat type with two athletes handling one oar each (sweep rowing). iii, 2, 6, 9, 11, 13

recover The part of the rowing stroke after the finish and before the next catch, when the rower prepares for the next stroke. xv, 8, 9, 14, 15, 20, 29, 30, 37, 43, 52, 53, 54, 55, 70

sculling Sculling is rowing with two oars per person. 2, 20, 25

segment Angle between the catch and the finish of a stroke. 7, 8, 33, 52, 59, 63, 68, 70

Standard Deviation of the Half Impulse Angle Standard Deviation of the Half Impulse Angle represents in what amount the angles are similar when the rowers have applied half of their impulse to the boat. Also referred to as kinetic similarity, and presented by symbol $\sigma_{\bar{\Phi}_{J50,rower}}$. xvi, xvii, 61, 63, 66, 73

Standard Deviation of the Time to Half Work Standard Deviation of the Time to Half Work, representing in what amount the time instances when the rowers have generated half of their work at the oar happen simultaneously. Also referred to as energetic synchronization, and presented by symbol $\sigma_{T_{W50}}$. iii, xv, 35, 41, 43, 45, 43, 46, 57, 63, 73

Standard Deviation of the Time to Half Impulse Standard Deviation of the Time to Half Impulse, representing in what amount the time instances when the rowers have applied half of their impulse to the boat happen simultaneously. Also referred to as kinetic synchronization, and presented by symbol $\sigma_{T_{J50}}$. iii, 34, 41, 43, 52, 57, 58, 66, 69, 70, 73

stroke 1: A stroke is a full cycle of the rowing motion, usually defined to start at the catch. It consists of the drive and the recover. 2: The stroke may also refer to the rower at the most backward seat of the boat, assigning the pace of the crew. iii, vii, xv, xvi, xvii, 1, 2, 5, 6, 7, 9, 10, 11, 14, 15, 17, 19, 20, 21, 22, 25, 27, 28, 29, 31, 37, 38, 39, 41, 43, 45, 43, 45, 43, 46, 48, 51, 52, 53, 57, 58, 63, 69, 70

stroke length Usually defined as the distance the boat travels during one full stroke, not to be confused with drive length. 8, 10

stroke duration The duration of a full stroke. 60 seconds divided by this duration makes the pace. 8, 14

stroke rate Refer to pace. 5, 7, 8, 9, 10, 16, 55

sweep rowing In sweep rowing, the athlete has one large oar that is pulled with the outer hand and handled with the inner hand. 2, 9

Velocity Efficiency The ratio of energy not lost as additional drag due to the non-constant velocity and the energy generated at the oars. Also noted as $\eta_{velocity}$. iii, 13, 17, 27, 32, 39, 48, 50, 51, 59

Velocity Fluctuation Losses Additional energy lost to drag because the boat does not have a constant velocity, and drag force scales quadratic with velocity. Represented by $W_{velocity}$. iii, 27, 31, 37, 39, 43, 48, 50, 51, 59, 69

W4X Women quadruple sculls, four women with two oars each rowing together in the open weight class. 19, 52

Work per Stroke Work that is generated by the rower rotating the oar around the gate, also represented by W_{stroke}. This is used to quantify performance of either one athlete or, when the work of all crew members together is considered, for the crew. iii, iv, xv, xvi, 10, 13, 27, 28, 37, 39, 43, 48, 55, 56, 57, 58, 59, 61, 63, 66, 69, 70

Symbols

E_{RMSE} Root mean square energy error over a set of recorded strokes. [J] 37, 39

E_{error} Mismatch between the amount of work generated during one stroke, and the sum of energy lost and change of kinetic energy. [J] 37

F_x Force acting on the gate, directed along the centre line of the boat. [N] 25

F_y Force acting on the gate, directed perpendicular to the centre line of the boat. [N] 25

F_{blades} Sum of the forces on the port and starboard blades. [N] 73

F_{blade} Force of the water acting on the blade. [N] 28, 29, 31, 34

F_{handle} Force acting perpendicular to the oar applied by the rower. [N] 28, 29, 30, 31, 73

F_{pin} Force acting perpendicular to the oar at the gate. [N] 25, 28, 29, 31, 73

I_{gate} Inertia of the oar around the gate. [Nm^2] 20, 21, 28, 29

J_{rower} Impulse generated by a rower during the drive. [Ns] 34, 35

$L_{inboard}$ Length of the inboard of the oar, from the gate to the tip of the handle. [m] 21

L_{oar} Length of the oar. [m] 21

M_{handle} Moment applied around the gate by the handle force. [Nm] 30

P_{handle} Power generated by the rower to move the handle around the gate. [W] 30, 35

$R_{F,blade}$ Distance of the tip from the blade to the point where the bladeforce is applied. [m] 19, 21

$R_{F,handle}$ Distance from the tip of the handle to the point of force application by the hand. [m] 19, 21

$R_{inboard}$ Distance from the gate to the center of force application by the hands $(L_{inboard} - R_{F,handle})$. [m] 28, 29, 30

$R_{outboard}$ Distance from the gate to the center of the blade force $(L_{oar} - L_{inboard} - R_{F,blade})$. [m] 28, 29, 31

T T-value of a student’s t-distribution. [-] 38

$T_{J50,rower}$ Time instant where the impulse, applied during the period from the catch to that instant, is half of the total impulse applied during the drive. [s] 35, 61

$T_{W50,rower}$ Time instant where the work, generated during the period from the catch to that instant, is half of the total work generated during the drive. [s] 35

T_{stroke} Duration of one stroke. [s] 31

W_{blades} Sum of energy lost at all the blades. [J] ix, 31, 32, 37, 43, 48, 63

W_{blade} Energy loss at the blade because of it slipping through the water. [J] 31

W_{drag} Energy lost by drag on the boat. Only viscous drag is assumed. [J] 31, 32, 37

W_{rower} Work generated by a rower during the drive. [J] 35

W_{stroke} Work done by the rower to move the handle during the entire stroke, where there negative work is possible [W] x, 30, 32, 37, 43, 48, 63

$W_{velocity}$ Additional energy lost on drag because of the non constant speed. [J] x, 31, 32, 43, 48, 63

$\Delta E_{kin,system}$ Change in total kinetic energy of the system compared to the stroke before. [J] 32, 37

Φ_{rower} Phase of the rower average oar motion. [°] 34

$\bar{\phi}_{J50,rower}$ Mean oar angle of one rower at the time when half of the impulse of the stroke was delivered. [deg] 61

$\bar{\phi}_{rower}$ Averaged port and starboard oar angle of the rower at a certain time instant. [deg] 33, 61

$\bar{\sigma}_{phase}$ Mean of the standard deviation of the rower phases during the stroke. [°] ix, 34, 41, 43

$\bar{f}_{rower}$ Average slope of the summed blade force signal between 30% and 70% of the maximum. [N/s] 73

$\ddot{\phi}$ Angular acceleration of the oar. [rad/s^2] 28, 29

$\ddot{x}'_{m,oar}$ Linear acceleration of the center of mass of the oar, in which the x'-axis is perpedicular to the oar and the positive direction is to the bow of the boat, when the oar is at 0°. The value is assumed 0, since s is small, but the specific value is not known. [m/s^2] 28, 29

$\dot{\bar{\phi}}_{rower}$ Averaged port and starboard oar angular speed of the rower at a certain time instant. [deg/s] 34

$\bar{\dot{x}}$ Average speed of the boat during one stroke. [m/s] ix, 28, 31, 32, 43, 48, 63

$\dot{\phi}$ Angular velocity of the oar, which is the derivative of the oar angle (ϕ). [°] 30, 31, 34

$\dot{x}'_{blade}$ Speed of the blade slipping through the water, inducing energy losses. [m/s] 30, 31

$\dot{x}$ Speed of the hull through the water. [m/s] 28, 31

η_{blade} Efficiency of the propulsion by the blades. [-] ix, 32, 43, 48, 63

η_{net} Net efficiency of the propulsion. [-] ix, 32, 43, 48, 63

$\eta_{velocity}$ Efficiency of the hull movement through the water, with respect to a constant speed. [-] x, 32, 43, 48, 63

$\dot{\hat{\phi}}$ Normalized oar angle speed. [-] 34

$\hat{\phi}$ Normalized oar angle. [-] 34

$\mu_{T_{J50}}$ Mean time to half impulse ($T_{J50,rower}$) of all athletes in the boat. [s] 35

$\mu_{T_{W50}}$ Mean time to half work ($T_{W50,rower}$) of all athletes in the boat. [s] 35

μ_{Φ} Mean phase of the rowers in the boat at a certain time. [°] 34

$\mu_{\bar{\phi}_{J50,rower}}$ Mean angle of half impulse ($\bar{\phi}_{J50,rower}$) of all athletes in the boat. [deg] 61

$\mu_{\bar{f}}$ Mean force slope ($\bar{f}_{rower}$) of all athletes in the boat. [N/s] 73

ϕ The oar angle, where value zero means the oar is perpendicular to the boat, and the positive direction is when the handle moves to the bow of the boat. [rad] 25, 31, 33, 34

$\sigma_{T_{J50}}$ Standard deviation of the time to half work ($T_{J50,rower}$) of all athletes in the boat. [s] x, 35, 41, 43

$\sigma_{T_{W50}}$ Standard deviation of the time to half work ($T_{W50,rower}$) of all athletes in the boat. [s] ix, 35, 41, 43

$\sigma_{\bar{\phi}_{J50,rower}}$ Standard deviation of the angles at the time to half work ($\bar{\phi}_{J50,rower}$) of all athletes in the boat. [deg] ix, 61, 63

σ_{phase} Standard deviation of the phase ($\bar{\Phi}$) of all athletes in the boat, at a certain moment in time. [°] 34

σ_{slope} Standard deviation of the force slopes ($\bar{f}_{rower}$) of all athletes in the boat. [N/s] 73

$f_{sampling}$ Sampling frequency of the peach input file. [Hz] 21

k Drag coefficient of the boat. [kg/m] 31, 39

m_{boat} Mass of the boat [kg] 21, 32

m_{oar} Mass of the oar [kg] 21, 28, 29, 32

m_{rower} Average mass of the rowers [kg] 21, 32

n Number of data pairs for calculating Pearson's r. Equal to number of strokes that were analyzed [-] 38

r Pearson's r, the correlation coefficient. [-] iii, iv, 37, 38, 39, 41, 43, 48, 50, 57, 63

$r_{E_{RMSE}}$ Percentual root mean square energy error. [%] 37, 39

s Distance between the centre of mass of the oar, and the gate. [N] 20, 21, 29

t Time variable. [s] 25, 29, 30, 31, 33, 34, 35, 73

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1

Introduction

Anyone that has tried rowing at least once has been told to follow the people in front of him or her, and to follow their motion. As a beginner, rowing feels clumsy, and once you do at least somewhat the same as the other crew members, things will quickly feel easier. The further one advances, the more one feels how to accelerate the boat together, or how to give it that ’swing’, or what other term a coach may use. Even in the highest level of rowing, the consideration is made when to do selections or seat racing, such that have enough time to prove themselves on one hand, but have time to get used to each other on the other. So, the statement that rowing in synchrony improves the performance is an empirical rule that is generally accepted throughout the rowing community [1, 2].

Another thing that coaches and spectators note about rowing, is ’how smooth the boat runs’. When one watches a video of any rowing race, it can be observed that the boat does not move with a constant velocity. The boat moves forth and back underneath the rower(s), the speed of the boat is the lowest around each time that the blade is put into the water and that the boat is pushed forward directly after. The difference between winning and losing can be determined by where during the stroke the rower is when crossing the finish line. This was the case during the men single sculls (M1x) finals at the Olympic Games in 2016, Rio de Janeiro. The photo finish showed a difference of a couple of centimeters between the bows, see fig. 1.1.

Suggestions have been done that these velocity fluctuations could be minimized by out-of-phase rowing [3, 4], and have been investigated by De Brouwer et. al. [5]. Although they suggest that antiphase (180° out of phase) rowing could indeed improve performance by decreasing the total drag losses, it is not yet accepted in general rowing. One of the drawbacks of antiphase rowing is e.g. the need for a longer boat, because the athletes will otherwise bump into each other. Therefore, antiphase is not (yet) a realistic option in elite rowing.

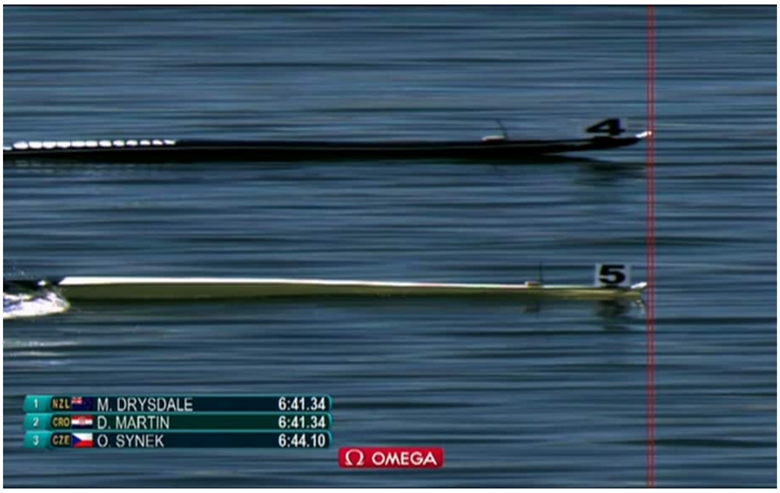

Figure 1.1: Photo finish between Mahe Drysdale and Damir Martin at the 2016 Olympics, Rio de Janeiro [6].

If antiphase rowing lies outside of the focus of the current national teams, then what about the differences between athletes rowing in-phase? This was the interest of Eelco Meenhorst, coach of the Dutch national men quadruple sculls (M4x). No two rowers are exactly the same. For example, force curves are specific to a rower because of his or her history in rowing, anthropometrics, physical capabilities, etc. So what is then the definition of synchrony in rowing? And another important question from Eelco Meenhorst was: ”If there are differences anyway, at what point during the stroke do I need to minimize these differences?”

The goal of this dissertation is to provide the Dutch Rowing Federation (KNRB) with practical advice about what features of the rowing stroke should be synchronized, and whether and how synchronization could be promoted by adjusting the rigging dimensions of the boat to the individual athletes.

The stated goal is twofold: On one hand more knowledge is needed on synchronization to specify the empirical rule into measurable quantities. On the other hand a link must be made to dimensions, which are by themselves not necessarily time related. Translating time based characteristics to dimensions enables the possibility to intervene in timing using static external means. Because of the two parts of this goal, two main research questions were formulated:

- What is the underlying mechanism of the empirical rule that synchronization improves performance?
- Can synchronization be improved by adjusting the rigging of the boat to the individual?

The first question can be subdivided into five more subquestions:

- What is the current state of research on the rowing stroke and its characteristics?
- What methods quantify rowing performance?
- What methods quantify crew synchronization?
- Which synchronization measure is the best performance predictor?
- Is the timing behind this measure consistent per individual, enabling it to select an athlete on his/her timing characteristic?

The second main research question is also divided into subquestions:

- Is synchronization over time translatable to similarity over angles?
- Are rowers consistent in this angle similarity? Enabling it to select or adjust rowers based on this dimension.

Thesis Outline

This thesis starts with a thorough investigation of literature, to learn what is already known on the rowing stroke, how to characterize it and what variations and interactions have been found between rowers, boat types, etc. Until now, most studies focus on sweep rowing oar rowing [1, 2, 7], which delivered the finding that at least in a pair an asymmetric fore pattern is requested. For sculling, which should be symmetric by definition, only one study has been made public [8]. Within the large amount of stroke characteristics, the methods used by Hill [7] acquired attention. He has explored the relation between synchrony and performance using a number of abstracted measures, parametrizing the force curve in its entirety.

All background information about this topic is presented in chapter 2, including a proposal for which methods to use to quantify performance and synchronization. This chapter answers the first three subquestions of the first main research question.

In chapter 3 the setup of the study is explained, so possible links between performance and synchronization measures can be explored. It is elucidated how data was obtained, which of the proposed methods from chapter 2 have been implemented and how they were implemented, and how the correlations between the characteristics are treated.

chapter 4 treats the results from the data analysis described in chapter 3. It presents the found correlations and whether the proposed measures achieve their effect. After this chapter, also the answer to the fourth subquestion of the first main research question is known.

After presenting the results from the data analysis, the outcome is discussed in chapter 5. Besides taking interest in consistency, which answers the final subquestion of the final research question, the implications and the reliability of the executed data analysis are treated.

In chapter 6 the link from synchronization to angular similarity is made, to investigate the second main research questions and its subquestions. This finalizes the investigation.

Finally, when all questions have been answered, an overview is presented of the obtained knowledge in chapter 7. The conclusion ends with a number of recommendations on how to improve the certainty of the results and how to continue researching this topic.

2

Background

Co-author: **J.T. Voordouw**

To find out more about the empirical rule that synchronization improves performance, the terms synchronization and performance must first be specified. This means that methods to quantify stroke characteristics must be found. This is the basis of any rowing related study, thus literature can provide answers on how to characterize the rowing stroke. Many studies focus on the force curve, so this will be the starting point of describing the current state-of-the-art in section 2.1.

It must be judged how consistent these force curves are for an athlete, in order for this study to have a high signal-to-noise ratio. This within rower consistency is analyzed in section 2.2. Also, rowers may already adjust their force curves because of interaction with the other crew members. Section 2.3 will discuss everything that has been published on this topic.

In section 2.4 and section 2.5 the step from stroke characteristic of one athlete to boat performance is made on one hand, and to crew synchronization on the other. Finally, a proposition on which characteristics may be used in this study is done in section 2.6. The second and third subquestions are answered by then: ”What methods quantify rowing performance?” and ”What methods quantify crew synchronization?” These answers enable a substantiated choice for the setup of this new investigation, and brings us to the next and most important question: ”Which synchronization measure is the best performance predictor?” But that question will be treated in the chapters hereafter.

This chapter was written in cooperation with Janneke Voordouw as a starting point for this study and her own, as we worked closely together on this topic.

2.1. How can the individual force curve be characterized?

This section will discuss the characteristics of force curves of rowers. Force curves can be obtained by measurements on the pin of the oarlock. The force curve can be plotted against time or the oar angle. The individual shape and amplitude of a force-time profile is characteristic for the individual rower. [1, 9] This was also an effect that was seen by Eelco Meenhorst when he analyzed pin force data. These individual characteristics are preserved through a session, even when peak force gradually declined in time. [1]

The definition of a optimal force shape is not defined as there is theoretical and experimental support for different shapes. [10] Therefore, this section provides an overview of pin force signal characterization and how this data can be interpreted. Properties that will be described are: catch and finish, peak force, other discrete points, area, smoothness and stroke rate.

Catch and Finish

To determine where in the force curve the catch takes place, either the oar angles or the force curves can be observed. The catch is the moment when the handle is the furthest towards the stern. Looking at the oar angles, the catch can be defined as the minimal angle in the stroke cycle. [11, 12] The finish is the point when the handle is furthest towards the bow, and thus belongs to the maximum oar angle.

In the force-time curve the catch can be distinguished as the small rise and drop before the large force peak of the drive starts. At the finish there is a small negative peak, which would correspond with the drag introduced at the retrieval of the oar from the water.[1] In figure 2.1 the moment of the catch and finish are made clear in both the force-time curve and the angle-time curve.

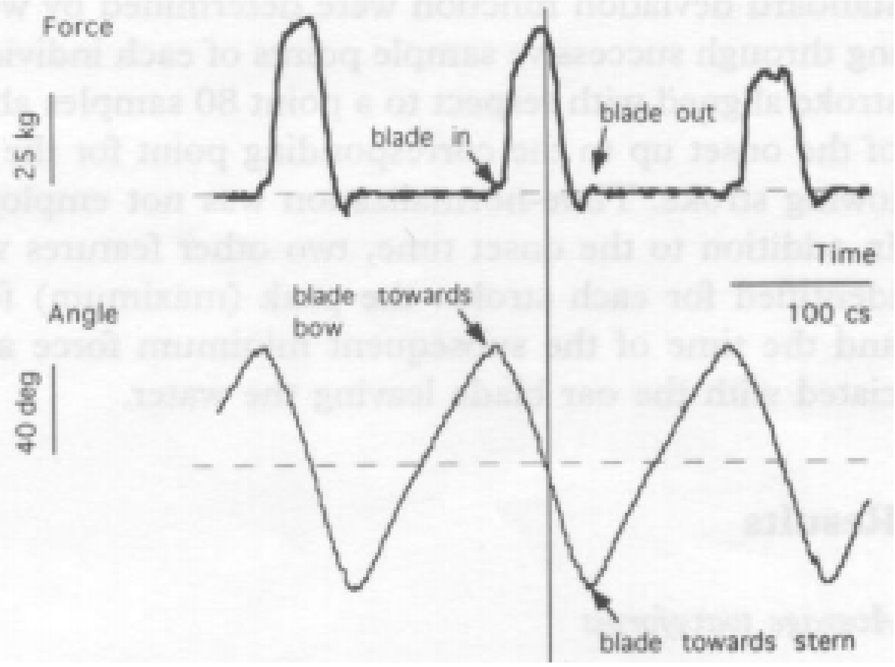

Figure 2.1: The catch and finish in a force-time (upper) and angle-time curve (lower) [1]

Peak force

The peak force (F_{max}) is the highest point in the force curve, see figure 2.2. The peak can be flat and long or very sharp and distinctive in time. [1]

The average force (F_{aver}) is equal to height of rectangle of which area is equal to area under curve. The ratio of average to maximal force $R_{a-m} = \frac{F_{aver}}{F_{max}}$ reflects flat or slim curves. The average ratio R_{a-m} is 50,9% $\pm$ 4.5%. [11, 13]

The position of the peak force shows at what moment in the stroke the rower delivers the most force on the oarlock. The accompanying torque with this force onto the water is dependent on the angle of the oar with respect to the boat. In the catch a relative small torque can be transmitted and therefore this might not be optimal, the same hold for the finish position. When the oar is perpendicular to the boat (0 °) the torque would be the biggest. In a pair, the position of the peak force of two rowers is found not to be at the same time [14]. This is because of the yaw, that is a result of the non symmetric lever arms of the two rowers. In section 2.3 this will be discussed in more detail.

Other discrete points in the force curve

Besides the peak force, more points in the force curve can be distinguished that have a physical meaning. Wing and Woodburn [1] determine the stroke onset as the moment that the force-time function crosses a threshold of 15kg for a period of at least 10 cs. This moment is associated with a rapid rise of force towards the major peak. At this point handle has already moved a bit without (much) force.

In rowing faster, Kleshnev [11] determines the following points: (see figure 2.2)

- A30: 30 % of Fmax, in front of stroke, thus before the peak force. A30 is a measure of how quickly the blade grips the water. It has correlation with the efficiency of the blade. It can say something about the oar handling with small muscles of arms and shoulders.

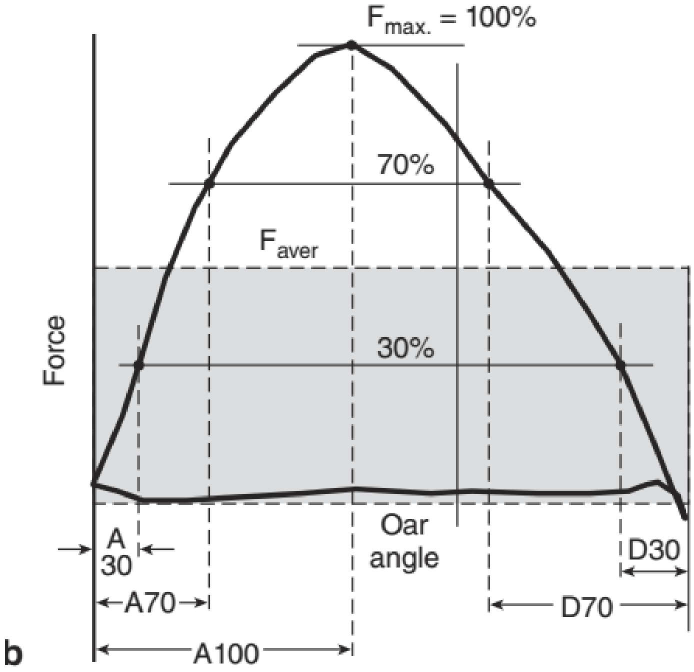

Figure 2.2: Some characteristic points in the force curve [11]

- D30: 30 % of Fmax, in back of the stroke, thus after the peak force.
- A70: 70 % of Fmax, in front of stroke, thus before the peak force. A70 can be used as a measure of the effectiveness of the rowing technique, mainly the dynamic acceleration of the rower's mass and involvement of the large leg and trunk muscles.
- D70: 70 % of Fmax, in back of the stroke, thus after the peak force.

A70 and D70 correlate with maximal leg velocity, quicker legs produce steep gradients of force. A30 and A70 are getting shorter at high stroke rates, but D70 and D30 longer, this causes changes in the force curves at high stroke rates.

These points are points in the force curve that mean relatively much. Of course more points in a rowing cycle for example based on the boat velocity, acceleration or the oar angle can be determined. In his BioRow newsletters, Kleshnev determines as much as twelve points in the stroke to compare force curves of different rowers. (see figure 2.5)

Area

The area under the force-angle curve is a direct measure of the work done in the rowing cycle. [10] The area under the force curve is roughly dependent on the peak force and the stroke length. If a rower delivers a higher force during the whole stroke, the area under the force-curve will be bigger. However, if the rower delivers a big peak force but over a short segment, the total area can be less than a rower who has a lower peak, but distributes his force over a longer segment.

Another characteristic that can be determined from the force-time curve is the location of the center. This is the point at which the area of the force graph can be divided into two equal halves with respect to the total duration of the drive phase. This method is shown in figure 2.3. The center of the force graph shows in what part of the drive the emphasis of force generation lies. So it can be used to compute whether the force pattern is more assigned to a harder catch, finish or middle of the stroke. This measure has about the same purpose as the position of the peak force, but shows the average position of the biggest power output, instead of the peak moment.

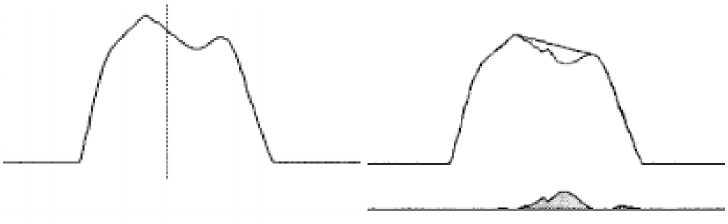

Figure 2.3: The force curve; center of area (left) and smoothness (right) [7]

Smoothness

Smoothness may be defined as the area between the force curve and a tangent touching the tops of the force peak, see figure 2.3. Smoothness of force curves discriminates rowers of different abilities. A small smoothness error probably shows a more optimal movement pattern, although it is not yet known exactly how smoothness and efficiency of movement are related. Smoothness was found to be better during intensive than during endurance rowing. [7]

Stroke rate

The stroke rate is the amount of strokes made per minute. So this is a measure of how much time a whole rowing cycle takes. A way to define the drive time (in some literature called stroke duration) is to determine the catch and finish moment in the force-time curve, the time in between is the drive time. The drive length (also called segment) can be expressed as the total oar angle completed in during one drive. The recovery time is also called interstroke interval. This is the period of time between the finish and successive catch. It is important to be aware of the different names and definitions.

The stroke rate is directly related to the drive time and recovery duration. For example if the drive time plus the recovery time (thus the total stroke time) is 2 seconds, will give a stroke rate of 30 strokes/minute. Stroke rate times stroke length (distance travelled by the boat during a stroke) gives the boat speed. The ratio between the drive time and recovery time is called the drive-recovery ratio. This ratio differs for different stroke rates and intensities. In a longer rowing series, the trend can be seen that the drive time gets a little longer and the recovery time shorter. [1]

Comparing force curves

Besides the absolute comparison that can be done with all the discussed force curve characteristics, the force curves can also be compared by looking at the shape. To compare the shapes of different force curves, each curve can be scaled as a percentage of F_{max}. If the oar angle is also scaled to the total length of the drive phase, different force curves can be plotted onto each other. With this approach, important biological landmarks and subtle harmonic components of the force pattern will be preserved.

The benefits of plotting the force-angle curve are; the angle acts as a measure of stroke length, the force-angle curve has the ability to examine differences in the shape of force development and regression (independent on stroke rate) and the area under the force-angle curve is a direct measure of the work done in the rowing cycle. However, the statistical analysis of the force-angle curve is difficult because of the bivariate data. Warmenhoven et al. (2017) came up with a bfPCA to identify the main modes of variance in the force-angle curves [10]. bfPCA stands for bivariate functional principal components analysis. This is a method used to identify features of a bivariate function, such as the force-angle graph, that relate to another factor, like performance.

2.2. What is the variability in the force curve for one athlete?

Section 2.1 mentioned that each rower has a distinguishable force curve. Although the athlete applies the force, the shape of the force curve is also dependent on the type of boat and its rigging, or in case of an ergometer the drag factor. The current knowledge on how different boats and ergometers compare to each other will be discussed. Furthermore a review is given on the relation between consistency and intensity, fatigue and skill. This way a complete overview of sources of variability will be given. Variability that is not accounted for reduces the signal-to-noise ratio of results later in the study, so it is important to have a proper understanding of all factors influencing the variables that may be used.

Ergometer versus boat

Many rowers have heard the term ”ergometers don’t float”, which means that someone who can output a lot of power on the ergometer, doesn’t necessarily produce the same effort in the boat. Although the ergometer is an often used training tool, there are apparently some great differences.

The first, most obvious difference, is that on the ergometer the athlete doesn’t have to handle an oar, which induces kinematic differences at the catch and the finish [15]. Lamb [15] concludes, however, that the drive phase is similar enough to confirm that ergometer rowing is similar enough to on water rowing, to be a useful training tool.

The fact that there are more differences is made clear by Dawson et al. [16]. On the ergometer, relatively less time is spent in the drive phase and increasing stroke rate is mainly done by speeding up the recovery [16]. Although the ergometer is an effective tool to gauge physical condition, and the principle of viscous drag is used to make it feel similar to rowing on water, Ritchie [17] concludes that it cannot improve poor technique or teach good technique. This is mainly because it doesn’t consider the catch technique and letting the boat run during the recovery.

The principle of letting the boat run sounds quite vague. Hofmijster et al. [12] use a modified ergometer to take velocity fluctuations into account. This is in our belief the way to quantify this principle. In addition to the velocity fluctuations within the stroke, Shimoda et al. [18] found that strokepower consistency also attributes to efficient power conversion. So just like the velocity fluctuates within one stroke, fluctuations over a couple of strokes also introduce losses.

Kinetic differences between ergometer and on water rowing are found as higher handle peak force [19]. Other studies mostly found higher forces in the lower limbs [20–22]. The higher loading of the lower limbs is explained by the fact that on a static ergometer, the total mass of the rower needs to be set in motion, before the handle is pulled. This is not seen in dynamic ergometering or rowing on water. It is advised that ergometer rowing is used with care in the competition season. Both because of the higher injury risk as well as not to practice the different kinematic and kinetic movement too much [20, 22].

Different boat types

Not many experiments have been done that compare the variability of the force curves for one athlete in different boat types. It is guessed that the gearing of the oar and rigger are adjusted for each boat type in such a way that the rower experiences the same loading characteristics.

In the experiment of Wing and Woodburn [1] relatively low variability between boat types was observed, which is consistent with Ishiko [9]. During the experiments, only the peak force declined due to fatigue. Only when athletes row in a pair, some adjust their force curves [2]. This is very specific for this boat type, and will be discussed in section 2.3.

Consistency

Consistency is defined as the variability between consecutive strokes of one athlete. Low variability means a high consistency. Consistency is influenced by the intensity of the trial, by fatigue, and by the skill of the rower. Intensity is often used together with stroke rate.

Intensity The influence of intensity on consistency can be observed in terms of kinematics and kinetics. When looking at kinematics, the variability in drive-recovery ratio decreases with stroke rate [16], so consecutive strokes are more alike. This was also observed by Hill [7]. He found that, when intensity increases, differences in general become less. This is in line with Lippens [23], who found that both individual and collective consistency increase with stroke rate.

Kleshnev [24] provides detailed insight in how the contribution of micro-phases to the total drive changes with stroke rate. He found changes in three micro-phases: The first micro-phase, the immersion of the blade, became faster with stroke rate. The third micro-phase, the initial boat acceleration, usually peaks around 32 strokes per minute. For scull rowing this is a lower rate than for sweep rowing rowing. The presence of this initial boat acceleration phase was found to be a discriminating factor in good technique. The last micro-phase of the drive is the blade removal, and it was found that this makes up a larger part of the drive at higher stroke rates.

Going back to kinetics, the lower total differences found in Hill [7] could not be subscribed to a specific difference type (e.g. form or area differences of the force curves). Furthermore, force area and form differences were found to be highly negatively correlated. This is attributed to a decrease of freedom when all muscles are maximally engaged. In the study, the average center of the force patterns shifted backwards with increasing intensity, this was mainly the case in rowers that otherwise have a front-loaded force curve. Fore curves also become more smooth.

In two studies, force generation was increased with stroke rate [7, 25], which is not in line with the common knowledge on muscle force versus contraction speed. Hofmijster et al. [26] found no change in work per strokeat different stroke rates. They concluded that power increase comes solely from increase in stroke rate. A possible explanation is a different task assignment: are the rowers focusing to keep their stroke rate constant or to produce maximal force in every stroke.

Fatigue Fatigue has a significant influence on the consistency of strokes during a 2000m all-out trial on a RowPerfect ergometer. Anderson et al. [27] defines his performance variable as Power-Stroke Dispersion, comparable to the standard deviation of Work per Stroke. He found a significant effect on the distance within the 2000m trial on this parameter. During the first 500 meters, the power output is not yet very consistent, probably due to the fact that the rower has to settle in a reproducible technique, and a period of re-familiarization with the task. During the middle 1000 meters, the Power-Stroke Dispersion is relatively low. This is in accordance with Korner [28]. During the final 500 meters, fatigue starts playing a role and consistency deteriorates with respect to all previous distance intervals. This is also displayed in the kinematic consistency.

Anderson et al. [27] concludes that athletes might be able to improve their performance by improving their kinematic consistency. With the deterioration of kinematic consistency, metabolic costs and losses due to velocity fluctuations increase. Plus, the improvement of consistency has a positive effect on crew harmonization, which in turn, improves boat speed [29].

Skill Černe et al. [25] identify kinetic and kinematic parameters, such as stroke length, duration of the strokephases, peak and average handle and foot stretcher forces, etc, for elite, junior and non-rowers. In elite rowers a relatively high consistency between all parameters as found. In junior rowers, this was not in the same amount, but Černe et al. [25] state that it follows the same principles. In non-rowers, rowing technique varies a lot. They were found to perform different movement patterns, and the movement pattern is not consistent with stroke rate. However, the kinematic pattern was fairly constant within one stroke rate.

2.3. What are the physics behind rowing together?

In this section the current state of knowledge on rowing together is discussed. In section 2.2 it was mentioned that there is relatively low variability between different boat types, except for pairs. And let pairs be the boat type that most studies discussing this topic focus on.

In pairs, something unusual happens. Usually it is believed that rowers need to be as synchronous as possible. However, this is not the case in a pair. Before this phenomenon is discussed, the knowledge on other boat types will be elucidated. This section provides possible explanations why perfect synchronization is not always beneficial.

In general, the common conception is that rowers should do exactly the same. There is no known argument why rowers in symmetric or larger boats should apply an asynchronous force pattern. However, Coker [8] found that also in doubles the strokeshould peak earlier than the bow seat. Coker gives a number of possible explanations. First of all the summation force patterns would be more rectangular, which is, according to Kleshnev [30] more efficient. Another possible explanation is that since the bow seat follows the stroke, the average peak force will be earlier in the drive. This is deemed more efficient [7] and therefore this effect could be a confounding variable. By testing in a double sculls with two athletes that apply their peak force simultaneous, an answer can hopefully be given.

In larger boats, it is observed that rowers do tend to do exactly the same. Even when two athletes switch from a pair to an eight, they switch to the synchronous pattern in about 40 strokes [7]. When looking closer, especially in a non elite crew, a hierarchical timing is observed, where the bow side has an extra delay compared to the strokeside [1].

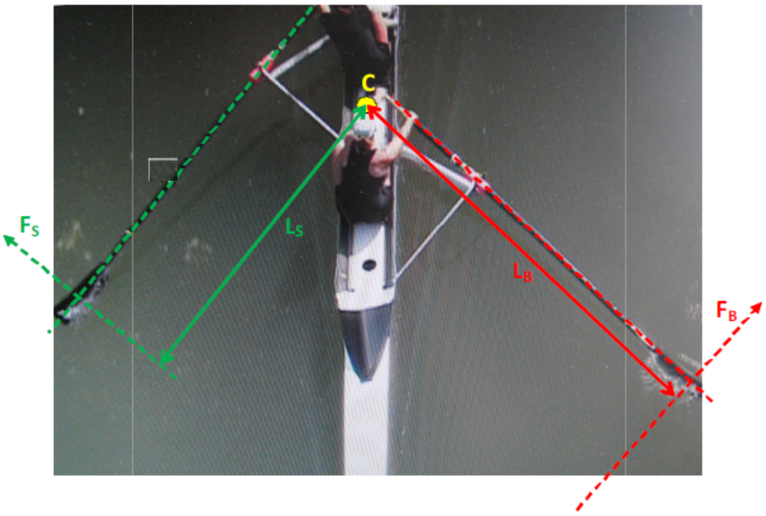

Figure 2.4: The lever arms of the bow seat (Lb) and strokeseat (Ls) around the rotation center. Since the lever arms are not symmetrical, the rowers have to apply a different force pattern [8].

Pair

As stated, rowers in a pair have to apply an asynchronous force pattern [2, 7, 31]. This has to do with the fact that the lever arms around the rotation center, as shown in figure 2.4, are of different lengths. Because the bow lever arm is longer, the force peak of the bow should be slightly delayed to make the boat go straight. The force difference should be about 10% [2].

This asymmetric force pattern is nowadays well established. How this is achieved, is more interesting. Some rowers adapt more easily than others. Especially building up force more slowly is easy. The rowers that have a more rear loaded force curve are often the least adaptable [2, 7].

Although one might expect the bow seat to do the steering and the bow seat adapts more easily, Lippens [23] found that the strokeseat varies the movement pattern significantly more, in order to control boat movements. Recent insight by R'Kiouak et al. [31], also revealed the link to the experience of the athletes. strokes that had peak forces both at the same level as well at the same time were 'Simultaneously and Similarly Experienced as Effective (SSE-E)', whereas strokes of different level, but at the same timing are 'Simultaneously and Similarly Experienced as Detrimental (SSE-D)'. In this case the peak force of the bow was higher, which would be expected from the previously discussed literature. Interestingly, the force profiles corresponding to the SSE-E strokes are indeed related to a more expert level of rowing [2].

2.4. How can Performance be Defined?

Over the years different methods of measuring performance have been used in research. These will be discussed in this section. Quantifying performance in a single number is necessary to be able to calculate correlations with other stroke properties. Because of the many variables involved in rowing, it is important to pick the right measure for performance.

Since the goal of rowing is to cross the finish line of a 2000m course in the shortest time possible, this would be a most obvious performance measure. However, this performance is influenced by many more factors, such as wind, water temperature and other weather conditions. In this section different performance measures are discussed, divided into those based on a kinematic approach and those based on energetics.

Kinematics

As mentioned, the most straight forward method is the 2000m race time. This isn't always measured in the boat although, Anderson et al. [27] used a RowPerfect ergometer. Measuring on an ergometer neglects many influences on the, unfortunately. An ergometer only looks at the power input.

Time over a certain distance is, evidently, known as speed. R'Kiouak et al. [31] looked mean velocity and mean accelerations. The fact that acceleration is also monitored already hints that velocity fluctuation play an additional role. These velocity fluctuations are accounted for by de Brouwer et al. [5], which makes their ergometer experiment more resembling to rowing on water. Still, an ergometer does not simulate propulsive efficiency of the blades.

The final kinematic performance measures that were found in literature are the detrimental boat movements, expressed in surge, heave, pitch and roll [32, 33]. These, in turn, contribute the total power lost as drag on the hull. It has not yet been studied how large these effects are.

Energetics

The kinematics of the boat are the result of forces. Combined with kinematics, power and work can be calculated. When measuring power and work during rowing, a deeper understanding of the kinematic rowing performance may be acquired. Altough Baudouin and Hawkins [2] were not yet able to predict rowing performance (speed) based on a simple linear model that considers total propulsive power, synchrony measures and total drag contribution of the hull, they did find that a pair requires an asynchronous force pattern, in accordance with other studies [7, 8] (as was discussed in section 2.3).

Measures of power and Work per Stroke are later used by Anderson et al. [27], although the focus lies on consistency of the average power per stroke. For gaining insight in the different power losses in rowing, the article of Hofmijster et al. [26] is most useful. After deriving the power equations for rowing in a single scull, Hofmijster et al. [26] defines three efficiency's: propulsive efficiency, Velocity Efficiency and Net Efficiency. Propulsive efficiency is defined as the power not dissipated at the blades, divided by the total power output at the handle. Velocity Efficiency is the power not lost by fluctuations of the boat forward velocity, divided by the total power output at the handle. Finally, Net Efficiency is defined as the power that contributes to the average velocity of the boat, divided by the total power output at the handle.

Hofmijster et al. [26] found that propulsive efficiency and Net Efficiency increased with stoke rate. Velocity Efficiency decreased, but was not enough in absolute sense to decrease the Net Efficiency. This insight in power losses was later used by de Brouwer et al. [5] to test whether losses due velocity fluctuations decreased in anti-phase rowing. Although this was an ergometer study and ergometer have no losses at the blades, Velocity Efficiency was a suitable measure to explain the results.

A note must be made on the method to derive rower power, used by Hofmijster et al. [26], Anderson et al. [27]. Hofmijster et al. argue in their latest paper that, in contrast to their earlier paper, these formula's are not sufficient. An additional power term is neglected, while constituting for over 10% to the total work generation. These are easily derived from the equations of motion of the rower, see their latest article [34].

2.5. How can synchronization be defined?

This section will discuss the definition of synchronization. This is the third subquestion of the first main research question, and it is the most crucial one for finding a relation with performance.

Synchronization has been defined in many ways, depending on the focus of the research. Some researches only want to determine the synchrony in one point of the stroke, others in several discrete points and some take the entire stroke into account. An overview will be given of the different ways that synchrony has been determined.

Time analysis

The most easy way to interpret synchronization is to define it as: ”the time lag relative to the stroke rower” [35]. This time lag can be determined with different tools in different points of the rowing cycle.

One way to look at the time lag is by video analysis of a high frequency sampled video. Look at for example the catch of the stroke rower, set this as time zero and see what the time difference of the other rowers with respect to the stroke is. This is the method that Tay and Kong [36] used for the analysis of a kayak crew. They measured the time difference at four points in the kayak stroke with a 120 Hz sagittal view video. Downsides of this approach are that it is very time consuming work to determine the same point in a stroke for every rower over a certain amount of strokes and that there is always a human error in determining exactly when the point in the stroke takes place (no measurable definition).

The variability within and between rowers can also be described by comparing the drive times and the recovery times [1]. The dependence of these metrics is characterized in terms of a cross correlation function for each rower.

Force-time curve

For a better measurable definition of synchronization, the force-time curve can be used to determine certain points in the stroke. For example, the way Hill [7] did; he calculated the absolute time difference between the rowers in the onset and the finish. The onset defined as the moment that the force-time curve crosses a certain threshold. This time difference is a more objective measure, although it is of course dependent on the quality of the measurements.

Hill [7] also used a few other measures based on the force-time curve. These measures are:

- Area difference: This is the area under a force-time curve compared to the average area (%).
- Area center difference: The position of the area centre of the force-time curve (%).
- Total difference: The total area difference between a force-time curve and the average force-time curve (%).
- Form difference : The form difference is calculated like the total difference, but with the area scaled to the average area (%).

All these measures are dependent on the area under the force-time curve. The area under the force time curve is dependent on several factors, see section 2.1.

Based on the level and timing of the peak force, different rowing strokes can also be compared to each other, both within and between rowers [1]. This can be done by calculating the gap between the timing of each individual peak force as a percentage of the rowing cycle, as for example is done by R’Kiouak et al. [31]. They also determined the mean gap between each individual peak force level (N). Baudouin and Hawkins [2] defined synchrony as the percentage of time increments that the rowers handle forces are within 10% of each other (factor 0,9-1,1). Which means for every time-step they calculated the difference between the handle force of the rowers, determined the percentage they were off, and if this percentage is below 10% the time step would count as synchronous. This method is an approximation of how synchronous a crew is rowing, but highly dependent on the threshold of 10% handle force that is defined, because 9,9% is now much more synchronous then 10,1%, while for real they do not differ very much. Also except for a percentage of the stroke duration, the exact time increments where the rowers are synchronous might be a valuable measure as well.

In his newsletters, Kleshnev [37] has measured the time-lag of the rowers relative to the stroke on twelve points in the rowing stroke, five points on the force-time curve, five on the handle and seat velocity and two on the vertical oar angle. (see figure 2.5) He did not only look at the average difference on each of the points, but also at the standard deviation of the differences magnitude. In other words the variability of the difference between the stroke rower and other rowers.

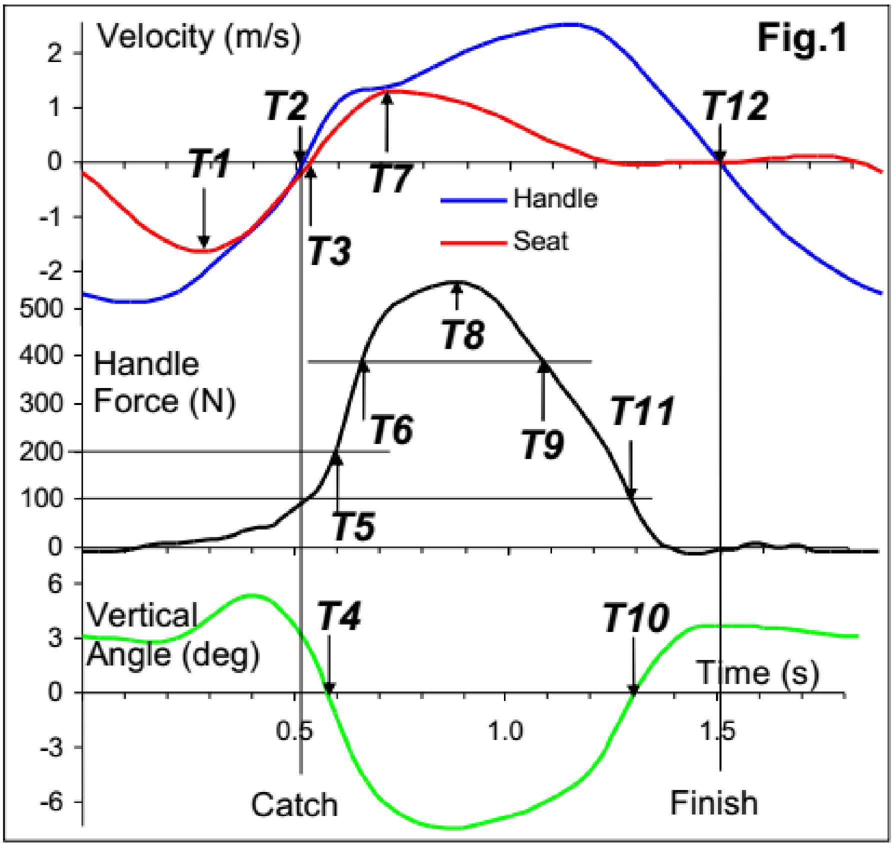

Figure 2.5: Twelve possible measurement points in a stroke. [37]

He also came up with putting this data in radar charts, this is an effective presentation of synchronization data. The twelve comparison points are all represented on one axis. More to the middle of the radar chart means a rower got to that point earlier then the stroke, and more to the outside is later.

Oar angles

As can be seen in the definitions of Kleshnev [37], oar angle measurements can also be used to determine the synchronization in several points in a stroke.

Hofmijster et al. [26] define the catch and finish as maximum and minimum oar angles. The deviations of timing and amplitude of the oar angles in the catch and finish can be calculated to determine how identical different rowers move through the catch and finish. The gap between the timing of both catch angles (%) is also a measure that can be used [31].

To compare different angles with each other during the stroke, the relative phase can be calculated. The relative phase gives a potential function that captures the dynamics between two non linearly coupled limit cycle oscillators [5].

$$\phi = \theta_1 - \theta_2 \tag{2.1}$$

For two oscillators (rowers in this case) to move in perfect synchrony, $\phi = 0$. Furthermore, there can be made a distinction between the continuous and discrete relative phase [32, 33]. The discrete relative phase, contains less information than the continuous relative phase, but it is not sensitive inharmonicities in the rowing stroke. Examples of inharmonicities are; the fact that the rower tends to spend more time around the finish than around the catch and the duration differences between recover and drive [32].

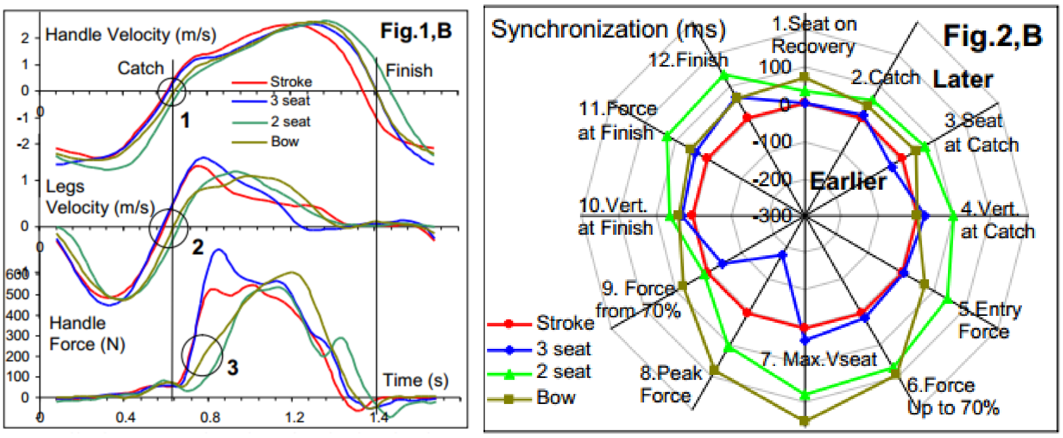

Figure 2.6: The data of 4 rowers in a quad(left) and corresponding radar chart to interpret synchronization (right) [35]

A small variation of the relative phase indicates that the crew is moving more synchronous than when a crew has a large variation. R'Kiouak et al. [31] calculated the mean of the continuous relative phase (°), the mean of the standard deviation of the relative phase to measure the synchrony.

The rate of change of the relative phase can also be determined with the following equation:

$$\dot{\phi} = -a \cdot \sin(\phi) - 2b \cdot \sin(2\phi) \tag{2.2}$$

a is affecting the attractor strength of in-phase coordination, b is affecting the attractor strength of both in- and anti-phase coordination The movement frequency (stroke rate) is directly related to $\frac{b}{a}$ [32].

The oar angle measurements can tell something about the coordinative performance of the crew. By using directional statistics on the calculations of the mean absolute error and standard deviations of both continuous and discrete relative phase, Cuijpers et al. [33] measured the coordinative performance.

Boat movements

From the boat movements, some information about the synchrony of the rowers can be conducted. The most easy movement to interpret is the surge. Surge is dependent on the movement of the masses of the crew relative to the boat. A bigger surge will result in a higher water drag, but surge will increase with a smaller variability of the relative phase [33]. Also, Cuijpers et al. [33] found that a smaller variability of the relative phase (better synchrony) is related to an increase in heave and pitch. Finally, a decrease in roll was found in the case of better synchrony. This could imply that by measuring the translational and rotational movements of the boat, some conclusion can be drawn about the synchrony in which the crew is rowing.

2.6. Conclusion

In this chapter the characteristics of the force curve were discussed, the variability in the force curve for one athlete and the specific differences when rowing together. Several ways to measure the performance have been explained. Finally the existing methods to define synchronization have been elucidated. With this, the answers have been given to the following subquestions: ”What is the current state of research on the rowing stroke and its characteristics?”, ”What methods quantify rowing performance?” and ”What methods quantify crew synchronization?”

To be able to determine the relation between performance and synchronization, a proposal for which measures to use in this study is now made. The exact variables will be picked, explained and correlated with each other to investigate the effect that synchronization improves performance in chapters 3 and 4.

Performance measures

In section 2.4 the methods to measure the performance of a rowing crew were presented. The most straight forward measure is the boat velocity. Since it is measured anyways and the meaning of this measure is clear to everyone, this will be the first performance measure.

A second way to investigate the performance of the crew is by the efficiency. The efficiency’s, as defined by Hofmijster et al. [12]: Propulsive, velocity and net, would be a proved way to determine the performance. It is important to define these efficiency’s very well, since the word efficiency is a word that is used soon, without proper definition.

The efficiencies we want to use can be defined as follows; Propulsive efficiency is the energy not lost at the blade, divided by the work exerted on the handle. Velocity Efficiency is the energy not lost by the boat speed fluctuations, divided by the work exerted on the handle. The Net Efficiency is the energy that contributed to the average boat velocity, so the dissipated drag energy in the case when the boat would move at the constant average speed of the stroke, divided by the work exerted on the handle.

Synchronization measures

We would prefer three synchronization measures, so that we are able to see whether the whole stroke is more synchronized or that the rowers adapted only a small part of the stroke.

The first measure of synchronization that can be used will focus on the build up of the force (the steep incline in the force curve). This measure has the most interest of Eelco Meenhorst. An example is to measure the slope around the 70% of the peak force point.

The second measure will take into account the emphasis of the power of the stroke. The area center is preferred over the position of the peak force, but there has to be a critical look at the smoothness of the curve. If a curve is not smooth, this can influence the area center.

The last measure will have to cover some of the coordination of the oar along with the force curve. The continuous relative phase of the oar angles may be a good example of a measure that can be used for this purpose.

3

Method

To analyze the relation between crew synchronization and boat performance, access to existing data was granted by the KNRB. This data was acquired using PowerLine Rowing Instrumentation (Peach Innovations Ltd.) and MiniMax (Catapult) by coaches during training in the past and was shared to gain new insights. In this chapter it will be explained how the data was processed and how synchronization and performance were quantified, and how these values were used to answer the research questions.

Information on the athletes and how the data from the different systems was delivered and merged is given in section 3.1. Section 3.2 explains the processing towards meaningful time-series data per rower and stroke. In section 3.3 the ways to quantify crew synchronization and boat performance are elaborated. Finally in section 3.4, the methods to determine the reliability and significance of the results will be discussed.

3.1. Data acquisition

In this section the features of the athletes, the boat and oars, and the measurement system are explained. The rowers are members of the KNRB, and the data used was gathered during their training. During these trainings, the athletes performed sprints according to a certain protocol.

The measurements were done using the PowerLine system combined with a MiniMax, which were installed in the boat. The boat type focused on was the quadruple sculls. In this section it is discussed how the values of all necessary parameters were obtained. The parameters and their final values are listed in table 3.1.

Athletes

Data from the Dutch equip was used in this study. The main contact for this research was Eelco Meenhorst, coach of the men's quadruple sculls (M4x). This was the crew the study initially focused on. Unfortunately, not enough data could be gathered from them in the time frame of this study, and therefore access was granted to old training data of the women quadrupple sculls (W4X).

The female group consisted of 5 athletes having experience with World and Olympic Games. At the time of the measurements, they were on average 27 years old, the youngest being 24 and the oldest 30. They were on average 1.76m in height (ranging from 1.69m to 1.85m) and weighing 71.4kg on average (range from 70kg to 74kg). The athletes were randomly assigned a key (A to E) and data was made anonymous.

Boat and oars

The boat that was used by the W4X was built by Filippi (Filippi Lido SRL) and has a length of 11.78m and a weight of 52kg. Concept2 Skinny Smoothy (Concept2 Inc) oars were used, weighing 1.6kg. A schematic of the oars can be found in fig. 3.2. Oar length was estimated at 2.88m, inboard length at 0.88m [38, 39]. These oar properties were either stated in the logging files or by Eelco Meenhorst, but were not checked. However, the 1.6kg is very comparable to the small diameter shaft, standard modulus carbon fiber, standard deflection oars from competing brand Croker (Croker Oars Pty Ltd). These weigh 1.5kg according to their catalog [40]. The oar and inboard length used are common

settings according to rigging charts.
The handle and blade forces do not act on the outer ends of the oars. So, these points had to be estimated. The locations where the forces are applied are not not evident as they are dependent on the pressure distribution on the blade and by the hand. The location of the handle force was assumed to lie at the middle finger. The distance of the end of the handle to the middle finger was measured using measuring tape, which resulted in $R_{F,handle}$ = 0.04m. The location where the blade force acts was taken from the Nielsen-Kellerman website (manufacturer rowing electronics) [41]. This is a distance of 0.225m from the tip of the blade ($R_{F,blade}$), which is roughly the area center.

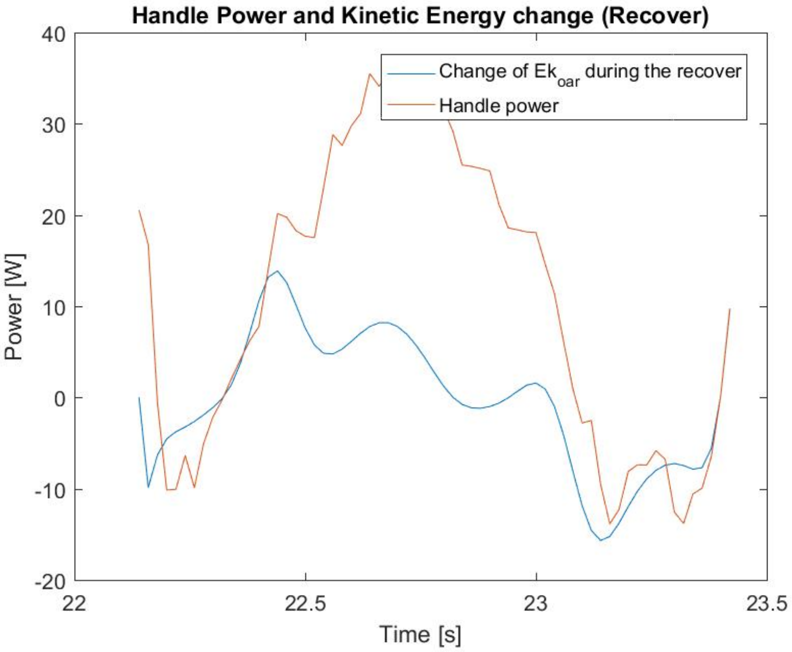

Figure 3.1: This graph presents the derived handle power and the change of rotational kinetic energy of the oar during the recover. This is the comparison between eqs. (3.8) and (3.9), and provides information on how well the assumptions hold that were done to derive the EOM. How these are derived is discussed in section 3.3. Both curves begin and end with similar profiles. During the middle part of the recover, the handle power was apparently influenced by more factors than inertia. E.g. air resistance and friction at the gate may have played a role. These have not been taken into account, since this would go too much into detail as the work during the recover was limited. Assuming only presence of inertia during the recover is in line with previously published models, like. [42].

Rotational inertia of the oar Because the inertia of the oar was not known, it had to be estimated. If the oar would be a perfect rod, the rotational inertia around the gate could be described by eq. (3.1). The location of the center of mass of the oar, s, was unfortunately unknown, and. If the center of mass would be at the gate, s is zero and I_{gate} is approximately 1.1 kgm^2. If the center of mass lies halfway of the oar, I_{gate} is approximately 1.6 kgm^2.

In case all the work during the recover is transformed to kinetic energy, these curves should be exactly the same. In that case the rotational inertia of the oar could be easily derived. Unfortunately, this is not the case. In fig. 3.1 it is explained that there is a difference between the derived handle power and the change of rotational kinetic energy of the oar during the recover. How these variables are calculated is explained in section 3.3.

One way to quantify the difference between the power and the kinetic energy change during the recover was to take the root mean squared error (RMSE) of the two curves. As the measured work during the middle of the recover was higher than the change of kinetic energy, possibly due to e.g. friction, minimizing RMSE does not necessarily lead to a good approximation of the oar inertia.

Another way to quantify the difference is to look at the minimal values of the curves. As the start and end of the recover probably experience less influence of unknown factors like air friction, matching the minimal values of the curve is also considered as a method to identify the oar rotational inertia. The two criteria were averaged over all recorded strokes, and compared for different values of the oar inertia.

The final used oar inertia was 1.2kgm^2 and was picked by trial and error. For this value, the average RMSE of the recover power was 34W and average difference between the minima of the curves was 7.5W. The final oar inertia was quite a bit higher than the value used for sculling oars by Cabrera, who used 0.85kgm^2 [42].

$$I_{gate} = \frac{m_{oar} \cdot L_{oar}^2}{12} + m \cdot s^2 \tag{3.1}$$

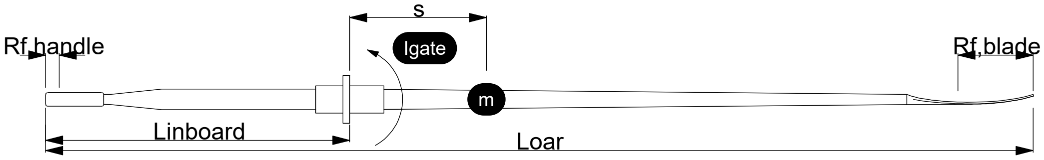

Figure 3.2: This schematic shows the oar and its properties that are taken into account in the analysis. The values of these properties are presented in table 3.1.

Measuring systems and combining data

The measurements in this study were done using the PowerLine System and a MiniMax S4. The Powerline system is a commercial sensor network (fig. 3.5d) consisting of an accelerometer, gyro, impeller (fig. 3.5b) and instrumented oarlocks (fig. 3.5a). Variables that can be recorded by the logger (fig. 3.5c) are longitudinal accelerations of the boat, transverse and longitudinal gate forces, gate angles, angular velocity of the gate, boat forward speed and roll-pitch-yaw angles. An example of raw PowerLine signals recorded during a stroke are presented in fig. 3.3. The PowerLine system samples at 50 Hz. The resolution of the force measurement in the oarlock is around 14 N, the angle sensor is accurate op to about 0.5° [43].

Although the PowerLine system is able to work with an impeller, this was not used. An impeller is not favored by coaches for measuring speed, as it is attached to the bottom of the hull and therefore causes additional drag (although this effect is minimal according to the impeller manufacturer [44]). Thus, another method had to be used to measure speed. The device used instead was the MiniMax S4. The device is shown in fig. 3.4b. The MiniMax is a sensor that combines GPS with accelero-, gyro- and magnetometer data. An example of the used raw output during a stroke is plotted in fig. 3.4a. More variables can be obtained, but are not specifically necesary for this study, e.g. raw gps locations. The MiniMax samples at a rate of 100Hz. This data must be combined by hand with the PowerLine data, into one tab-separated table. The data granted access to was already combined and used for analysis in Excel (Microsoft). It has been exported to text files to be usable for the calculations done in this study.

Table 3.1: The parameters and their values used in the data analysis.

Parameter	Value	Unit	Description
$f_{sampling}$	50	Hz	Sampling frequency
$L_{inboard}$	0.88	m	Inboard
L_{oar}	2.88	m	Oar length
$R_{F,handle}$	0.04	m	Handle center
$R_{F,blade}$	0.225	m	Blade center
m_{oar}	1.6	kg	Oar mass
I_{gate}	1.2	kgm^2	Oar inertia
m_{boat}	52	kg	Boat mass
m_{rower}	67	kg	Average rower mass

Protocol

The data to which access was granted was collected in 2015. Therefore, the exact conditions and protocol are not known. Especially because the data was delivered in the format for a different protocol. Luckily, the most important information could still be deduced.

The group did trials for four days in a row, two trials a day. On each day one of the crew members was switched. During each trial, they rowed approximately 30 seconds at high intensity. The aim during the first trial was to row at 30SPM (strokes per minute). Then there was some rest, and then the second trial was performed at 32SPM. Each trial resulted in approx. 15 registered strokes. The total number of registered strokes was 124.

Approximate weather conditions were retrieved from a nearby weather station. The rowing direction compared to the wind could not be deduced, but trials are usually not rowed upwind, so that leaves side- to downwind conditions. The weather conditions for crew the configurations are tabulated in table 3.2.

Table 3.2: The approximate weather conditions at the days of the trials for each crew configuration.

Crew	Mean Wind Speed [m/s]	Mean Temperature [° C]	Rain [mm]
EABC	4.3	2.9	0.0
DEAB	4.2	3.2	1.7
EACD	6.2	4.2	3.1
ECBD	7.3	6.8	11.3

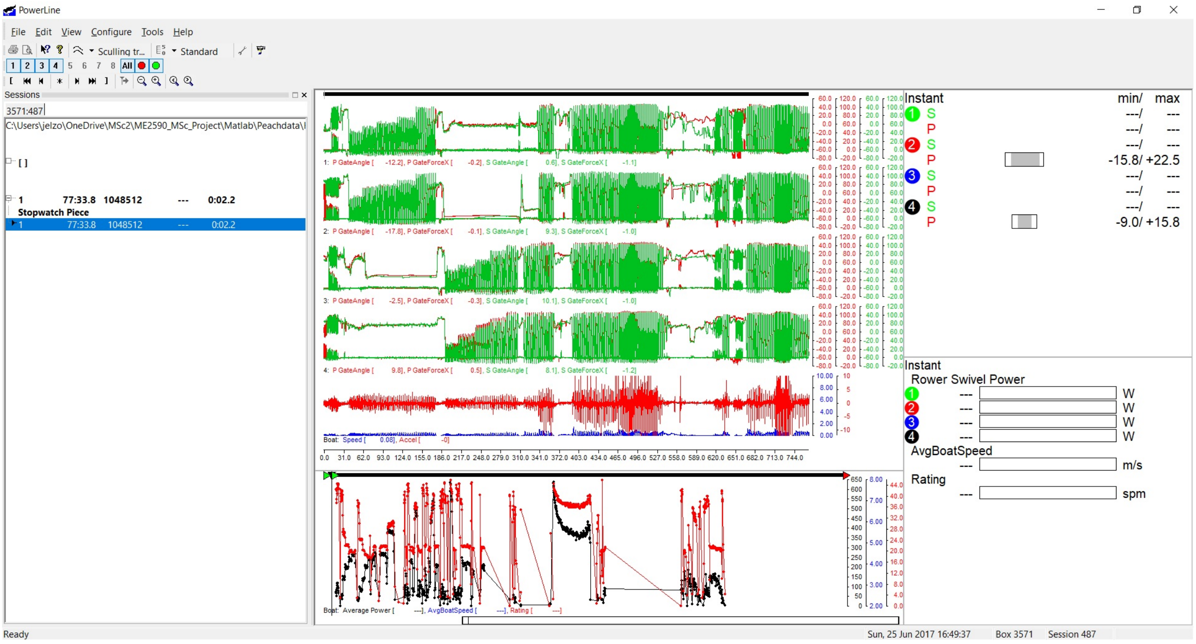

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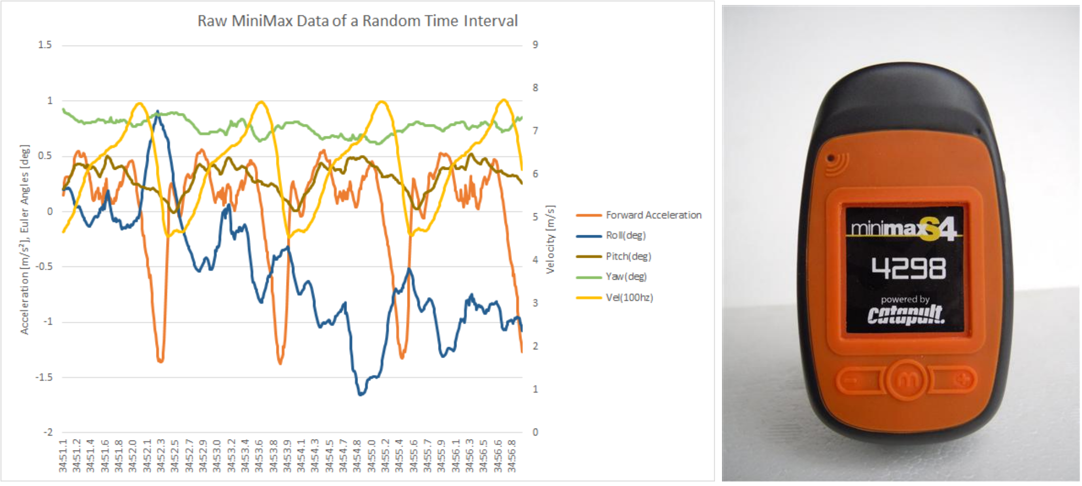
Figure 3.3: The PowerLine software downloads the data from the logger and presents the recorded traces for analysis. It is also able to do some calculations of stroke parameters like average power and speed per stroke. The data can be copied for use with other software. Note that the data in this screenshot is an example and the data is unrelated to the data in the study



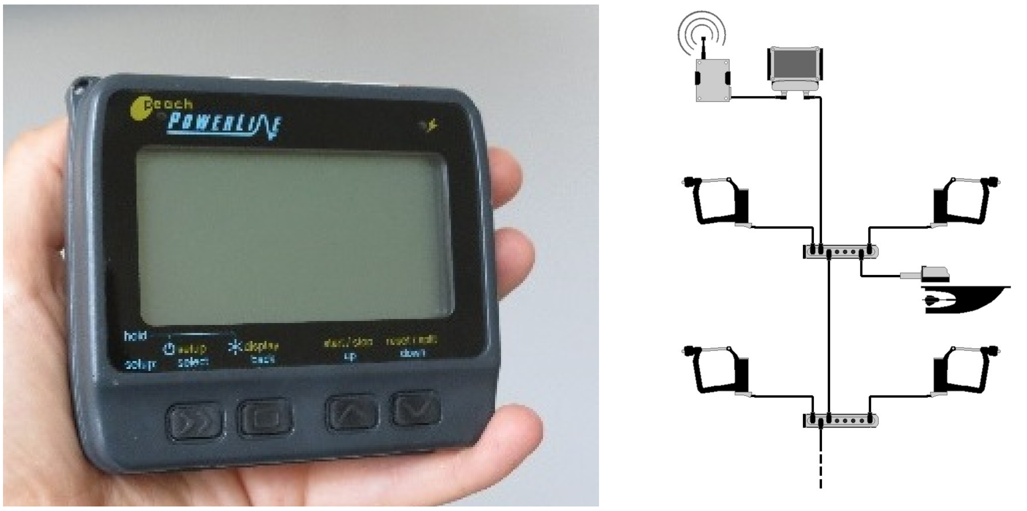
(a) In this graph a piece of raw data is presented that was obtained by the MiniMax. Four strokes can be recognized in the velocity and acceleration signal. Also, the pitching of the boat show this cyclic pattern. The data was combined with the PowerLine measurements by comparing the recorded accelerations of both systems. The data in this graph is just a sample for visualization, and not from the final dataset.

(b) This is the MiniMax S4, which can be used to track athletes in all kinds of sports. In rowing, the device is attached on the bow or stern of the boat. [45]

Figure 3.4: In fig. 3.4a an example of raw data is given, that was recorded by a MiniMax S4, see fig. 3.4b.

(a) The oarlock of the PowerLine system measures the forces between the oarlock and the pin in two directions: in line with the boat (x-direction), and perpendicular to the boat (y-direction). the local y-direction of all oars are pointing outwards,away form the center line of the hull. In addition to forces, the oarlock measures the gate angle as well. The gate angle is zero when the oar is perpendicular to the boat and the positive direction is towards the finish. [43]

(b) In addition to the oarlocks, the powerline system uses an IMU (top) and an impeller (bottom). The IMU measures linear acceleration in three axes, and yaw, pitch and roll angles. Therefore, the IMU should be placed horizontally on a flat surface, and must line up with the longitudinal axis of the boat. The impeller should attached to the bottom of the hull, where it measures the speed of the water along the boat. The impeller was not used in this study, therefor the speed data had to be recorded via GPS. The device used was the MiniMax S4, see fig. 3.4. [43]



(c) The logger of the PowerLine system records the sensor values at a sample frequency of 50 Hz. It has several real-time functions, similar to other rowing feedback electronics. The logger can be connected to the computer to read out the data, using the PowerLine software. [43]

(d) The network of an installed PowerLine system consists of a logger, for each rower a junction box, oarlocks, an impeller and an IMU. In addition, seat position sensors can be attached (not shown). All sensors are optional and the logger records all available data. [43]

Figure 3.5: The Powerline system consists of several, optional, sensors, such as oarlocks (fig. 3.5a), an IMU and impeller (fig. 3.5b) and a logger (fig. 3.5c). The sensors are connected in a network via junction boxes (fig. 3.5d).

3.2. Processing

Filtering

The data was filtered to improve peak force identification and identification of the catch and finish during the stroke. Raw data that has been filtered are the speed and gate angle signals. During processing, the calculated pin forces are filtered to improve the robustness of the catch and finish finding. The filtered gate angle signal was used to derive a smooth gate angle velocity signal. Together with the filtered speed, these signals are used for determining blade slip, which highly influences propulsive efficiency.

For filtering, a 4th order Butterworth filter was selected. Cutoff frequency was estimated to be between 1-10 Hz, based on the sense that rowing is a large motion an higher frequencies cannot be human induced. The final cutoff frequency was selected by plotting the effect on the gate angle signal 3.6a) and the speed signal 3.6b). These figures show that a cutoff frequencies below 5 Hz influence the minimal and maximal values of the curves quite a lot. Therefore, a cutoff frequency of 5 Hz was chosen.

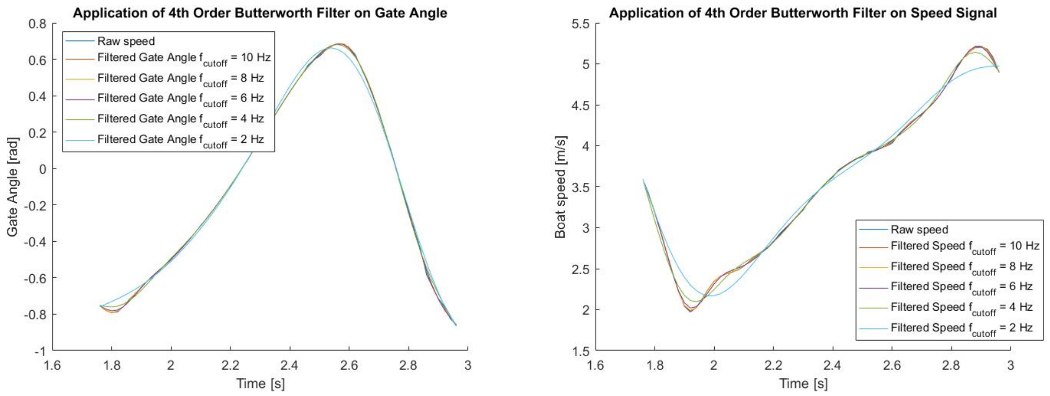
Pin force

In this section, it is explained how the pin force was derived. Pin force is defined as the perpendicular component of the force at the gate. The force at the gate was measured along the boat (F_x), and perpendicular to the boat (F_y). The oar angle was defined as the angle in the xy-plane, where the angle is zero when the oar is perpendicular to the boat, and the direction of rotation is positive during the drive. The two measured forces were decomposed into the vectors in line with the oar, and perpendicular to it. The perpendicular components were summed, see eq. (3.2). This is also illustrated in fig. 3.7.

$$F_{pin}(t) = F_x(t) \cdot \cos\phi(t) - F_y(t) \cdot \sin\phi(t) \tag{3.2}$$

Catch finding

The catch and finish of the stroke can be defined in several ways, for example by minimal and maximal oar angles [2, 10]. Other methods based on kinetics are force thresholds, for example a threshold of 20 kgF, which is the preset value in the PowerLine software for sculling. However, 30% of the maximal force has also been proposed as a threshold [46], and in another study 15 N of blade force is used [47]. A third method uses maximal deceleration for catch and finish identification. In this study, the catch was found by linearizing the force curve between 30% and 70% of the maximal force value. The time instant when the rising force line intersects zero force is the catch. The finish was defined likewise, at the intersection of the falling force line with zero force. This is illustrated in fig. 3.8. This method is comparable to the method of Hill, with the difference that Hill uses the steepest part of the slope to extrapolate [48]. This was deemed too sensitive to small variations during the first part of the drive.



(a) Gate angle graph of a randomly selected stroke.

(b) Speed signal of a randomly selected stroke.

Figure 3.6: Effect of different cutoff frequencies on the filtered signals. It was estimated that the cutoff frequency should be in the range of 1-10 Hz. 2 Hz shows too much deviation of the raw curve and 4 Hz still influences the minimal and maximal values of the speed signal. Higher cutoff frequencies show more or less the same signal. Therefore, a cutoff frequency of 5 Hz has been chosen.

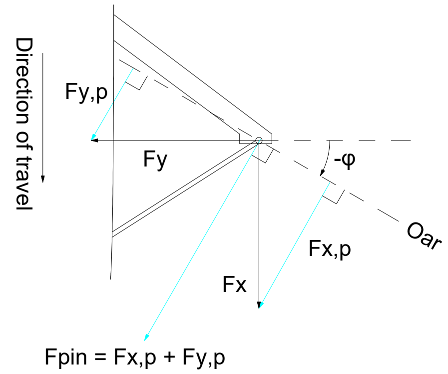


Figure 3.7: F_{pin} was calculated by vector decomposition of F_x and F_y. F_x and F_y are the measured forces at the gate in the boat coordinate system (x being parallel to the boat centerline in the direction of travel, y perpendicular to it and pointing inwards). The measured forces are decomposed to get the parts orthogonal to the oar. These are summed to get F_{pin}. The measured forces are presented in black, the derived components in cyan. The mathematical derivation is given in eq. (3.2).

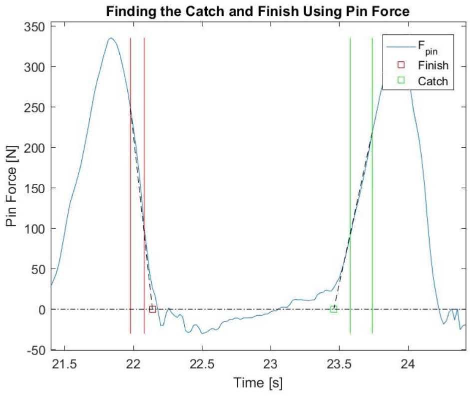


Figure 3.8: The catches and finishes were identified by linearization of the pin force signal, between the 30% and 70% of the maximal force of the closest peak. The zero-crossing of these lines is where the catch or finish lies. This figure shows a random piece of pin force signal, and visualizes how the finish was found for the first stroke in the time frame, and the catch for the consecutive stroke

3.3. Quantifying synchronization and performance

Crew synchronization and performance were quantified for each stroke. This way, each stroke was rated using several methods.these ratings form the variables between which relations may be found. In this section, the performance measures are explained first. They elaborate the basic mechanics and energetics in rowing and are divided in primary and secondary measures. Secondly, the synchronization measures are defined. The synchronization measures translate the instant when certain a certain characteristic occurs in the kinematics, kinetics and energetics of a rower, to a score for how well the crew is rowing together.

Performance measures

In sections 2.1 and 2.2 the methods to describe or quantify performance that have been used in the past were discussed. The proposed approaches were speed and efficiency: Blade Efficiency, Velocity Efficiency and Net Efficiency. These variables were defined by Hofmijster to rate performance of a rower not just by power output, but also by effectiveness of the power supplied [26].

In fig. 3.9, the used approach is elaborated in a visual way. Each stroke is analyzed by measuring energy input to the system and tracing back where it goes to, so called 'energy consumers'. The energy input and the speed are the primary performance measures as they are raw performance and effort. The energy consumers are the secondary performance measures, as they explain what happens between input and output. The energy supplied to the system (boat and crew) is equal to the work generated by the athletes. The system dissipates energy at the blades, because the blades do not stand still in the water, and along the shell where drag is applied. Drag is considered to be viscous and caused by the friction of the water that moves along the hull. Air drag is considered negligible at these speeds, plus, wind speed and direction during the measurements were not known.

The amount of energy lost to drag during a stroke is more when the speed is not constant versus when the speed is constantly the corresponding average. Therefore, drag can be subdivided into two parts, of which the second part is the amount of additional Velocity Fluctuation Losses. Using Velocity Fluctuation Losses, Blade Losses and Work per Stroke, the three efficiencies defined by Hofmijster can be calculated [26]. In the next paragraphs, the mathematical derivations of all performance measures are elaborated.

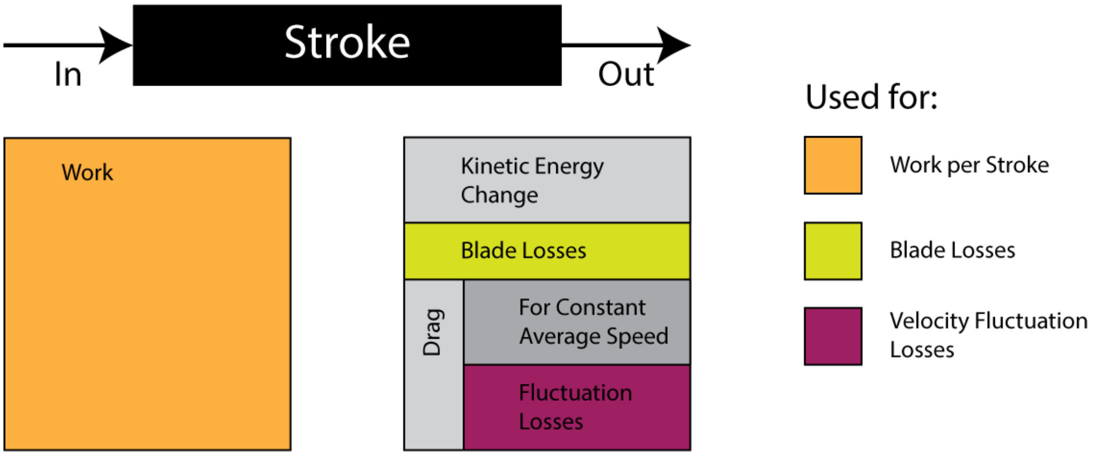


Figure 3.9: During a stroke, energy is added to the system (boat and crew), and energy is dissipated. This visual shows the components that add energy to the system, and the components where this energy goes to, the so called 'energy consumers'. The energy that goes into the system is provided by the rowers as work. The energy output of the system consist of work exerted by the blade onto the water, and drag on the hull. The amount of energy that is not dissipated contributes to the kinetic energy of the system. In case of a constant average velocity over different strokes, this is zero. The net amount of kinetic energy of the system determines the average speed during a stroke (which is performance measure 'Average Speed').
The drag on the boat can be subdivided into the drag losses that would be when the speed was constant, and the additional energy that is dissipated because the speed is not constant. The amount of input work is used as performance measure 'Work per Stroke', the amount of Blade Losses is performance measure 'Blade Losses' and the energy lost to drag because of the non-constant speed is equal to performance measure 'Velocity Fluctuation Losses'. The ratios of these last two measures with Work per Stroke form the efficiencies, which are the last three performance measures.

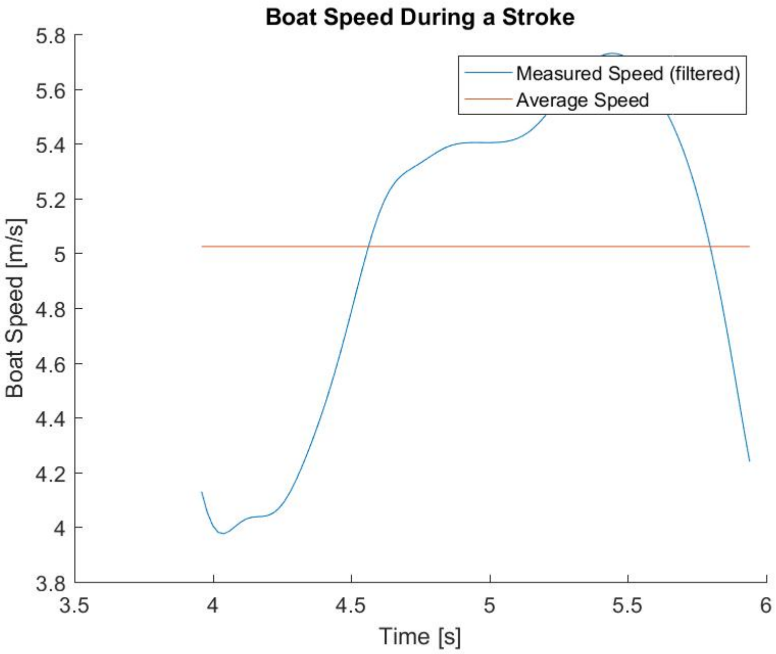


Figure 3.10: This figure shows the speed signal during a stroke, and the average during that stroke. The speed fluctuates during one stroke between 4 and 5.7 m/s. In order to compare performance of different strokes, the Average Speed per stroke was used.

Average Speed The average boat speed is the most straight forward method to measure performance, as the goal of rowing is to cross the finish before your opponents. Speed is, however, strongly influenced by wind and water temperature etc. so it's not a very strong measure to compare runs held on different days. Data samples were recorded at consistent intervals, so Average Speed was calculated by taking the mean of all boat speed samples during the stroke, like stated in eq. (3.3). Boat speed and the corresponding Average Speed of one stroke are shown in fig. 3.10

$$\bar{\dot{x}} = \frac{\sum_{i=1}^{N_{samples}} \dot{x}_i}{N_{samples}} \tag{3.3}$$

Work per Stroke In section 2.4 it was noted that the commonly used method to derive power is incomplete. Hofmijster et al. [34] notes that there is the common proxy, used to determine up to 90% of the total work, and but that it lacks a residual power term generated by the force on the stretcher. Calculation of the residual work requires either the stretcher forces or the acceleration of the center of mass of the rower. Unfortunately, neither of these were measured in the available data set, so this study uses the common proxy.

The dynamics of the oar are now derived, so the Work per Stroke for the crew can be calculated. The common proxy describes the handle power based on pin force and oar angle. The first step to go from these signals to a power signal, is the Free Body Diagram (FBD). The FBD of the oar is presented in fig. 3.11. Using the FBD, the Equations Of Motion (EOM) of the oar were derived in eqs. (3.4) and (3.5).

$$\sum F_{x'} = F_{pin} - F_{handle} - F_{blade} = m_{oar} \cdot \ddot{x}'_{m,oar} \tag{3.4}$$

$$\sum M_{oar} = F_{handle} \cdot R_{inboard} - F_{blade} \cdot R_{outboard} = I_{gate} \cdot \ddot{\phi} \tag{3.5}$$

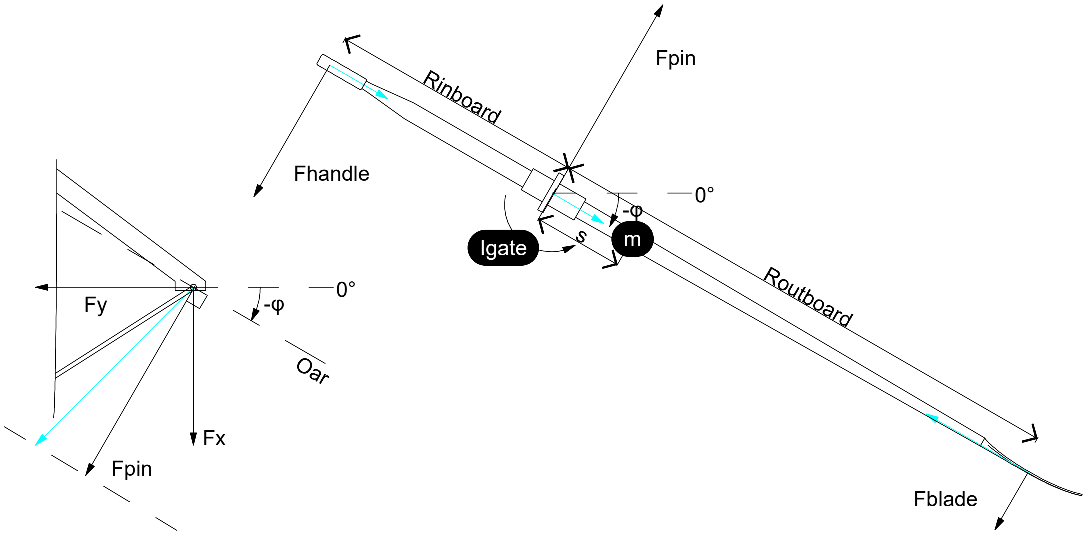


Figure 3.11: In this figure the Free Body Diagram (FBD) of the oar and a schematic of the reaction forces on the gate are presented. The forces depicted in black are of interest. The forces in cyan were neglected, because axial oar forces could not be measured. Using the FBD, the Equations Of Motion (EOM) were derived. These are presented in eqs. (3.4) and (3.5).

The EOM are two equations with two unknowns: F_{blade} and F_{handle}. The equation for forces in the y'-direction is missing because, unfortunately, there is not enough information to derive them. The axial component of the blade force is necessary to estimate the Blade Losses correctly. This subject is further discussed in the paragraph on Blade Losses.

$$F_{handle} = \frac{F_{pin} \cdot R_{outboard} + I_{gate} \cdot \ddot{\phi} - R_{outboard} \cdot m_{oar} \cdot \ddot{x}'_{m,oar}}{R_{inboard} + R_{outboard}} \tag{3.6}$$

By combining the EOM, the unknowns were described as function of the known parameters. The formula for unknown F_{handle} is presented in eq. (3.6). This formula was further simplified using the following assumption: $\ddot{x}'_{m,oar}$ is dependent of $\ddot{\phi}$ and s, and s is zero. Because of the tapered construction of the oar, its center of mass lies close to the gate. The oars used in the trials were not known, so the exact value of s was not known. Combined with the fact that its contribution is minor, s and thus $\ddot{x}'_{m,oar}$ too were neglected. This led to eq. (3.7) for the handle force during the drive.

The oar forces times the inboard radius is the moment of the handle around the oar, eq. (3.10). The handle moment multiplied with the rotational velocity of the oar is the handle power, eq. (3.11). Integration of power over the drive gave the work of each oar, and summing these values gave the total of the generated propulsive work by the crew for that stroke eq. (3.12).

The second part of the stroke, the recover, was not used in the calculation of work. Because the recover power was used in fig. 3.1, the handle force during the recover are still given: In this situation the blade is not submerged and therefore there is the additional assumption that there is no force on the blade ($F_{blade} = 0$). So, eq. (3.4) was changed to eq. (3.8) and eq. (3.5) to eq. (3.9). It was already noted in fig. 3.1 that eqs. (3.8) and (3.9) may not completely comply with each other. All assumptions concerning the recover will now be discussed.

$$F_{handle,drive}(t) = \frac{F_{pin}(t) \cdot R_{outboard} + I_{gate} \cdot \ddot{\phi}(t)}{R_{inboard} + R_{outboard}} \ \forall \ t \in drive \tag{3.7}$$

$$F_{handle,recover}(t) = F_{pin}(t) \ \forall \ t \in recover \tag{3.8}$$

Figure 3.12: Handle force and power were derived for the drive, using eqs. (3.7) and (3.10) to (3.12). The work during the drive is the integral of power during the drive, visualized as the surface below the power curve.

$$F_{handle,recover}(t) \cdot R_{inboard} = I_{gate} \cdot \ddot{\phi}(t) \;\forall\; t \in recover \tag{3.9}$$

It was explicitly chosen to use only the work during the drive. This choice is based on the assumption that the center of mass of the oar lies at the gate. Under this assumption the state of the oar is exactly the same in the finish as in the catch: it has zero rotational kinetic energy. Although this is of course a rough assumption, it eases calculations a lot. Because of the limited weight of an oar, most studies neglect them completely. In the case that oars would be realistically incorporated, the motion of the oars mass would introduce a similar power term as the residual power term of the rower: the oar mass multiplied with its acceleration and the boat speed.

An additional term that was neglected by excluding the drive phase was mentioned with fig. 3.1: air drag acts on the oar and blade. This is also neglected for now, as it goes way too much in to detail compared to the quite severe assumptions that have already been done.

Summarizing these paragraphs, quite some factors influence the work applied during the recover. Because of the relatively low impact of this on the results, and the additional complexity, these factors were neglected. Because of this, the state of the oar is the same in the catch as in the finish, and thus the recover is excluded from the power calculation.

$$M_{handle}(t) = F_{handle}(t) \cdot R_{inboard} \tag{3.10}$$

$$P_{handle}(t) = M_{handle}(t) \cdot \dot{\phi}(t) \tag{3.11}$$

$$W_{stroke} = \sum_{n=1}^{N_{oars}} \left(\int_{drive} P_{handle,n}(t)\,\mathrm{d}t \right) \tag{3.12}$$

Blade Losses The energy losses at the blades are the work that was performed by the blades, so they are dependent on the blade force and the movement of the blade through the water. Blade force was assumed to be always perpendicular to the oar. The axial component was neglected because it could not be measured. The systematic error that is introduced by this was found to be approximately 18%, but is generally accepted because there is no practical way of measuring it [47].

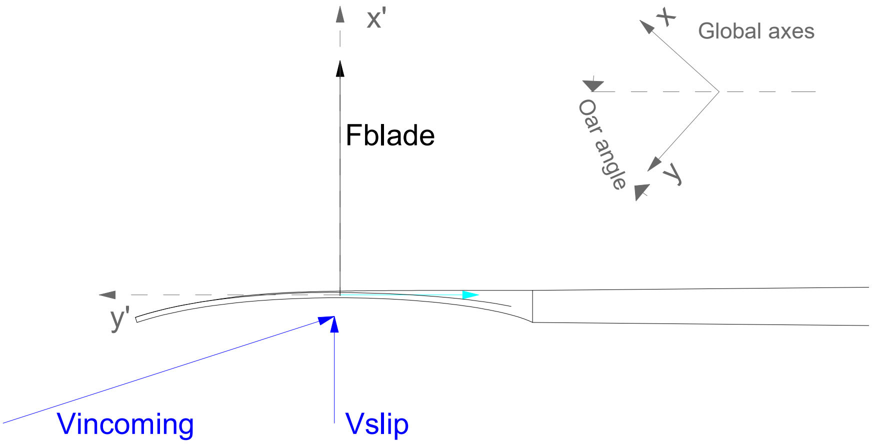


Figure 3.13: Blade slip: when the blade is moved through the water, there is some incoming velocity (Vincoming) under some angle. The component perpendicular to the oar is called Vslip in the schematic, and $\dot{x}'_{blade}$ in eq. (3.13). Forces in line with the blade (cyan) cannot be measured or derived and are thus neglected. This leads to a systematic error [47], but is accepted in most studies. Blade Losses are the product of the blade force and the blade slip, see eq. (3.15).

To determine the Blade Losses, a secondary set of axes was defined with its origin in the point of blade force application, the x'-axis perpendicular to the blade and the y'-axis along the shaft of the oar. The speed of the water moving along the blade, perpendicular to the oar shaft, was defined as $\dot{x}'_{blade}$. See eq. (3.13). A visual representation is given in fig. 3.13. Blade force was the resultant from the pin force and handle force, see eq. (3.4), leading to eq. (3.14). From the blade force and motion, the Blade Losses were derived in eqs. (3.15) and (3.16). An example of the power lost on the blades during the drive is presented in fig. 3.14. The profile of the curve is somewhat similar to the force curve of fig. 3.12.

$$\dot{x}'_{blade}(t) = R_{outboard} \cdot \dot{\phi}(t) - \dot{x}(t) \cdot \cos\phi(t) \tag{3.13}$$

$$F_{blade} = F_{pin}(t) - F_{handle}(t) \tag{3.14}$$

$$W_{blade} = \int_{stroke} \dot{x}'_{blade}(t) \cdot F_{blade}(t)\,\mathrm{d}t \tag{3.15}$$

$$W_{blades} = \sum_{n=1}^{N_{oars}} W_{blade,n} \tag{3.16}$$

Velocity Fluctuations Losses Velocity Fluctuation Losses are the additional drag losses introduced by the non constant speed during one stroke. Assuming only viscous drag, the drag power loss was some constant k times the speed $\dot{x}$ power three. This led to eq. (3.17) for the energy lost to drag for one stroke. Velocity losses were then defined as the total drag losses minus what would be lost if the speed was constantly the Average Speed of the stroke, see eq. (3.18). This is visualized in fig. 3.15.

$$W_{drag} = \int_{stroke} k \cdot \dot{x}(t)^3\,\mathrm{d}t \tag{3.17}$$

$$W_{velocity} = W_{drag} - k \cdot \dot{\bar{x}}^3 \cdot T_{stroke} \tag{3.18}$$

The value of drag coefficient k had to be found to determine the amount of drag losses correctly. Since it could not be derived beforehand, all drag losses and velocity calculations were done twice. First with an additional assumption, and afterwards with the found k-value.

The additional assumption was that the work generated during the stroke is equal to the sum of the Blade Losses and the kinetic energy difference. The change of total kinetic energy of the system was

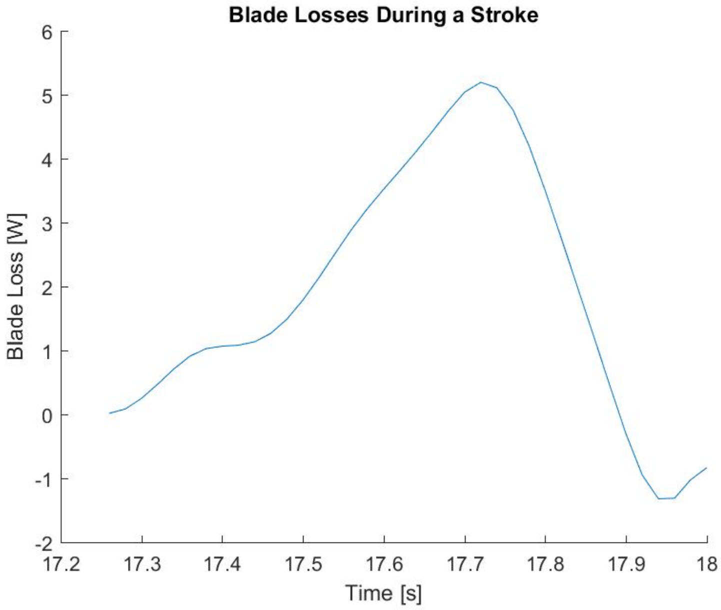


Figure 3.14: The power lost on by the blades moving through the water was calculated using eqs. (3.13), (3.15) and (3.16). In this graph an example of the Blade Losses during the drive for one rower (port and starboard blade) is plotted. The profile looks a lot like the force profile, suggesting that the Blade Losses are mainly dependent on the blade force. The curve shows a negative dip at the end. It is not known whether this is because of the assumption of a perfect finish, or because the blade was still in the water when the rower stopped applying force to the handle.

determined using the average velocity during the stroke and the stroke before, see eq. (3.19). Then, W_{drag} is determined as in eq. (3.20). Combined with eq. (3.17), k was calculated for each stroke. After each trial, the median of the k-values for the strokes was picked as the 'true' drag coefficient. The median is used instead of the mean, because it is less sensitive to single sided outliers, which were observed.

$$\Delta E_{kin,system,s} = \frac{1}{2}\left(m_{boat} + N_{oars} \cdot m_{oar} + N_{rowers} \cdot m_{rower}\right)\left(\dot{\bar{x}}_s^2 - \dot{\bar{x}}_{s-1}^2\right) \forall N_{oars} = 8,\ N_{rowers} = 4 \tag{3.19}$$

$$W_{drag} = W_{stroke} - W_{blades} - \Delta E_{kin,system} \tag{3.20}$$

Blade Efficiency Blade Efficiency is also called propelling efficiency [26], and is the ratio between the energy not lost on the blades and the total work of the stroke. This was calculated according to eq. (3.21)

$$\eta_{blade} = 1 - \frac{W_{blades}}{W_{stroke}} \tag{3.21}$$

Velocity Efficiency This is the ratio of energy not wasted on velocity fluctuations over the total work applied by the rowers during that stroke. Velocity Efficiency was calculated as in eq. (3.22).

$$\eta_{velocity} = 1 - \frac{W_{velocity}}{W_{stroke}} \tag{3.22}$$

Net Efficiency Net Efficiency eq. (3.23) was defined as the ratio of energy neither lost at the blades, nor wasted by the fluctuating speed of the hull, versus the total work of the stroke. This means it is a combination of equations 3.21 and 3.22.

$$\eta_{net} = 1 - \frac{\left(W_{blades} + W_{velocity}\right)}{W_{stroke}} \tag{3.23}$$

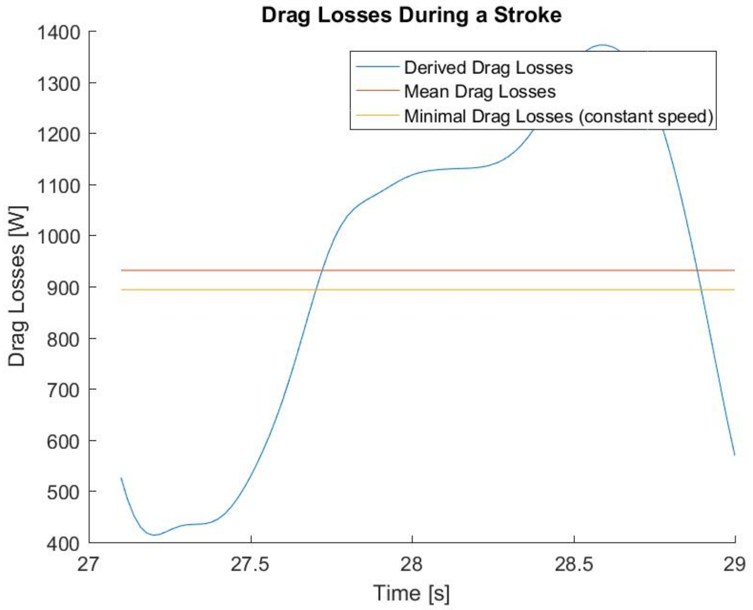


Figure 3.15: The drag losses were calculated using eq. (3.17). The power lost to drag during a stroke is plotted (blue), and its average was calculated (red). Because drag is linear with speed to the power three, total energy lost to drag would be less if the speed was constant. This drag loss for a constant speed is presented in yellow.

Synchronization measures

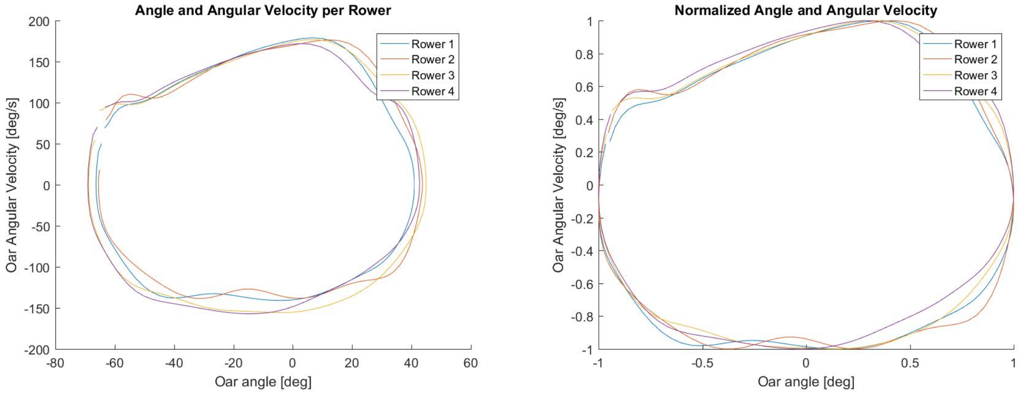
In this part, the measures of crew synchronization are elaborated. For each stroke of each rower, a set of timing characteristics were defined. How well these characteristics correspond between the rowers says how well the they were synchronized. In section 2.6, methods were proposed in the fields of kinematics and kinetics. Several methods have been piloted and are listed in appendix A. In the end, three time-characteristics were picked. These are the phase of the oar motion, the time instant when half of the impulse has been delivered and the time instant when half of the work has been generated. Their respective standard deviations are the variables used for analysis, the so called synchronization measures. These measures will further be elaborated in the paragraphs hereafter.

Mean Standard Deviation of the Phase Because rowing is a constantly repeating motion, one could recognize it as a wave with corresponding characteristics, such as phase. In fig. 3.16a, the oar angle velocities (port and starboard averaged, eqs. (3.24) and (3.25)) are plotted against the oar angles (again, port and starboard averaged). It can be noticed that it looks somewhat like a circle. In case the oar angle is a perfect sine wave with a constant frequency, the figure would indeed be a perfect circle around the origin.

Phase is defined as the angle around the origin between the horizontal (zero velocity) axis and a certain point on the circle. In the case of the sine wave with constant frequency, the phase changes at a constant rate from 180° to +180°. If this was to be plotted, it would mean that a straight line at a certain slope was drawn.

To apply this theory to the rowing motion, the oar angles and angular velocities must first be normalized. The angles were normalized using the segment. The segment is the maximal angle minus minimal angle. The angular velocities were normalized by their range. Both variables were then shifted to put the origin halfway their minimal and maximal values. Refer to eqs. (3.26) and (3.27) for the mathematical notation of this procedure. The outcome of applying the procedure to the data from fig. 3.16a is presented in fig. 3.16b.

The phase is then defined as the four quadrant inverse tangent of the angular velocity and the gate angle, see eq. (3.28). This gives a phase angle from -180° to +180° at each sample. At all time instants during the stroke, the standard deviation was calculated over the rower phases, eq. (3.29). Finally these were averaged over the entire stroke, to find the Mean Standard Deviation of the Phase eq. (3.30).



(a) Gate angle (average of port and starboard) versus angular velocity of the gate of a random stroke. The shape is somewhat circular, suggesting the rotating motion is cyclic. At what point of the stroke a rower is at a certain time, can be described with phase. Phase divides the motion into 360 degrees. To calculate phase, the angle and angular velocity need to be normalized, see fig. 3.16b.

(b) This figure shows the normalized gate angle and normalized angular velocity of the gates (again, port and starboard averaged). The limit and the domain no go from -1 to +1, and are dimensionless. These curves were obtained by normalizing the data from fig. 3.16a, using eqs. (3.26) and (3.27).

Figure 3.16: These figures show the gate angle and angular velocity of the gate (port and starboard averaged per rower), in their normal form and the normalized form. Normalization is performed in order to calculate the phase of the cyclic motion of the oar.

$$\bar{\phi}_{rower}(t) = \frac{\phi_{starboard}(t) + \phi_{port}(t)}{2} \tag{3.24}$$

$$\dot{\bar{\phi}}_{rower}(t) = \frac{\dot{\phi}_{starboard}(t) + \dot{\phi}_{port}(t)}{2} \tag{3.25}$$

$$\hat{\phi}(t) = \frac{\phi(t) - 0.5\left(\phi_{rower,max} + \phi_{rower,min}\right)}{0.5\left(\phi_{rower,max} - \phi_{rower,min}\right)} \tag{3.26}$$

$$\hat{\dot{\phi}}(t) = \frac{\dot{\phi}(t) - 0.5\left(\dot{\phi}_{rower,max} + \dot{\phi}_{rower,min}\right)}{0.5\left(\dot{\phi}_{rower,max} - \dot{\phi}_{rower,min}\right)} \tag{3.27}$$

$$\Phi_{rower}(t) = \arctan 2\left(\hat{\dot{\phi}}(t),\ \hat{\phi}(t)\right) \tag{3.28}$$

$$\sigma_{phase}(t) = \sqrt{\frac{\sum_{n=1}^{N_{rowers}} \left(\Phi_{rower,n}(t) - \mu_{\bar{\Phi}}(t)\right)^2}{N_{rowers}}} \tag{3.29}$$

$$\bar{\sigma}_{phase} = \text{mean}\left(\sigma_{phase}(t)\right)\ \forall\ t \in stroke \tag{3.30}$$

Standard Deviation of the Time to Half Impulse Time to Half Impulse is determined by splitting the surface under the force-time curve in half. This is one of the methods to describe force curves used by Hill [7], see fig. 2.3. Impulse is the integral of force over time. The blade force from eq. (3.14) was used as the force to integrate. Impulse over time during the stroke is calculated in eq. (3.31). In reality, time was discrete and therefore this function too, so trapezoidal integration was used. The rule for retrieving the time instant at which half of the impulse was applied is stated in eq. (3.32). This was implemented using linear interpolation. An example of a blade force curve and the corresponding time to half impulse is plotted in fig. 3.17. Finally, the standard deviation of these time instants for the entire crew was taken eq. (3.33).

$$J_{rower}(t_n) = \int_{catch}^{t_n} \left(F_{blade,starboard}(t) + F_{blade,port}(t)\right) \mathrm{d}t \; \forall \; t_n \in stroke \tag{3.31}$$

$$T_{J50,rower} = t_n \; \forall \; J_{rower}(t_n) = \frac{J_{rower,drive}}{2} \tag{3.32}$$

$$\sigma_{T_{J50}} = \sqrt{\frac{\sum_{n=1}^{N_{rowers}} \left(T_{J50,rower,n} - \mu_{T_{J50}}\right)^2}{N_{rowers}}} \tag{3.33}$$

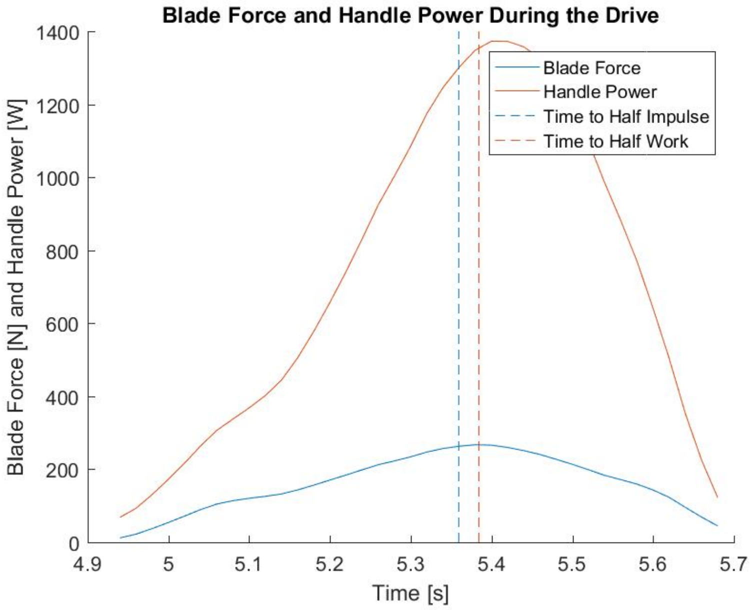


Figure 3.17: For a random stroke, blade force and handle power are plotted during the drive. These signals were used to determine the time instant at which half of the work and half of the impulse had been applied. The standard deviations of these time instants for the entire crew are used to rate the synchrony.

Standard Deviation of the Time to Half Work The equation for work was presented in eq. (3.12). Since the work was requested per athlete, N_{oars} = 2: the power of the starboard and port side oar of the rower were summed. Time to half work was defined as the time when half the work by the rower during the drive was delivered. To find this moment, eq. (3.34) was introduced.

The calculation are similar to the time to half impulse. Trapezoidal integration was used to find work, eq. (3.34). In eq. (3.35) the rule is stated for determining the value of $T_{W50,rower}$. It was found using linear interpolation in the work over time function, eq. (3.34). This time instant is illustrated in fig. 3.17. Standard deviation of these values for all four athletes was calculated as the measure of synchrony eq. (3.36).

Note that in these calculations the power signal according to the common proxy was used, and not the complete power signal as proposed by Hofmijster et al. [34].

$$W_{rower}(t_n) = \int_{catch}^{t_n} \left(P_{handle,starboard}(t) + P_{handle,port}(t)\right) \mathrm{d}t \; \forall \; t_n \in stroke \tag{3.34}$$

$$T_{W50,rower} = t_n \; \forall \; W_{rower}(t_n) = \frac{W_{rower,drive}}{2} \tag{3.35}$$

$$\sigma_{T_{W50}} = \sqrt{\frac{\sum_{n=1}^{N_{rowers}} \left(T_{W50,rower,n} - \mu_{T_{W50}}\right)^2}{N_{rowers}}} \tag{3.36}$$

3.4. Reliability and significance

The output of any analysis is influenced by the assumptions that were made, and so it is in this analysis. Some assumptions introduce systematical errors and some random. For one, this study relied heavily on existing data, but how the conditions were at that time was not known in detail. Neither was it known when the stated rower weights were measured, and how accurate they were during the trial period. Another systematical error was introduced by not knowing exactly which oars were used and having to derive their properties from the results. Other sources of error include the catch finding method (and assuming an instant blade entry and removal), neglecting axial oar forces in the calculation of Blade Losses, assumptions made for calculating power during the recovery (e.g. air drag on the oar and whether kinetic energy is returned or dissipated) and the drag coefficient of the boat.

Many of the mentioned sources of error are either small and accepted in previous studies, or not possible to measure with the current state of the art. For two matters a method was found to quantify the errors, these will be explained in this section.

The final part of this section will discuss the method to obtain the significance of the results. Since this study is set up to find correlations between synchrony and performance, the critical value of Pearson's r was determined.

Drag coefficient of the boat

As explained in section 3.3, in the paragraph on Velocity Fluctuation Losses, the drag coefficient of the boat was assumed to be a constant. The median was taken of all the values resulting from the initial drag losses estimation. Thus, for each trial there was one value for the drag coefficient. This value varied between trials, because of the wind and other weather conditions, e.g. water temperature. How much the value varied was taken into consideration to determine whether or not the speeds, and to a certain extend the dynamics, in the different trials were comparable.

Energy balance

The method to calculate Work per Stroke was explained in section 3.3. Consecutively, the losses were calculated from the kinetics and kinematics of the boat and oars. In reality, the sum of all losses (blade and drag) plus the change in overall kinetic energy of the system should be equal to the work generated to propel the system. A number of assumptions and simplifications were made in the mathematical derivation of the losses and the work supplied, which led to under- and overestimation of different energy components. This in turn leads to different amounts of energy on both sides of the energy balance. This imbalance was called the energy error, E_{error}. The value of this energy error for a stroke is an indication of a wrong amount energy being assigned to the individual components.

A low energy error may be the results of one component being overestimated and another underestimated by the same amount, because the individual errors are not exactly known. So the actual errors for each component might balance each other out. This means there is some ambiguity in the name-giving. The reason for naming it an error is that it refers to the fact that there is an error in the calculations.

The amount of work generated during one stroke was derived in eq. (3.12), the magnitude of the Blade Losses in eq. (3.16) and the amount of energy lost to drag in eq. (3.17). The change of total kinetic energy was determined in eq. (3.19). These losses were summed and subtracted from the stroke work in eq. (3.37). This resulted in the energy error for each stroke. To judge the validity of the assumptions for each trial, the root mean square energy error (RMSE) was calculated, eq. (3.38). The energy error was also expressed as a percentage of the work generated during the stroke, and of these values the root mean square was calculated too, eq. (3.39).

$$E_{error} = W_{stroke} - W_{blades} - W_{drag} - \Delta E_{kin,system} \tag{3.37}$$

$$E_{RMSE} = \sqrt{\frac{\sum_{n=1}^{N_{strokes}} E_{error,n}^{2}}{N_{strokes}}} \tag{3.38}$$

$$r_{E_{RMSE}} = \sqrt{\frac{\sum_{n=1}^{N_{strokes}} \left(\frac{E_{error,n}}{W_{stroke,n}}\right)^2}{N_{strokes}}} \cdot 100\% \tag{3.39}$$

Significance

To find links between the proposed variables, correlations were calculated based on Pearson's r. A students-t distribution was assumed, of r could be calculated using eq. (3.40). Since the sample size (n) was 124 strokes, the critical T-value is 1.658 for a 95% confidence interval and a one-sided test. A one sided test is applicable because the sign of the correlation is prescribed in the hypothesis.

Entering these values into eq. (3.40) gives a critical r of 0.152. This is the minimal value, so all positive correlations above 0.152, and all negative correlations below -0.152 are significant on $p<0.05$.

Because multiple comparisons were made in this study, one could argue that the chance of false positives increases and that the confidence interval should be corrected for this. The compared variables are, however, far from independent. The study aims to explore the methods for quantifying the effect of the crew synchronization on the performance and to propose the best. Therefore, no correction was made.

$$r = \frac{T}{\sqrt{n - 2 + T^2}} \tag{3.40}$$

4

Results

This chapter presents the results from the data analysis as performed in chapter 3. The data of all eight recorded trials has been analyzed, and was combined to find correlations. First of all, properties of the trials are presented to see whether is is legitimate to use all trials. Also the ranges of all variables are given to get an idea of the values of the performance and synchronization measures. Next, the correlations within the synchronization measures (section 4.2) were calculated to evaluate how independent they were with respect to each other. Third, significant correlations between synchronization and performance were found and they are presented in section 4.3. Finally, correlations within performance measures were analyzed to see which performance aspects relate to each other (section 4.4) and whether these are expected.

Table 4.1: Number of registered strokes, mean absolute energy error, percentual error and drag coefficient for each trial. There is around 5% of energy error in each trial, and the drag coefficient fluctuates around 6.4. Although there was some variation, it can be stated that the trials were overall similar enough to combine.

Trial	# Strokes [-]	E_{RMSE} [J]	$r_{E_{RMSE}}$ [%]	k [-]
T30 C1	14	113	5.29	6.40
T30 C2	17	105	5.09	6.39
T30 C3	17	121	5.56	6.48
T30 C4	17	93.5	4.31	6.16
T32 C1	14	130	6.16	6.42
T32 C2	17	105	5.15	6.56
T32 C3	14	78.2	3.59	6.70
T32 C4	14	97.3	4.40	6.41

4.1. Details of trials and strokes

In section 3.4, a number of methods were proposed to compare reliability of trials and whether the conditions were similar. These details on the trials are presented in table 4.1. By coincidence, each trial consisted of 14 or 17 recorded strokes. For each trial, the E_{RMSE} was around 100 Joule, or about 5% of the work generated during each stroke. The estimated drag coefficients were around 6.4.

In four of the trials the assigned pace was higher than the other four. This is denoted by the T30 or T32 leading the name of the trial, referring to a target pace of 30 or 32 strokes per minute (SPM). The second part of the names indicates the crew composition. Although the assigned pace differed, there was no clear indication that strokes in the 32 SPM trials differed much from the 30 SPM strokes. This judgment was made based on the scatter plots later in this chapter. Because of this, the strokes from all trials were combined into one large data set of 124 strokes, leading to a critical r-value of 0.152 for a significance level of p<0.05.

The performance measures and synchronization measures, derived in section 3.3, were calculated for all strokes. The ranges, averages and standard deviations of all these measures are tabulated in table 4.2 to get a proper overview of the order of magnitude of the calculated variables. The primary

Table 4.2: The ranges, average value and the standard deviations over all strokes for the performance measures and the synchronization measures.

Performance Measure	Minimal Value	Maximal Value	Average	Standard Deviation
Average Speed [m/s]	4.883	5.436	5.127	0.1304
Work per Stroke [J]	1931	2252	2116	65.4
Blade Losses [J]	210.1	428.9	328.6	43.89
Velocity Fluctuation Losses [J]	48.51	99.89	74.42	11.77
Net Efficiency [%]	74.61	86.60	80.96	2.251
Blade Efficiency [%]	79.17	89.12	84.48	1.97
Velocity Efficiency [%]	95.17	97.58	96.48	0.5738

Synchronization Measure	Minimal Value	Maximal Value	Average	Standard Deviation
Mean SD of the Phase [°]	2.759	5.000	3.683	0.5182
SD of Time to Half Impulse [ms]	3.166	31.98	17.23	6.429
SD of Time to Half Work [ms]	2.012	30.69	16.79	6.154

performance measures (Average Speed and Work per Stroke) could be described as narrow-banded as they show relatively small standard deviation compared to the average value (order of $1/30^{th}$). The losses show a higher relative variation (order of $1/7^{th}$). The efficiencies in turn are in the same relative range as the primary performance measures, due to their nature (the combination of losses with work). The standard deviation of kinematic synchrony is again in the range of $1/7^{th}$ of the average value. And kinetic and energetic synchrony in the range of $1/3^{rd}$ of the average value. These ranges of course only say something about the relative variability of the parameters in this data set. In section 5.1 it will be discussed whether the results correspond with findings from literature. If they do, it is an indication that our results are realistic. If they don't, it must be found out what could be the cause.

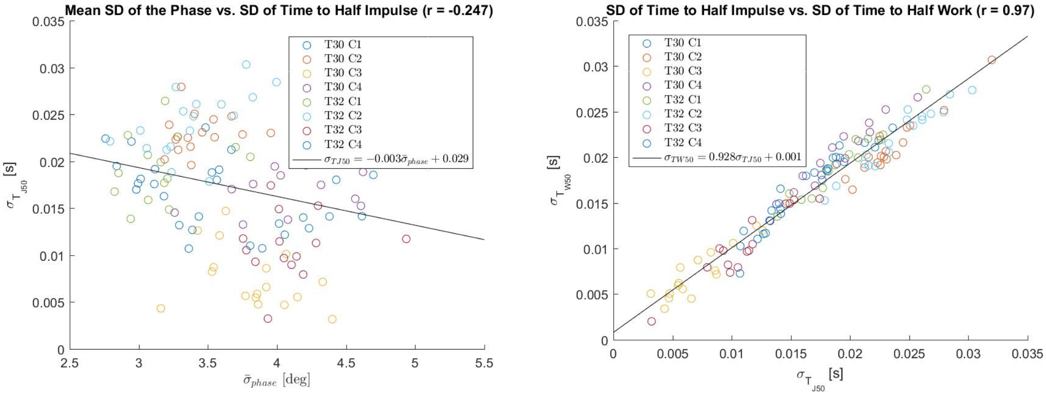
4.2. Independence of synchronization measures

The three synchronization measures were correlated with each other to find out whether the measures were independent, or that they quantify similar effects. These correlations are presented in table 4.3 and are discussed individually in the list below, and the results are plotted in fig. 4.1. Two of the three measures correlated close to perfect, indicating that they are very similar. The implications of the dependence of synchronization measures will be discussed in section 5.4.

- **Mean Standard Deviation of the Phase versus Standard Deviation of the Time to Half Impulse:**
  $r = -0.247$. The kinematic synchronization measure was found to be weakly correlated to the kinetic synchronization measure. The scatter plot is presented in fig. 4.1a.
- **Standard Deviation of the Time to Half Impulse versus Standard Deviation of the Time to Half Work:**
  $r = 0.970$. The very high correlation shows that these measures were practically the same. In fig. 4.1b the scatter plot is given, showing the correlation between the two measures.
- **Mean Standard Deviation of the Phase versus Standard Deviation of the Time to Half Work:**
  $r = -0.161$. There was a significant but low and negative correlation between these measures. This indicates that, just like with time to half impulse, there is no complete independence. The negative sign means that improvements in oar phase synchrony led to a deterioration in synchrony of the time to half work. The scatter plot of the measures for all strokes is presented in fig. 4.1c.

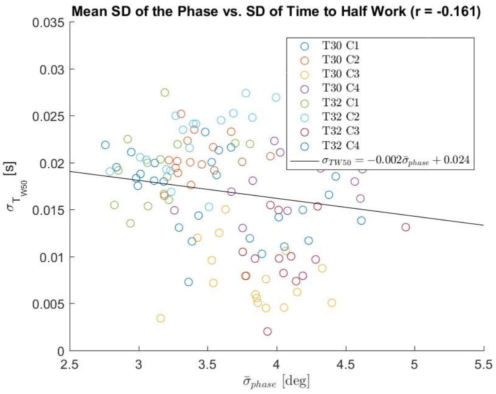
Table 4.3: The calculated Pearson's r for all three combinations within the synchronization measures. The bottom half is not given because the table is symmetrical.

	$\bar{\sigma}_{phase}$	$\sigma_{T_{J50}}$	$\sigma_{T_{W50}}$
$\bar{\sigma}_{phase}$	1	-0.247	-0.161
$\sigma_{T_{J50}}$	-	1	0.970
$\sigma_{T_{W50}}$	-	-	1



(a) This scatter plot shows the weak correlation between Mean Standard Deviation of the Phase and Standard Deviation of the Time to Half Impulse ($r = -0.247$).

(b) This plot shows the correlation between Standard Deviation of the Time to Half Impulse and half work. These measures were found to be almost equal in effect ($r = 0.970$).



(c) In this figure the Mean Standard Deviation of the Phase is plotted against the Standard Deviation of the Time to Half Work for all recorded strokes. Only a weak correlation was found between the two ($r = -0.161$).

Figure 4.1: These figures show the correlations within the synchronization measures, indicating how (in)dependent they actually are.

4.3. Correlation between performance and synchronization

The 7 performance measures were correlated to the 3 synchronization measures as explained in section 3.3. The correlation coefficients for all combinations are presented in table 4.4. The significant or otherwise important results are discussed in more detail.

It was found that the synchronization measures correlate with multiple performance measures: Mean Standard Deviation of the Phase correlates with Average Speed, Work per Stroke, Net Efficiency and Blade Efficiency. Furthermore, significant correlations were found between standard deviation of the force slopes correlates and Velocity Fluctuation Losses and the corresponding efficiency. Finally, Standard Deviation of the Time to Half Work was found to correlate with Average Speed and with Work per Stroke. The found effect was opposite of sign with respect to Mean Standard Deviation of the Phase.

Table 4.4: Pearson's r for all combinations of performance and synchronization measures. Many combinations deliver non significant correlations, and from the significant ($|r| > 0.152, p \leq 0.05$) correlations all but one are weak. Interesting results are the opposite effects between Mean Standard Deviation of the Phase and Standard Deviation of the Time to Half Work, in terms of work generation and speed. Furthermore, more different force slopes correlate with lower Velocity Fluctuation Losses.

	$\bar{\sigma}_{phase}$	σ_{TJ50}	σ_{TW50}
$\dot{x}$	0.387	-0.193	-0.169
W_{stroke}	0.363	-0.574	-0.476
W_{blades}	-0.114	-0.013	0.005
$W_{velocity}$	-0.021	-0.001	-0.008
η_{net}	0.202	-0.134	-0.115
η_{blade}	0.206	-0.124	-0.110
$\eta_{velocity}$	0.087	-0.100	-0.076

Mean Standard Deviation of the Phase

The first synchronization measure to zoom in to is the Mean Standard Deviation of the Phase. All correlations that were found are positive, so work ($r = 0.387$), Average Speed ($r = 0.363$), Blade Efficiency ($r = 0.206$) and Net Efficiency ($r = 0.202$) all increase when the Mean Standard Deviation of the Phase increases. This means that performance increases when kinematic synchrony decreases, which is the opposite effect of what was expected.

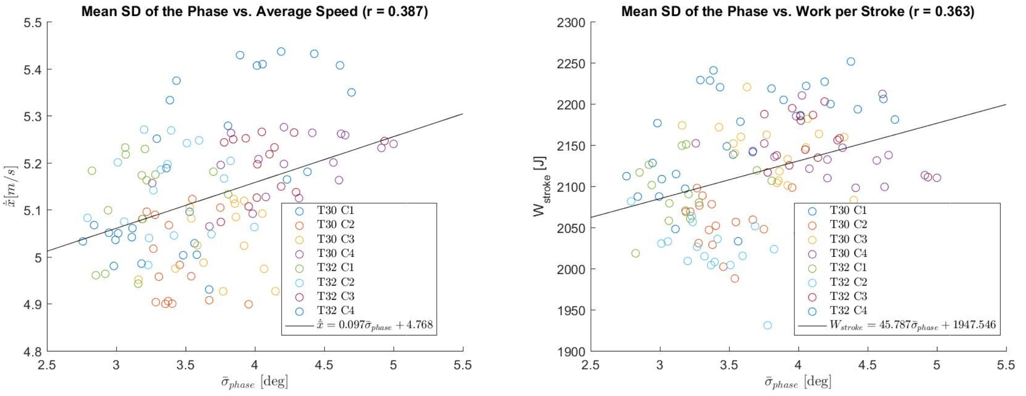
It must be noted that synchronization by phase is the only measure that shows a significant correlation with other performance measures than work and speed. Although the correlations are not very strong (about 0.2), apparently Blade Efficiency and Net Efficiency go hand in hand with less synchronized rower phases.

All found significant correlations are presented in scatter plots in fig. 4.2. In the figures the linear fits have been plotted, to quantify the magnitude of the effect. Two strokes were selected out of these scatter plots. In fig. 4.3, a well synchronized stroke and a lesser one are presented, to visualize the difference between both ends of the phase synchrony spectrum. To get an idea of the actual performance difference in terms of speed: the Average Speed during the less synchronous stroke was 5.24 m/s, versus 4.96 m/s for the more synchronized stroke.

Standard Deviation of the Time to Half Impulse

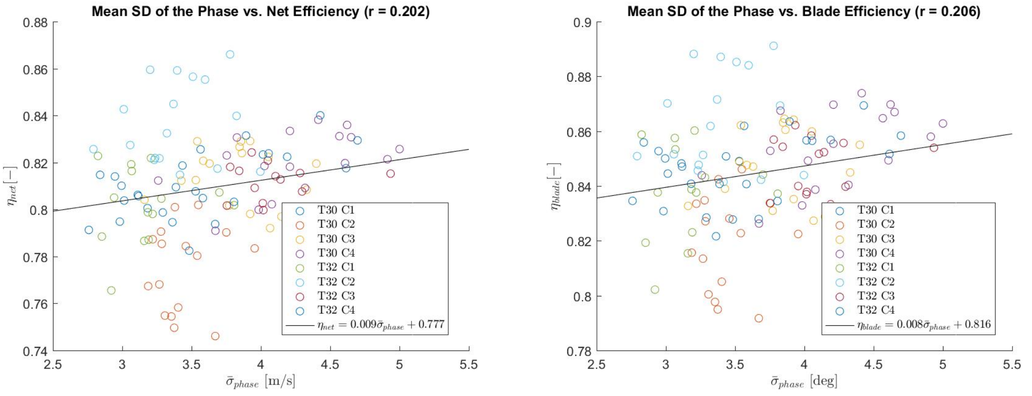
The kinetics based synchronization measure was found to correlate significantly with Average Speed ($r = -0.193$) and Work per Stroke ($r = -0.574$). The negative correlations indicate that the found effect is in line with the idea that better synchronization leads to higher performance. The correlation with Work per Stroke was the highest found correlation in the comparison between all the measures. The found correlation with average boat speed may not be as strong as that of the phase with Average Speed, but it was the strongest result in line with the hypothesis.

From the results, one well synchronized stroke and one lesser synchronized stroke were picked. These two strokes are presented in fig. 4.5. This figure shows that the time to half impulse is a good way to determine in what amount the blade force signals are similar. The Average Speed for the lesser synchronized stroke was 4.88 m/s, versus 5.25 m/s for the better synchronized stroke. Again, these are not outliers in



(a) A deterioration in oar phase synchrony led to a significant increase of speed ($r = 0.387$).

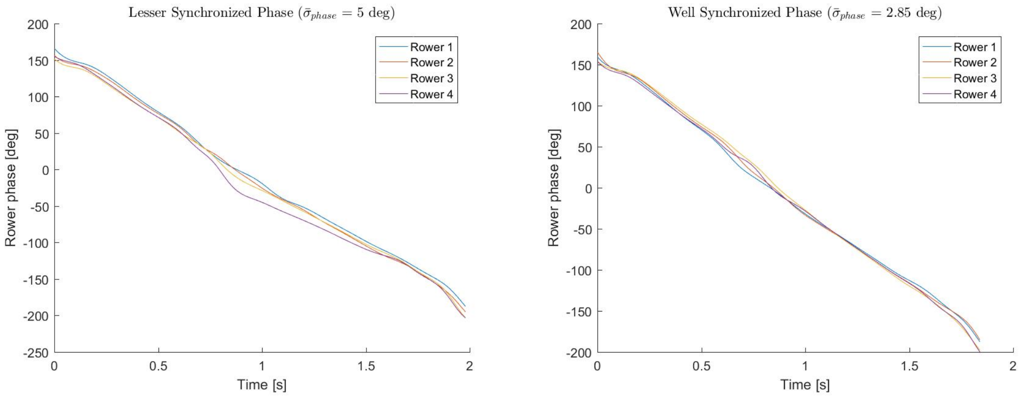
(b) Lesser phase synchronization correlates with a significantly higher Work per Stroke ($r = 0.363$).



(c) Higher phase shifts between rowers correlate with higher Net Efficiency ($r = 0.202$)).

(d) The correlation between standard deviation of force slopes and Blade Efficiency in this figure, shows that less synchronized kinematics correlate with a higher Blade Efficiency ($r = 0.206$).

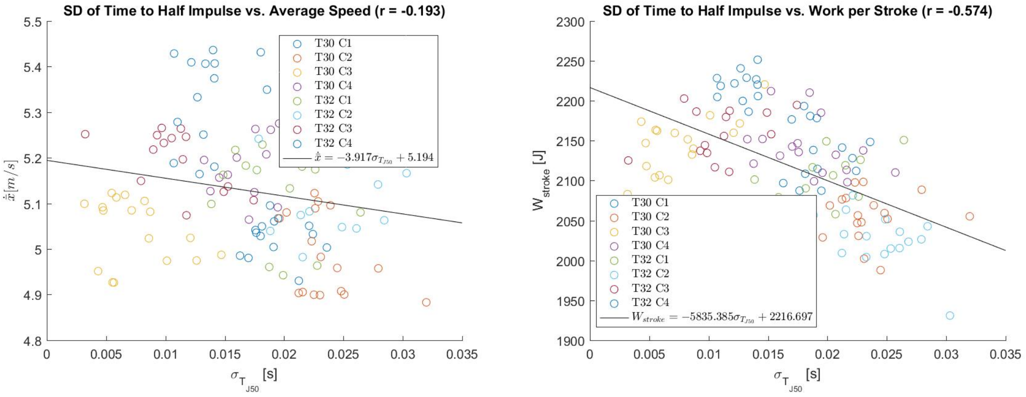
Figure 4.2: Correlations between the mean standard deviation of the rower phases on one hand, and Average Speed, Work per Stroke, Net Efficiency and Blade Efficiency on the other. Improved kinematic synchronization led to decreased performance.



(a) This stroke was selected on the right side of the synchrony spectrum, meaning the Mean Standard Deviation of the Phase was high, about 5 degrees in this case. The Average Speed during this stroke was 4.96 m/s.

(b) This plot shows the phase over time during a well synchronized stroke. The Mean Standard Deviation of the Phase was in this case 2.85 degrees, so about half the magnitude of the stroke in fig. 4.3a. The Average Speed was 5.24 m/s.

Figure 4.3: These plots show the phase over time for each crew member during a well synchronized stroke and during a lesser synchronized stroke. The strokes were selected from the outer ends of the synchronization spectrum in fig. 4.2a, on condition that they were located more or less along the trend line. It is interesting to see that during the lesser synchronized stroke, seat number 4 clearly does not move in phase with rest of the crew during the second half of the recover. The stroke seat seems to lead a bit too fast for the other crew members.



(a) More variation in time to half impulse correlates with lower Average Speed ($r = -0.193$). In contrast to the results from the kinematic synchronization, this correlation is in line with the hypothesis.

(b) In this scatter plot the correlation between Standard Deviation of the Time to Half Impulse and Work per Stroke is presented. It empowers the result in fig. 4.4a, that more synchronous impulse generation matches with better performance ($r = -0.574$). The found correlation was the highest of all results.

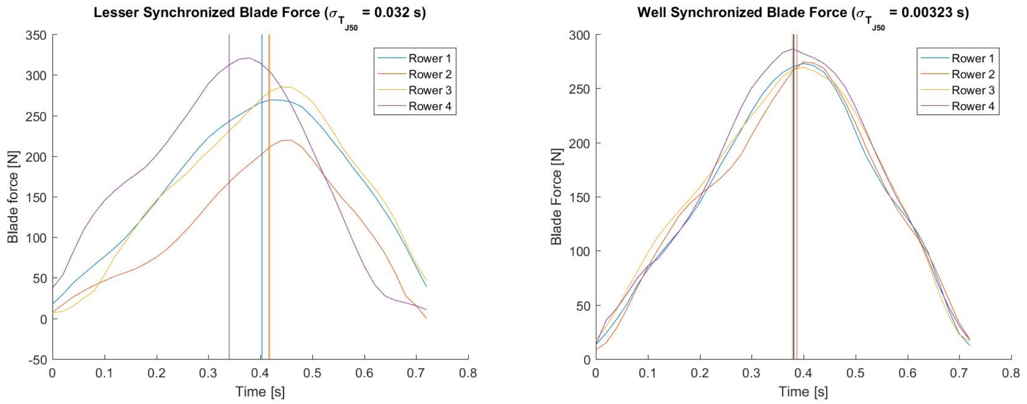
Figure 4.4: Correlations of Standard Deviation of the Time to Half Work with Average Speed and Work per Stroke.

Standard Deviation of the Time to Half Work

The Standard Deviation of the Time to Half Work was found to have significant correlations with average hull speed ($r = -0.169$) and Work per Stroke ($r = -0.476$). The results are very similar to the results with standard deviation time to half work, but less strong. The scatter plots of the significant correlations can be found in fig. 4.6.

The fact that energetic synchrony is so similar to kinetic synchrony may be explained in the following way: Power is force multiplied with velocity, and apparently the velocity terms are very similar for the athletes. More about this dependence of energetics on kinetics and kinematics will be discussed in section 5.4.

The drive phases of two strokes from both ends of the energetic synchronization spectrum are pre-

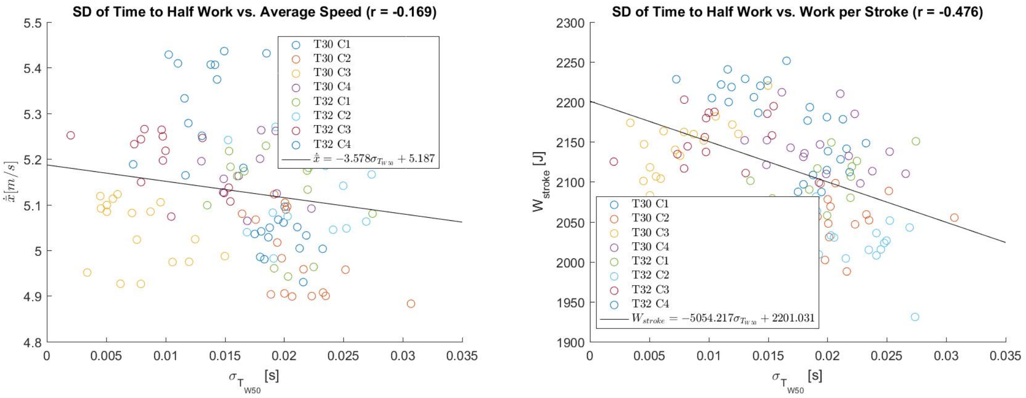


(a) A stroke with a high Standard Deviation of the Time to Half Impulse (about 0.032 s), meaning the synchronization is less good. The blade force curves of the rowers lie apart, just as the vertical lines representing the time to half impulse.

(b) This plot shows the blade force for a better synchronized stroke. Both the curves, as the lines dividing the surface below the curves in half, lie close together.

Figure 4.5: The blade force profiles in a lesser synchronized (fig. 4.5a) stroke are a lot further apart than for a well synchronized stroke (fig. 4.5b). The Standard Deviation of the Time to Half Impulse shows a factor ten improvement between both ends of the synchronization spectrum. The Average Speed during the lesser synchronized stroke was 4.88 m/s, against 5.25 m/s for the well synchronized stroke. Again the stroke seat was quicker than the other crew members.

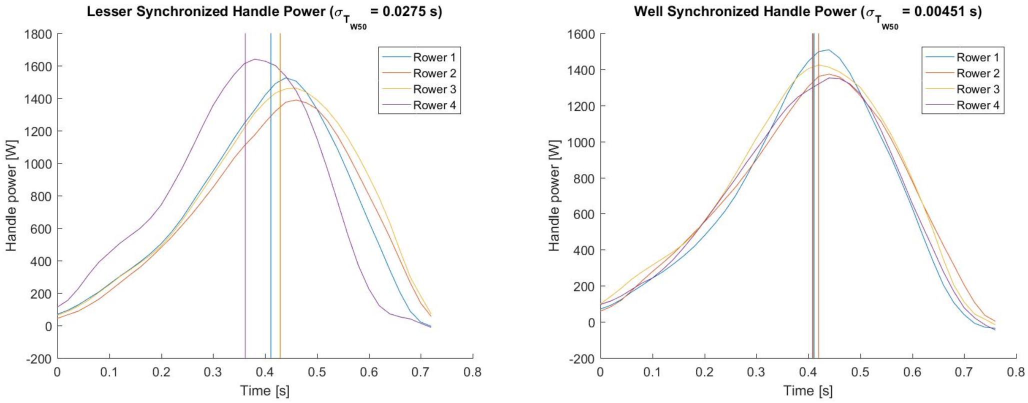
sented in fig. 4.7, like in the previous sections. The Standard Deviation of the Time to Half Work ranges from approximately 0.005 seconds to 0.03 seconds, about a factor 6 difference. The time to half work occurs around 0.4 seconds after the catch, similar to the time of half impulse. Furthermore, the Average Speed was 5.08 m/s for the lesser synchronized stroke and 5.12 m/s for the better synchronized stroke. Clearly this is less distinctive than in the previous synchronization measures.



(a) This scatter plot shows the negative correlation between the variability of time to half work, and the hull speed. The correlation is weak (r < 0.3) but statistically significant on the 95% confidence interval ($r = -0.169$).

(b) The plot shows a significant and moderate negative correlation ($r = -0.476$) between variability of time to half work and Work per Stroke. This suggests a relation between more synchronized energy delivery and the total amount of work delivered per stroke.

Figure 4.6: Correlations of the Standard Deviation of the Time to Half Work with Average Speed and Work per Stroke.



(a) The handle power signals of the crew members during a stroke with a relatively high Standard Deviation of the Time to Half Work. The time to half work instances are again provided as the vertical lines.

(b) This graph shows the power over time for each crew member, during the drive phase of a well synchronized stroke. The time to half work instances all lie around 0.4 seconds after the catch. Both the vertical lines as well as the power signals lie closer together than in fig. 4.7a.

Figure 4.7: These graphs show the power over time for each crew member during the drive of a well synchronized stroke and a lesser synchronized stroke. The strokes were selected from the outer ends of the synchronization spectrum, but not being outliers. The lesser synchronized stroke had an Average Speed of 5.08 m/s, while during the better synchronized stroke the Average Speed was 5.12 m/s. It must be noted that also for this third synchronization measure, the stroke leads before the other crew members.

4.4. Correlations within performance measures

In the final part of this chapter the performance measures will be compared to each other. Since e.g. blade and Velocity Fluctuation Losses were used to calculate their respective efficiencies, some relations are very straight forward. These two losses can be seen as components of the total performance, which going from A to B as quick as possible.

The goal of comparing performance measures was to determine which of the found effects in section 4.3 were coupled. The results can be found in table 4.5. Almost all combinations of performance measures show significant correlations, which means the performance measures are far from independent from each other. Noting the mathematical derivation from section 3.3, this may be no surprise.

The components that couple with speed (first row) are discussed first in this section. Then the couplings with Work per Stroke will be discussed (second row). Finally, the correlations within the secondary performance measures, the losses and efficiencies, are discussed.

Table 4.5: Pearson's r for all combinations within the performance measures. Some of these values are obvious, but some correlations with Average Speed and Work per Stroke will be discussed in more detail. Because the table is symmetric, only the top half is given. The values for the bottom half are mirrored over the diagonal.

	$\dot{x}$	W_{stroke}	W_{blades}	$W_{velocity}$	η_{net}	η_{blade}	$\eta_{velocity}$
$\dot{x}$	1	0.265	-0.547	-0.205	0.631	0.648	0.254
W_{stroke}	-	1	0.395	0.009	-0.114	-0.179	0.167
W_{blades}	-	-	1	0.375	-0.929	-0.974	-0.309
$W_{velocity}$	-	-	-	1	-0.612	-0.414	-0.984
η_{net}	-	-	-	-	1	0.972	0.592
η_{blade}	-	-	-	-	-	1	0.386
$\eta_{velocity}$	-	-	-	-	-	-	1

Speed

The performance measures that correlated strongest with Average Speed were Blade Losses ($r = -0.547$, fig. 4.8a), Blade Efficiency ($r = 0.648$, fig. 4.8b) and Net Efficiency ($r = 0.631$, not plotted). The values of latter two are very similar, as Blade Efficiency was the main contributor to the Net Efficiency. That is also the reason why it was not interesting to plot the Net Efficiency against speed.

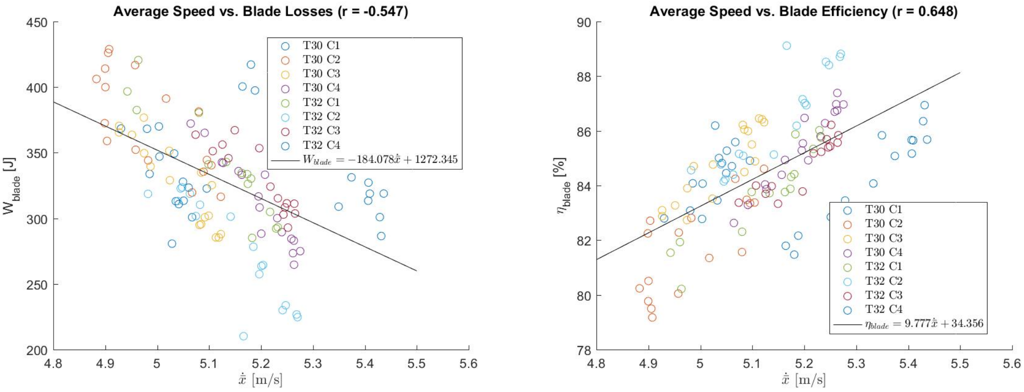
Velocity Fluctuation Losses and Velocity Efficiency correlated weakly with speed ($r = -0.205$, and $r = 0.254$). The effect was not just less clear, the magnitude of the Velocity Fluctuation Losses are also a lot smaller. The Blade Losses were in a range of approximately 200J to 450J per stroke, while the Velocity Fluctuation Losses were in the range of 50J to 100J. This means that the influence of the Velocity Efficiency on the Net Efficiency is relatively small compared to the Blade Losses. This is also the reason these correlations are not further looked in to, even though the correlations are significant.

Work per Stroke

The second performance measure that was specifically investigated is Work per Stroke. The two strongest correlations with Work per Stroke were Average Speed (fig. 4.9b) and Blade Losses (fig. 4.9a). This is interesting because in fig. 4.8b it was seen that although Work per Stroke is used in calculating Blade Efficiency, it had no clear influence.

The moderate positive correlation between Work per Stroke and Blade Losses ($r = 0.395$) indicated that in general a more powerful stroke leads to higher Blade Losses (more than proportionally, because the Blade Efficiency shows a weak negative correlation with Work per Stroke, $r = -0.179$). The weak positive correlation between work and speed ($r = 0.265$) also showed a positive correlation: In general, more power meant a higher speed. Combined with the information from the previous section, one could conclude that prioritizing Blade Efficiency is more beneficial for the Average Speed than focusing on maximizing Work per Stroke. Unfortunately, correlation does not confirm causality. Improved Blade Efficiency may very well be the result of the higher speed, as lift force is linked to incoming velocity squared. This means that for the same applied force, the angle of attack on the blade, and thus the slip component (fig. 3.13), is smaller. The implications of these results will further be discussed in section 5.4.

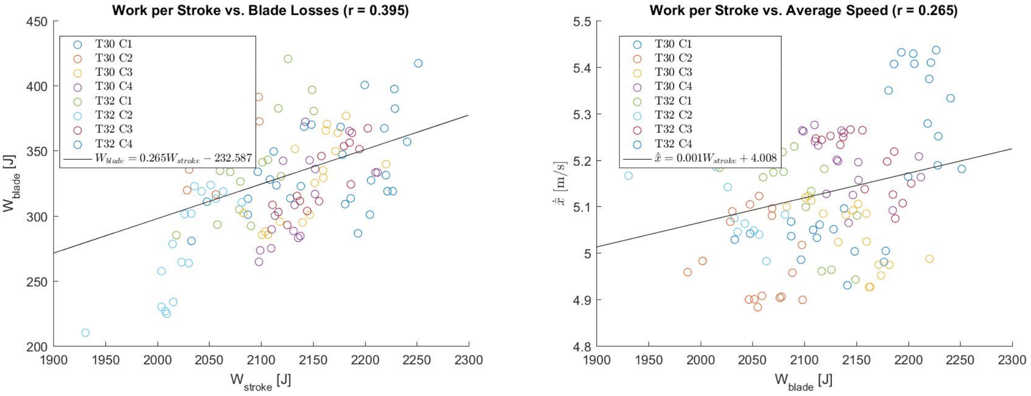
Finally, Velocity Efficiency showed a significant but weak positive correlation with Work per Stroke.



(a) This plot shows the moderate negative correlation between Average Speed and Blade Losses ($r = -0.547$). Blade Losses appeared to be closely related to Average Speed. Higher losses mean a lower Average Speed and viceversa.

(b) The Blade Efficiency correlated moderately with Average Speed ($r = 0.648$), confirming the relationship seen in fig. 4.8a. In the calculation of Blade Efficiency, work is present too, eq. (3.21). But because the correlation between Blade Efficiency and Blade Losses was very strong ($r = -0.974$), its influence is negligible.

Figure 4.8: These graphs present the correlations between Average Speed and Blade Losses and efficiency. These factors were found to have the strongest relation with boat speed.



(a) Scatter plot of Work per Stroke versus Blade Losses. A moderate positive correlation was found ($r = 0.395$). This indicates that, on average, applying more Work per Stroke leads to higher Blade Losses.

(b) The correlation between Work per Stroke and Average Speed was weak positive ($r = 0.265$), indicating that higher speeds are generally achieved by applying more Work per Stroke.

Figure 4.9: The correlations between Work per Stroke on one hand, and Blade Losses and Average Speed on the other.

There was no correlation with Velocity Fluctuation Losses, so strokes during which a higher amount of work was generated did not increase the magnitude of the velocity fluctuations, and therefore the efficiency improved slightly.

Within secondary performance measures

The secondary performance measures were the energy losses at the blades, the additional drag losses because of the non-constant speed, the corresponding efficiencies and the combined Net Efficiency. In table 4.5 the values of the correlations between these measures are given from the third row onwards.

The correlations between the losses components and their efficiencies are close to -1 ($r = -0.974$ and $r = -0.984$ for the Blade Losses/Blade Efficiency and velocity fluctuations losses/efficiency respectively). The two types of losses are linked with a correlation smaller than 0.4 ($r = 0.375$ for the losses and $r = 0.386$ for the efficiencies). Just like when one efficiency is compared to the other type of energy loss ($r = -0.414$ for the Velocity Fluctuation Losses with the Blade Efficiency and $r = -0.309$ for the other way around). So apparently there is some connection between both types of losses. If one deteriorates, the other will too, and vice versa.

The Net Efficiency correlates very strong with the Blade Losses and efficiency ($r = -0.929$ for the Blade Losses and $r = 0.972$ for the Blade Efficiency). The connection with velocity fluctuations is less strong, but still moderate ($r = -0.612$ for the Velocity Fluctuation Losses and $r = 0.592$ for the Velocity Efficiency). This is in line with what was seen between speed and the efficiencies: Net Efficiency is mainly determined by Blade Efficiency and in a lesser amount by velocity fluctuations.

5

Discussion on synchronization

In this chapter the results from the synchronization study are discussed. First of all, the results are checked with the results from previous studies in section 5.1. If the found speeds, work, energy losses etc. are not in line with literature, it is not acceptable to derive conclusions from the results without finding out why these differences are present. Luckily, the results are deemed reliable enough to continue with. Since kinetic synchronization was found to predict performance best, it was checked if the timing is consistent per rower. This is discussed in section 5.2. Next, causality is investigated in section 5.3. Finally the meaning and implications of the found correlations are discussed in section 5.4.

5.1. Reliability

The first topic to discuss is the reliability of the results, and with that the strength of the conclusions that can be made out of this data. In section 3.4 two methods were proposed. The first method was to compare the drag coefficient between the trials. The better these correspond, the more similar the conditions of the different the trials were. Therefore, the results from the different trials were better comparable. The second method that has been discussed to rate reliability was the energy balance. This means the difference is calculated between estimated work and the sum of the energy 'consuming' components: kinetic energy change, Blade Losses and drag, see fig. 3.9. The energy imbalance means that the used simplifications and assumptions do not assign the right amount of energy to each of the individual 'consumers'.

Drag coefficient The found drag coefficients were in the range of 6.16 to 6.70 (table 4.1), slightly lower than the value that was reported by Kleshnev. He found a drag coefficient of 6.68 for fours and quadruples [49]. This may be caused by the weather conditions and the crew weight. The approximate weather conditions from table 3.2 show that the conditions for crews C1 and C2 were most comparable. Apparently the drag coefficient for crew C3 was the highest on average, with more wind and rain and slightly higher temperature. Crew C4 had the most wind and rain, the warmest day, and the lowest drag coefficient. Possibly crew C4 had the most favorable wind direction. In future studies with better recorded conditions, it would be advisable to correct speed for the differences in drag coefficients.

Energy error The found values in (section 4.1) were in the order of 100 Joule or 5% of the work that was generated during each stroke. To judge whether this is good or bad, this approximate amplitude can be compared to the ranges of the energy 'consuming' components.

The energy error is on average higher than the estimated Velocity Fluctuation Losses, which were approximately 74 Joule, or 3.5% of the work supplied, table 4.2. The Velocity Efficiency in the data set ranged in total from 95.2% to 97.6%, which is higher than values found in literature. Hofmijster, et al. found velocity efficiencies of 86% to 94% in their ergometer study [12]. It must be mentioned that they used a linear relationship between drag force and velocity, instead of the quadratic relation for viscous drag. Also, the test group in the study of Hofmijster was larger (22 subjects), the weight of the rowers was in general higher (74 versus 71.4 on average, maximum of 90kg [12]), and the level of the athletes was more diverse compared to the five elite level athletes in this study. Overall, it can be concluded from this that the magnitude of the Velocity Fluctuation Losses and Velocity Efficiency is in a realistic range.

The measured velocities are in a realistic range as well. The current world record for the W4X was retrieved from worldrowing.com [50], and is 6:06.84. This corresponds to an average velocity of 5.45 m/s over 2000m. The data in this study was gathered at the same location, but in different condition, and the recorded speeds ranged from 4.88 m/s to 5.44 m/s. This confirms that the analyzed data matched racing intensity, and the implications of this study therefore apply to racing situations.

The found Blade Losses in this study ranged from 210 Joule to 429 Joule, corresponding to a Blade Efficiency of 79% to 89%. This is better than the values found in previous studies, which reported efficiencies ranging from approximately 70% to 80% [26, 49, 51]. During the study, it was found that the Blade Efficiency is highly susceptible to the assumptions on the catch and the finish. The assumptions of a perfect catch and finish are clearly not true, and the instant when it when it is assumed influences the magnitude of the losses. Additionally, the bending of the oars influences the assumed path of the blade through the water as well, and therefore the instantaneous power loss at the blade. However, the influence of oar bending on the overall Blade Losses was not significant [47]. The final remark on the measured Blade Losses is that parallel blade forces were not measured, and therefore not incorporated, as explained in section 3.3. This leads to an underestimation of Blade Losses of approximately 18%. This might declare some of the error in the energy balance.

Precision and synchronization derivation

No reference material exists to compare the synchronization values with, except some schematic on how the moment of half impulse is calculated [7]. This means the values can't be compared to external sources. Another way to check whether there are any problems regarding the found values for synchronization is to compare them to the limits of the measurement equipment.

The first synchronization measure to check is the Mean Standard Deviation of the Phase. The average of this measure over all strokes from all trials is 3.683°, in a range of 2.759° to 5.000° (table 4.2). The average value is approximately 1% of a total cycle of 360°. On a pace of 30 SPM, meaning a period of 2 seconds, this means that the 3.683° corresponds with a lag of 0.02 seconds, the same as the sample period. It can also be converted to approximate oar angle lag. In one cycle, double the segment is covered. The segment covers approximately -65° to 40°, so in one cycle around 210° is covered. So the lag corresponds roughly to 2.1°, which is over four times the resolution of the angle sensor (section 3.1).

The derived Standard Deviation of the Time to Half Impulse and time to half work are both in a larger range. The range is about a tenfold, ranging from 2 or 3 milliseconds to about 30 milliseconds. The average of all these standard deviations (both measures) work over all strokes and trials is approximately 17 milliseconds, see table 4.2. With a sample period of 20 milliseconds, it is questionable whether the linear interpolation in the time frame is truly accurate.

From the comparisons between the sensor resolutions, sample period, and the derived values for the synchronization, it can be concluded that at least a higher sampling frequency would be favourable. Since the highest correlations in section 4.3 were found for the synchronization of impulse, the resolution of the oar angle sensor is not so much of a problem.

Inaccuracies by simplifications and assumptions

In section 3.3 the methods used to quantify performance were derived. To this end an energy balance was introduced in which generated work going into the system was traced back to the different energy outputs of the system (drag, Blade Losses, kinetic energy change). A visual representation was given in fig. 3.9. During the derivation of the performance measures assumptions were made to deal with the inability to measure certain energy components. For example, Blade Losses were only calculated perpendicular to the blade, because axial blade forces were not recorded. In fact they couldn't even be measured using the PowerLine system.

More importantly, a significant part of the power outputted by the rower is not recorded, as the data set did not contain foot stretcher forces. This makes up over 10% of the work generated by the athlete [34], and can be measured by the Powerline system if the right equipment is used.

fig. 3.9 is be expanded to fig. 5.1, to show all the components that have been neglected because of the assumptions. Next to the transverse Blade Losses, external influences on the drag, handle work during the recover and foot stretcher work have been added. So, on both sides of the energy balance parts have not been recorded.

On the input side there is an unknown amount of residual work. The residual work is the net work generated at the stretcher, by the force component thatis responsible for the acceleration of the rowers mass. Also, the recover work is not used. The equations of motion were derived for the recover in section 3.3 too, just like for the drive. The recover power over time was used to estimate the oar inertia in fig. 3.1, but it was already noticed that it costs more energy to move the oar than just necessary for accelerating and decelerating the inertia. Because of this, it was chosen to stick to just the handle work during the drive. This is the amount that was truly intended to move the boat with. The left out work components, however, do contribute to the effort of the athlete.

On the output side, the Blade Losses were systematically underestimated because the axial blade force was not known. As discussed in section 3.3, Hofmijster et al. found an underestimation 18% [47]. This is an underestimation of 59 Joule on the average found Blade Losses, see table 4.2.

The final influences that could not be computed were the external influences on drag, such as wind and waves. The drag coefficient was computed for each trial, meaning that some constant or average weather influences were taken into account. However, wind gusts and waves induce additional variations in the drag between individual strokes.

Only mechanical output terms have been discussed up till now: It is good to note that also internal losses are possible. Muscles have properties as viscosity and elasticity, so whenever a human moves their muscles, some energy is dissipated. These internal losses are not in the scope of this study. However, one should be aware of the fact that someone can get tired from moving their body even when there is no net work is done. This makes that a rower may feel like he is outputting the same power in two cases, but the mechanical output may be different between the cases.

A quick example of this is the one introduced by Hofmijster et al. [34] of a rower without oars, but then with two rowers. Imagine two exactly the same rowers that apply the same stretcher force profile when pushing and pulling from or towards the stretcher, except that the direction is opposite. Now they move in exactly the opposite manner, so their stretcher forces cancel each other and the boat itself does not move. Then no net work has been recorded over a complete cycle, but the rowers do get tired.

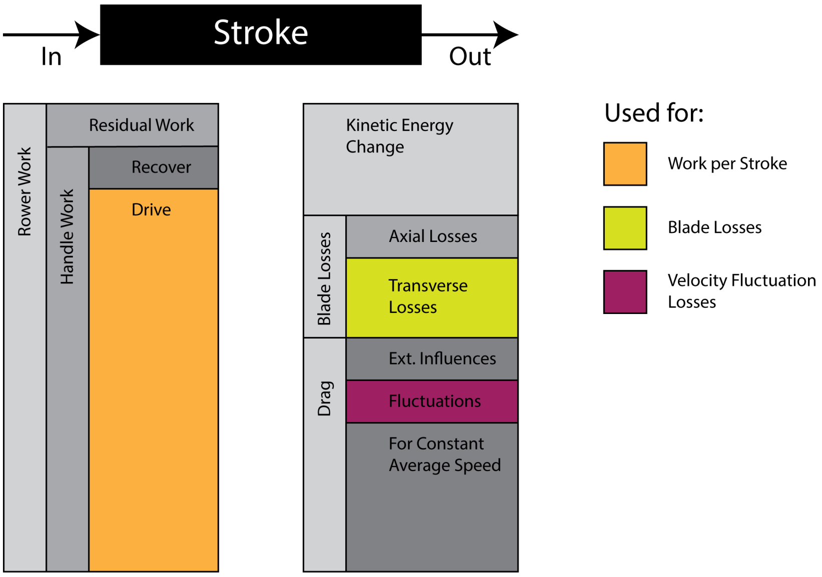


Figure 5.1: This figure is an expanded version of fig. 3.9. In reality, work and Blade Losses and drag are not so easily estimated as was proposed in section 3.3. Inertial work, and handle work during the recover are not taken into account. Furthermore, Blade Losses were underestimated by approximately 18% [47], and sudden changes in drag because of external influences like wind and waves were not taken into account. All of these non-derivable components can be the source of error in the energy balance, and cause additional variance that was not explained by synchrony.

5.2. Consistency in synchronization

A closer look was taken at the consistency in the synchronization of the crew members. This was only done for the kinetic synchronization measure, as this was the measure that showed the clearest link with performance. Consistency is interesting because it shows whether the amount of (non-)synchronization comes from specific differences between individuals or that there is some other factor.

For each trial and each rower the mean and standard deviation of her time to half impulse was calculated. These numbers are presented in table 5.1. From this table it becomes clear that rowers are somewhat consistent. Especially rower B is always early. The averages of athletes C and D are quite similar to each other, and have their half impulse time after B. In general, rowers E and A are last with their half impulse.

The real difference is between B and the other athletes, because the differences between the other athletes means often fall within a range of one standard deviation of each other. Another observation in this table is that the time to half impulse is in the order of 10 ms lower during the trials at 32 SPM compared to the trials at 30 SPM. Therefore, interpreting the table should focus on relative differences between rowers (horizontal order), and not on averages over all trials together. Interesting to note is that this decrease in time to half impulse shows that higher pacing is not just a quicker recover, but there is also a change in force buildup.

Table 5.1: In this table the mean and standard deviations of the time to half impulse are given for each athlete and each trial. The values show that mostly athlete B is consistently early within a trial and between different configurations. The others are fairly close together compared to their standard deviations. The absolute values seem to depend on the assigned pace, but the order is more consistent.

Trial | Rower:	A	B	C	D	E
T30 C1	420±9.05 ms	371±6.58 ms	411±7.67 ms	*	411±12.4 ms
T30 C2	411±10.5 ms	357±9.79 ms	*	396±10.9 ms	414±11.1 ms
T30 C3	410±10.4 ms	*	399±10.1 ms	399±13.4 ms	398±11.4 ms
T30 C4	*	359±6.30 ms	397±7.13 ms	392±11.1 ms	405±11.7 ms
T32 C1	409±9.44 ms	358±7.36 ms	397±9.33 ms	*	394±8.59 ms
T32 C2	406±6.65 ms	349±6.94 ms	*	384±7.46 ms	408±6.51 ms
T32 C3	400±10.0 ms	*	381±7.91 ms	373±8.61 ms	386±10.2 ms
T32 C4	*	356±7.31 ms	375±8.51 ms	376±7.19 ms	392±8.28 ms

5.3. Investigating causality

In this final section of the discussion the direction of the found relation is shortly investigated. Does performance improve because synchronization improves, or does synchronization improve because performance increases? This reasoning goes deeper into individual consistency, which was introduced in section 5.3. figs. 5.2 and 5.3 show scatter plots of the individual timing versus Average Speed and individual Work per Stroke. The following was reasoned:

If the timings of the half impulse delivery is consistent for a rower and not dependent on the (individual) performance, synchronization is the result of rower selection. However, if the timing of half impulse delivery of the rowers converge with increasing performance, the magnitude of the synchronization measure is (also) a result of the higher value of the performance measure.

Figure 5.2 globally shows this converging behaviour. The correlations per athlete can provide information on the cause of this triangular shape of the point cloud. Athlete B shows consistent early half impulse delivery (low correlation). The other athletes have moderate negative correlations, meaning the half impulse delivery happens quicker.

This is not that much of a surprise, as when stroke rate stays equal and speed increases, the drive time should automatically decrease and the recover time should increase. If the drive phase takes up a shorter amount of time, any instant during that period happens quicker after the catch.

The half impulse delivery quickens but does not clearly converge, when observing all athletes excluding rower B.

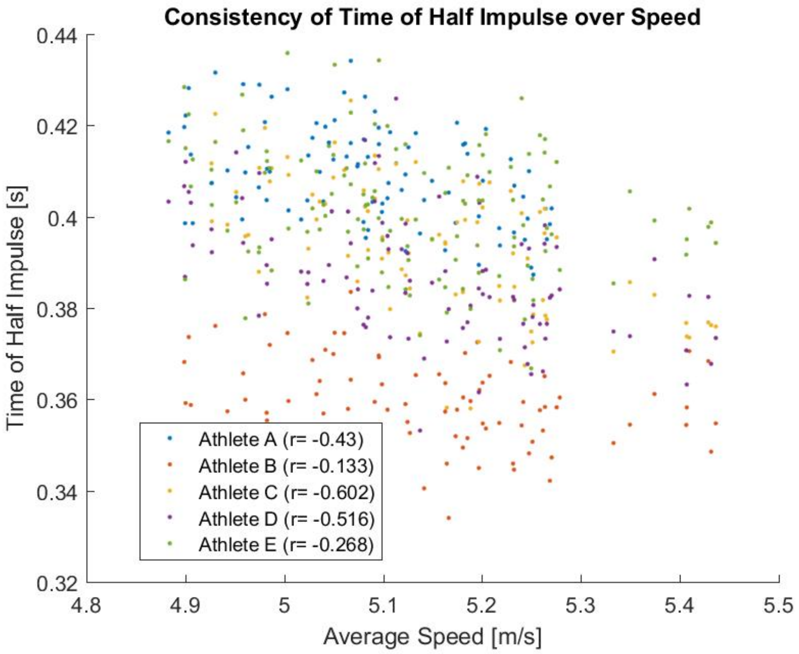


Figure 5.2: Scatter plot of the individual timing of half impulse delivery versus Average Speed. If the timing of the individuals converges with higher Average Speed, the synchronization improves as a result of the improved performance. This does not mean the relation only works in this direction, but at least part of the found correlation between kinetic synchronization and performance is due to this phenomenon.

Figure 5.3 is a lot less clear about this behaviour. Mostly because athlete E clearly had a day at which she performed much less then at the other days. Other than that she was the only athlete performing in all trials, no clear explanation can be given for this anomaly.

The correlations calculated for the individual data are low for athletes A, B and C. Athlete D shows a moderate negative correlation. Athlete E too, but the distant point cloud has a big influence on the correlation value, so this data set is not ideal to analyze.

This investigation on causality is concluded by stating that impulse delivery timing decreases with boat speed (unless it is already very quick to begin with) but that there is no clear converging behaviour of timing with individual performance. This supports the hypothesis that performance is dependent on crew synchronization.

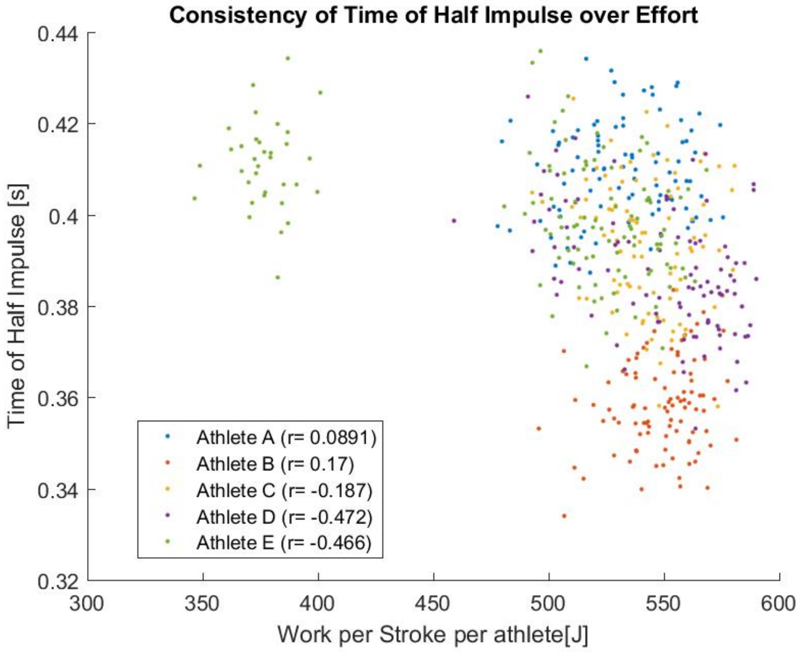


Figure 5.3: Scatter plot of the individual timing of half impulse delivery versus the individual Work per Stroke. Similar to fig. 5.2, however, in this case the performance is also a strictly individual measure. Athlete E clearly has had one day during the trials at which she did or could not perform well. It is not known what is the cause of this. This separated cloud of data influences the strength of the correlation

5.4. Implications

This section will discuss the results within both types of measures and between them, that were presented in sections 4.2 to 4.4. The implications of these results are elaborated in the same order as in the results: first the dependence of the different synchronization measures on each other, then the link with performance and finally the influence of performance measures on each other.

Within synchronization measures

In section 4.2 the found correlations within the synchronization measures were presented. First of all it was found that Standard Deviation of the Time to Half Work and Standard Deviation of the Time to Half Impulse correlated very strongly ($r = 0.970$). In hindsight this may understandable because power consists of force times speed and the oar motions are overall very similar. So the only addition compared to the impulse is the handle speed. Could the residual power term be calculated, results might have been different. But with this approach energetic synchronization is almost the same as kinetic synchronization.

Slight negative correlations were found between both of the previous synchronization measures and the Mean Standard Deviation of the Phase. So the kinematic synchronization deteriorated with improved kinetic synchrony. The correlation with Standard Deviation of the Time to Half Impulse was more negative ($r = -0.247$) than with Standard Deviation of the Time to Half Work ($r = -0.161$). As said, the time to half work calculation depended on both kinetics and kinematics of the rower. Looking at the values of the correlations, energetic synchronization is basically kinetic synchronization that has been diluted with a bit of kinematics. So its correlation with kinematic synchronization is less negative than for kinetic synchronization.

Between performance and synchronization measures

Between the synchronization measures and the performance, the found correlations were generally weak to moderate. Even in the best part, only one third of the variance of a performance measure was explained by the synchronicity of the crew. There are of course more factors that influence performance: external factors like wind, waves, things happening around the boat, or internal factors like focus or fatigue. The goal of this section is to discuss what can be truly said about the relation between synchronization and performance.

Phase synchronization: the opposite effect The effect of phase synchronization being negatively correlated with the other synchronization measures was seen in the synchronization-performance comparison. Phase synchronization was found to correlate positively with Average Speed and Work per Stroke, meaning they improved when the Mean Standard Deviation of the Phase increased. So this implicates that rowers should not try to move their oars in sync. The phase measurements were, of course, in a limited range, as the crews consisted of top level athletes. Therefore, it should not be said that being the oars should move completely out of phase with each other. Instead, this finding is more an indication that rowers need their bit of freedom of movement within a stroke.

Net and Blade Efficiency showed a positive correlation too, meaning a less synchronized crew was also more efficient. An remark must be made on this, as it was found in section 4.4 (discussing the relations within the performance measures) that Blade Efficiency rises with average boat speed. Therefore these two are intertwined. The reasoning on what causes what is not evident. It just can be said that speed and Blade Efficiency improve together.

Kinetic and energetic synchronization: the expected effect The standard deviations of time to half impulse and time to half work behaved very similar. In both cases, a lower standard deviation, so better synchrony, was found in strokes with a higher Average Speed and especially higher Work per Stroke. The problem with Work per Stroke is that it also depends on what a rower can maximally deliver. And of course, what can be measured. In section 3.3 it was stated that the residual power could not be measured and accounts for over 10% of the mechanical output of the rower.

The reason why the first problem is not present in this study is that all measurements were done with rowers of a similar level. For example, in fig. 4.5b it can bee seen that at least these four rowers are capable of delivering approximately the same peak forces. What happens when not all of the rowers are able to deliver these peak forces? If one rower is significantly weaker, but does have similar time to half work values? First of all, data of more crews should be gathered to answer this question. Second of all, the results should be corrected for the maximal force or power that each rower can deliver, so different crews can be compared better.

Concerning the problem that the residual power was not included: The fact that the measured Work per Stroke is lower for less well synchronized stokes does not mean the rower does not output the same mechanical effort. It is possible that in less synchronized strokes, more net work is generated at the stretcher interface, such that the total mechanical output is the same. But where does the stretcher work go?

The residual work is energy outputted by the rower, but not via the blades and excluding the amount that is returned because of the cyclic kinetic energy transfer between boat and rower. Neither is the energy internally dissipated, for example by other rowers: The final paragraph of section 5.1 presents an example of how rowers dissipate each others energy, but because the boat does not change velocity, no stretcher work would be measured in that case.

Now think about the example of the rower without oars from Hofmijster et al. [34]: The rower pushes against the stretcher, and both boat and rower start to move. After one cycle both boat an rower are in the same relative position compared to each other. The only mechanism that can have exerted a force, an thus have caused a net displacement of the system, is the drag on the moving boat. So the residual work is a propulsive component in this case.

Boat speeds during the trials were all positive, so in reality the residual work at the stretcher is not propulsive, but just part of the boat drag. No matter where the residual work flows to, the fact remains that propulsion via the blades is the must effective way make the boat move from A to B. That means residual work should be minimized. Residual power is calculated as rower mass times rower acceleration times boat speed. A strategy for minimizing it in general could be by avoiding a high acceleration when the speed is also high. So a rowing technique is recommended where one pushes hard against the stretcher right after the catch (when the speed is lowest) and gently rides forward during the recover (when speed is high). This is exactly how rowing is commonly taught, and it might also be a reason why kinetic synchronization might be beneficial: if one applies their force late, they also accelerate later, when the boat speed is already higher. But this should be checked of course, e.g. by calculating synchronization with the stretcher force curve instead of the handle force curve. Not the least because minimizing the power terms does not automatically mean that the integral of it over time is also less.

Causes of asynchrony Another interesting topic is the possible cause of asynchrony in the boat? The focus lies specifically on kinetic synchronization, as this showed the strongest correlations with performance. Why does one stroke show relative high Standard Deviation of the Time to Half Impulse, while these instances lie closer together during another stroke?

The answer to this question was found by visual inspection of (random) strokes from the measurements. It appeared that, when the kinetic synchronization was not so well, the stroke usually leads the force buildup (or the other crew members lag behind). Checking this with all strokes of trial ’T30 C4’, it is not necessarily the stroke, but most often rower B that leads before the others. This trial was picked because it forms the middle part of the kinetic synchronization range, and athlete B was not at stroke position.

The trials with the highest synchronization were the ones where athlete B was not part of the crew. This could also mean that athlete B delivers less power in general. However, this was not the case because the trend is also visible without this crew. The trend might actually be steeper if crew C3 was excluded, because this crew does not show the highest Average Speeds or Work per Stroke. This suggests synchrony should never be pursued at all costs, but always be seen in perspective.

Interstroke effect? To conclude the discussion on the interplay between synchronization and performance, a final remark is made: It is certainly possible that the level of synchronization (also) expresses itself in the next stroke. It could be speculated that e.g. a disturbance in one stroke could shift the attention of the rower from maximal power production to cancelling the disturbance. Or the rowers might try to compensate a not so well stroke by pushing harder during the next stroke. Researching this delayed effect would extend Anderson’s study on consistency [27], by specifying synchronization as the source of inconsistency.

Within performance measures

To conclude this chapter, the implications of the within performance measures comparison are discussed. The correlations were presented in section 4.4. The first of the main findings was that a higher Average Speed correlates with higher Blade Efficiency, and (although less strong) with higher Work per Stroke. The higher Blade Efficiency and decreasing Blade Losses were most likely due to the fact that lift force increases with the square of incoming speed on the blade. For a certain blade force that a rower can exert, a higher incoming speed means the angle of attack must decrease and thus the Blade Losses.

The correlation between Average Speed and Work per Stroke is fairly straight forward. To achieve a higher speed, more power must be generated. The pace is more or less constant (30 to 32 SPM) so to increase the power higher Work per Stroke must be generated. During a real race the pace is not fixed, so the average power might be a better measure than Work per Stroke.

Another finding was that more work leads to higher Blade Losses, the correlation with Blade Efficiency was also significant but less strong. To understand how this works, fig. 3.13 is observed again. The reasoning is the following: The only option to increase Work per Stroke on a certain pace, speed and segment is to increase the force. To increase force on a blade, the angle of attack must increase, which in turn increases the Blade Losses. Not just in absolute sense, but also relatively because the lift and drag coefficients change with the angel of attack. The exact mathematics behind this effect are not elaborated, because this is not of interest for the goal of this study.

The final remarks on the findings within the performance measures are that Blade Efficiency contributes more to the Net Efficiency than the Velocity Efficiency, which was explained by the size of the effect, and that both types of losses are connected. This interconnection might originate from the fact that the correlations between Average Speed and Blade Losses and Velocity Fluctuation Losses both have the same sign. Because of the common link with speed, the losses automatically correlate too, even though there might not be a direct physical link.

6

Improving synchronization

The goal of this research is, as it was stated in chapter 1, to provide practical advice about what features of the rowing stroke should be synchronized, and whether and how synchronization could be promoted by adjusting the rigging dimensions of the boat to the individual athletes. In the previous chapters it was found that the feature of the rowing stroke that should be synchronized is the area center of the handle force over time curve (time to half impulse). This was also named kinetic synchronization and it was discussed how this can be explained mechanically. The time to half impulse was found to vary in a range of a couple of hundredths of a second (tables 4.2 and 5.1), something that is not useful to feed back to an athlete. Also, no link has been made to the rigging.

Now the step has to be made to go from measuring synchronization in time to tuning synchronization by changing rigging dimensions of the boat (e.g. oar length, span, catch angle, etc.). It is most interesting to see whether a link could be made between the time to half impulse and the corresponding angles. It was hypothesized that these half impulse angles behave similar to the time of half impulse. In addition, the hypothesis was made that these angles are consistent for an individual, such that customized rigging per rower could improve synchronization and thus performance. How these hypotheses were tested will explained in section 6.1. In section 6.2 the results of this investigation are given and they are discussed in section 6.3.

6.1. Method

The method used to investigate the link between similarity over time and over angle will be discussed in this section. This method is an extension of the kinetic synchronization measure. In section 3.3 it was proposed to measure kinetic synchronization by calculating the standard deviation over the time when half impulse was delivered per rower. This measure was found to relate the most to Work per Stroke and Average Speed of the entire boat, see section 4.3, and is therefore taken as the starting point. The proposed extension is to use the oar angles at the time of half impulse to do a similar calculation.

The so called angle of half impulse is retrieved from the average oar angle signal per rower eq. (3.24), at the time of half impulse ($T_{J50,rower}$) that was calculated usingeq. (3.32). Next, the standard deviation was calculated. The formulas of this process are given in eqs. (6.1) and (6.2). The Standard Deviation of the Half Impulse Angles was is also referred to as kinetic similarity.

$$\bar{\phi}_{J50,rower} = \bar{\phi}_{rower}(T_{J50,rower}) \tag{6.1}$$

$$\sigma_{\bar{\phi}_{J50,rower}} = \sqrt{\frac{\sum_{n=1}^{N_{rowers}} \left(\bar{\phi}_{J50,rower,n} - \mu_{\bar{\phi}_{J50,rower}}\right)^2}{N_{rowers}}} \tag{6.2}$$

First, it is compared with the kinetic synchronization measure to see whether or not these angles actually relate to synchronization, or if it quantifies a completely different effect. Then, similar to the comparison of the synchronization measures with the performance measures in section 4.3, the standard deviation of the angles at half impulse will be compared with the performance measures. Finally, is is investigated whether individual rowers are consistent in their half impulse angle. This enables judgment on the effectiveness of adjusting individual rigging.

6.2. Results

The analysis described in section 6.1 delivered a similarity value for each stroke in the same manner as with the synchronization measures in section 4.1. The Standard Deviation of the Half Impulse Angles ranged from 2.019° to 4.676°, with a mean of 3.182° and a standard deviation of 0.6221° (order of $1/5^{th}$ of the average).

The resemblance between Standard Deviation of the Time to Half Work and Standard Deviation of the Half Impulse Angle was investigated first. The correlation was calculated and the scatter plot is given in fig. 6.1. The value of Pearson's r was 0.624, meaning that 39% of the variance of one of the parameters is explained by the other. The moderate positive correlation shows that the measures are similar for a large part, but still more than half of the variance was generated by other sources.

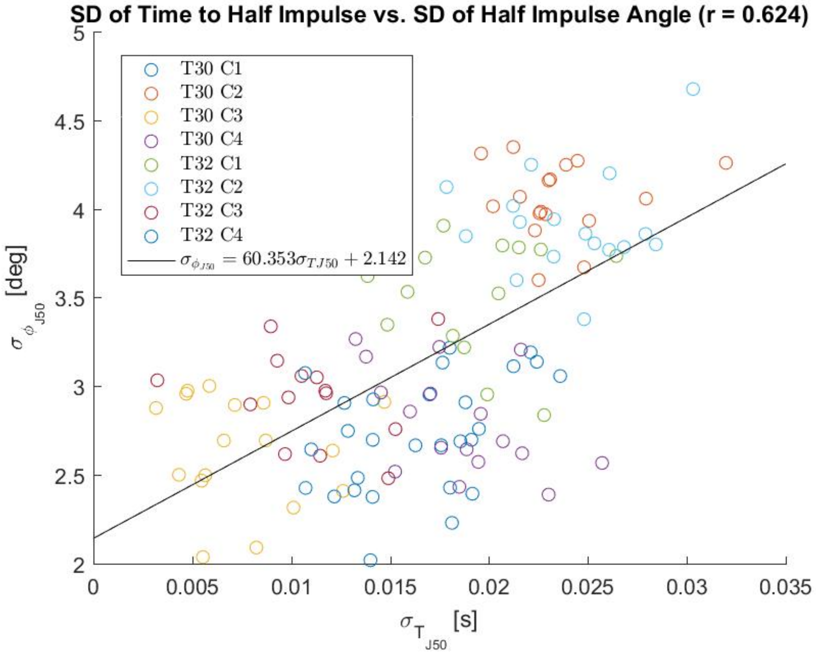


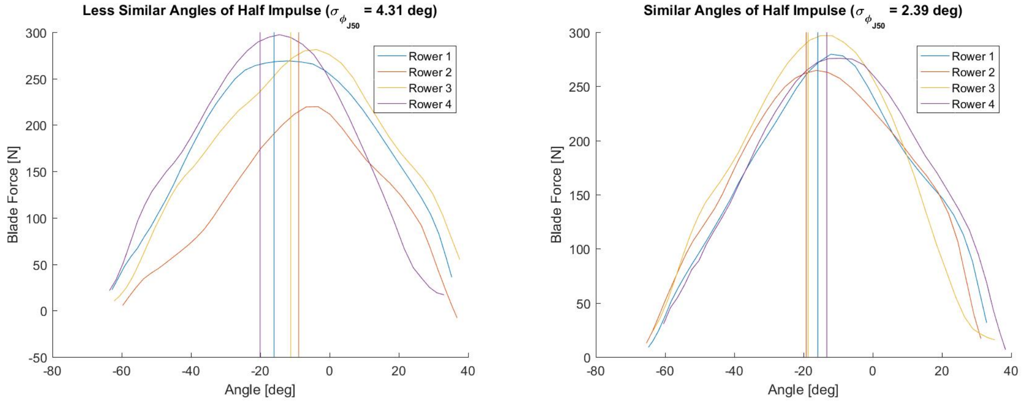
Figure 6.1: This figure shows the scatter plot correlating the standard deviation of half impulse with the standard deviation of the angles at the time to half impulse instances. Pearson's r is $r = 0.624$, meaning a moderate correlation. It must be noted that crew DEAB has quite a significant (positive) influence on the correlation.

The second step was to compare the new measure with the performance measures, similar to section 4.3. The correlations with the performance measures are tabulated in table 6.1. Significant results are the correlations with Average Speed, Work per Stroke and Net Efficiency. For these combinations the scatter plots are given in fig. 6.3. Not just the found correlations, also the figures for Average Speed and Work per Stroke are quite similar to figs. 4.4a and 4.4b.

Table 6.1: Pearson's r for the combinations of performance with Standard Deviation of the Half Impulse Angles. Three of the seven combinations deliver significant correlations ($|r| > 0.152, p \leq 0.05$). Overall, it must be noted that they are in line with the results for kinetic synchronization in table 4.4, but all slightly higher. In this case the Net Efficiency was increased to just above the significance level. The correlations with the individual efficiencies are still too low.

	$\dot{x}$	W_{stroke}	W_{blades}	$W_{velocity}$	η_{net}	η_{blade}	$\eta_{velocity}$
$r =$	-0.292	-0.748	-0.040	0.017	-0.159	-0.138	-0.151

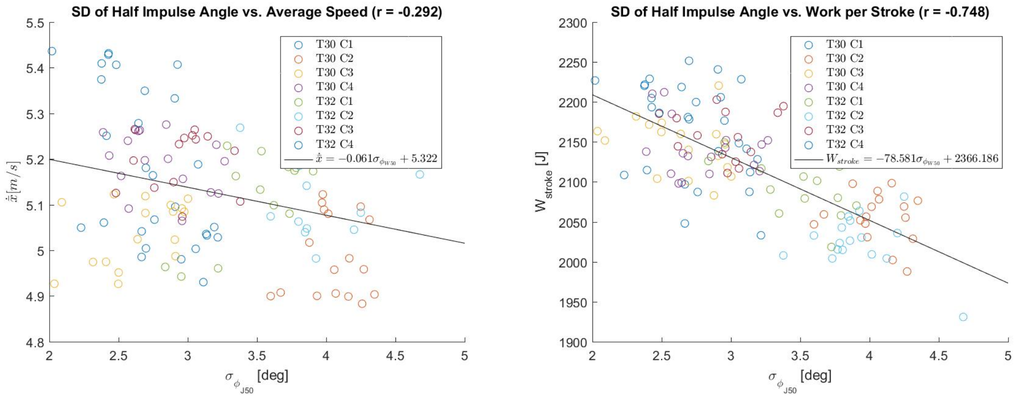
Finally, also similar to section 4.3, the signals used to calculate the similarity measure value are plotted for a 'good' and 'bad' stroke. This way they can be compared, and it can be investigated if the purposed effect was indeed achieved. Of each side of the spectrum one stroke was picked, the force-angle curves are plotted in fig. 6.2. This effect is indeed observed, as the force-angle curves overlap much better in fig. 6.2b than in fig. 6.2a. It must be noted that the vertical lines correspond to the angles at the time to half impulse, and thus do not, unlike with the time signals, divide the surface under the graph in half.



(a) The blade force over the oar angle for a stroke with less similar angles of half impulse ($\sigma_{\bar{\phi}_{J50,rower}} = 4.31deg$), and the respective half impulse angles.

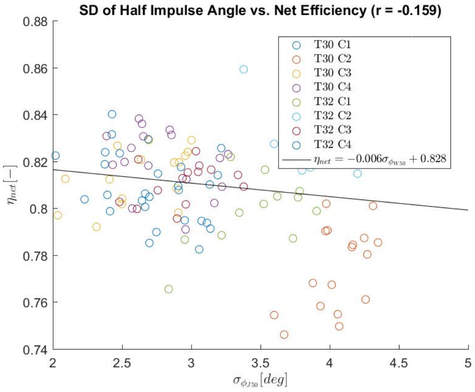
(b) The blade force over the oar angle for a stroke with more similar angles of half impulse ($\sigma_{\bar{\phi}_{J50,rower}} = 2.39deg$), and the respective half impulse angles.

Figure 6.2: Blade force over oar angle for the rowers during a stroke with a relative low similarity (fig. 6.2a), and during a stroke with relative high similarity (fig. 6.2b). When both are compared it is clear that the variable is a good predictor of in what amount the force-angle curves of the rower are alike. What must be noted is that the segment and the peak forces of the individual rowers are different but have little influence on the location of the half impulse angle, although it does influence the overall correspondence of the curves.



(a) In this plot the Average Speed is plotted against the Standard Deviation of the Half Impulse Angles is plotted. They showed a weak but significant negative correlation ($r = -0.292$). The correlation is higher then that of the kinetic synchronization ($r = -0.193$).

(b) This scatter shows the correlation between Standard Deviation of the Half Impulse Angles versus Work per Stroke. Pearson's r was significant and strongly negative ($r = -0.748$). Also, it was stronger than for kinetic synchronization ($r = -0.574$).



(c) Net Efficiency plotted against the Standard Deviation of the Half Impulse Angles. There is a significant but weak negative correlation between the two ($r = -0.159$), indicating that improving kinematic similarity has a positive effect on the Net Efficiency of a stroke. Crew C2 is again an outlier, and although the kinematic similarity in the crew was within more or less the same range for both trials, the efficiencies were completely on the opposite sides of the efficiency spectrum.

Figure 6.3: These scatter plots show the correlation between kinetic similarity and several performance measures. Significant correlations were found in combination with Average Speed (fig. 6.3a), Work per Stroke (fig. 6.3b) and Net Efficiency (fig. 6.3c).

6.3. Discussion and conclusion

In section 6.1 a method was proposed to translate time synchronization to oar angles, so that the findings on kinetic synchronization can be used to improve performance. The results were presented in section 6.2. In this section, a number of remarks will be made on these results. Finally, a conclusion is drawn from it, and recommendations are made to improve the reliability in followup studies.

First of all, there was a moderate correlation between kinetic synchronization and kinetic similarity over the angles. Of the variance in one of the two measures, 39% could be explained by the other measure. This is deemed sufficient to be able to state that kinetic synchronization expresses itself in angular differences. However, it is not satisfactory that still more than half of the variance in synchronization was left unexplained.

Secondly, significant correlations were found between Standard Deviation of the Half Impulse Angles and Average Speed, Work per Stroke and Net Efficiency. The correlations were higher than for Standard Deviation of the Time to Half Impulse, meaning kinetic similarity performs better as a rowing performance predictor than kinetic synchronization. This makes up for the fact that the two measures do not fully correspond with each other.

Thirdly, crew C2 was observed to be critical for the found trend. Without it the correlation would be much lower. This is not necessarily bad, because the crews are already very close together as only one athlete is changed each trial, but it gives an indication that data of more crews would improve the strength of the conclusions that can be drawn.

The fourth remark concerns a similar investigation as in section 5.2, that was done to judge on the effectiveness of individual rigging. This is similar to the investigation on consistency in section 5.2. In table 6.2 the mean angle of half impulse and its standard deviation is presented for each athlete and each trial. First thing to note is that the standard deviations are in general less than one degree, while the differences between rowers in a crew are in the order of a couple of degrees. This means the rowers are indeed consistent in their half impulse angles within a trial. Also, especially athletes B and C are very consistent between trials. Their half impulse angles are around -19°, which is more forward than the others.

A second note is made on crew C2, on rowers A and E: Apparently, in this combination both of these rowers shift their half impulse angle backwards to around -10°, while the other two crew members stay consistent and keep their half impulse angles more forward. So even though the half impulse angles of individuals stay fairly consistent, crew members clearly do influence each other.

Table 6.2: In this table the mean angles of half impulse and the respective standard deviations are given for each athlete and each trial. The table is similar to table 5.1. The values show that individuals are relatively consistent within a trial and between different configurations, with the remark that certain crew members do influence each other.

Trial | Rower:	A	B	C	D	E
T30 C1	-12.6±0.575°	-19.5±0.563°	-18.3±0.576°	*	-14.1±0.807°
T30 C2	-9.61±0.834°	-19.3±0.693°	*	-15.6±0.353°	-10.1±0.569°
T30 C3	-13.7±1.27°	*	-19.2±0.853°	-12.9±0.878°	-13.7±0.855°
T30 C4	*	-19.2±0.813°	-18.3±0.567°	-12.2±1.09°	-15.5±0.969°
T32 C1	-11.7±0.708°	-19.8±0.754°	-19.5±0.981°	*	-14.1±0.609°
T32 C2	-10.4±0.836°	-19.1±0.607°	*	-16.4±0.373°	-10.0±0.561°
T32 C3	-13.1±0.689°	*	-20.7±0.635°	-14.3±0.444°	-15.1±0.879°
T32 C4	*	-19.3±0.367°	-19.5±0.684°	-14.0±0.936°	-14.8±0.826°

The fifth and final remark on the results in this chapter is that a similar investigation on causality was performed as in section 5.3. The angle of half impulse was checked for absolute converging behaviour with (individual) performance. See the scatter plots in figs. 6.4 and 6.5. No converging behaviour is visible, so this excludes the possibility that a relation was found due to a poorly chosen similarity measure.

In summary, it is concluded that there is a link between kinetic synchrony and kinetic similarity. Kinematic similarity is specified as the Standard Deviation of the Half Impulse Angles. These half im-

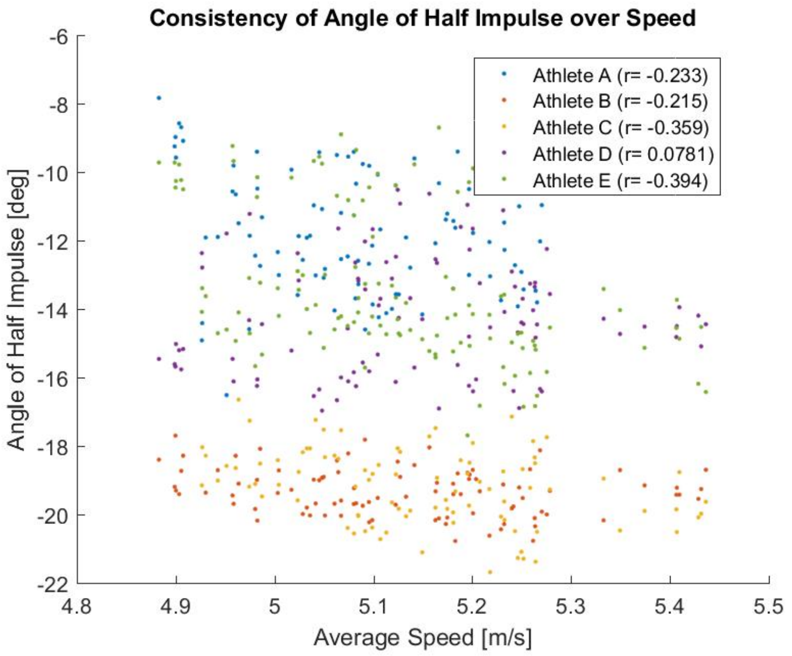


Figure 6.4: Scatter plot of the individual half impulse angles versus Average Speed. If the angles converge with higher Average Speed, the similarity measure improves because the half impulse angles grow closer together in an absolute sense. On visual inspection this does not appear to be the case. The most right point clouds might suggest so, but globally the data forms more of a square shape. Also the correlations are low to moderate, mostly, but not strictly, negative.

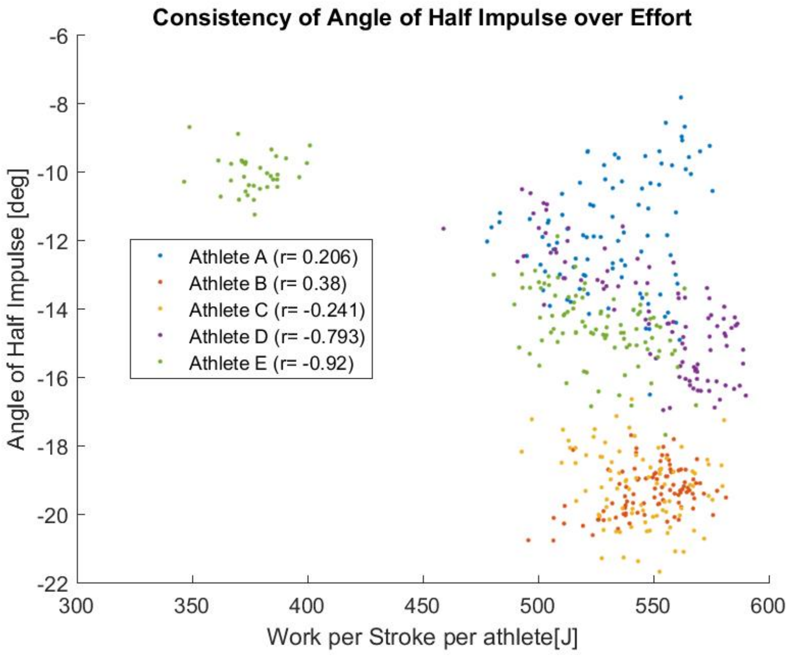


Figure 6.5: Scatter plot of the individual half impulse angles versus the individual Work per Stroke. Similar to fig. 6.4, but in this case the performance is also strictly individual. There is a separated data cloud of athlete E, like in fig. 5.2, partly responsible for the high correlation. Overall, taking the strengths and signs of correlations into account, there is no converging behaviour visible.

pulse angles were found to be a valid way to judge on similarity of entire force-angle curves. In fact, the link between rowing performance and kinetic similarity is even clearer than what was the case with kinetic synchrony. Finally, rowers are fairly consistent in their half impulse angles, within trials and in different crew combinations, suggesting similarity can likely be improved by individualizing the rigging. This supports the hypothesis.

To further enhance the strength of this conclusion, it is recommended to:

- Retest with more and more different crews, to get a wider spectrum of results, instead of having to rely on the exchange of one or two rowers.
- Test whether individual rigging, shifting the half impulse angles on top of each other, improves both synchrony and the performance in practice.
- Investigate whether the segment and peak blade force should also be made similar. In that case, the rower does not only have to be moved forward or backward, but the inboard length and gearing would also have to be changed.

7

Final conclusion and recommendations

The goal of this thesis was to provide practical advice about what features of the rowing stroke should be synchronized, and whether and how synchronization could be promoted by adjusting the rigging dimensions of the boat to the individual athletes. The different research questions have been answered during the chapters.

The first main research question, finding out the underlying mechanism of the empirical rule that synchronization improves performance, was answered via its subquestions. The first subquestion, 'What is the current state of research on the rowing stroke and its characteristics?' was discussed in chapter 2. An extensive review was given on the current knowledge is given, and the currently used methods to quantify synchronization and performance were analyzed, answering the second and third subquestions.

The proposed methods from this background chapter were implemented in chapter 3. Two primary performance measures were defined: Average Speed and Work per Stroke. Average Speed because it determines directly the result of a race, and Work per Stroke as it measures the effort of a crew. Also, speed is highly influenced by weather conditions. Besides the primary measures, a set of secondary performance measures was defined: Blade Losses and Velocity Fluctuation Losses and their respective and combined efficiencies.

Three methods of synchronization were proposed, one focusing on the kinematics by using oar phase, one focusing on kinetics by quantifying timing of impulse delivery, and one focusing on energetics by quantifying timing of work generation.

The fourth and fifth subquestions were answered in chapters 4 and 5. Within the performance and synchronization measures, the strongest performance predictor was the the Standard Deviation of the Time to Half Impulse, correlating with Average Speed and Work per Stroke. The timing of impulse delivery was found to be quite consistent per individual, the absolute timings differed throughout the trials but a pattern could be recognized. Furthermore, it was explained what the mechanism behind the relation could be, how the fact that not all rower work could be derived, and how this had might interact with the results.

The second main research question was whether synchronization of the boat could be improved by individualizing the rigging. Synchronization was found to be translatable into kinetic similarity over oar angles, it actually predicted performance better. The half impulse angles are consistent per rower, although some interaction was found, meaning it is likely that synchronization can indeed be improved by individualizing the rigging.

These answers make up the advice to the KNRB: There is strong indication that better rowing performance can be achieved if the half impulse angles of the rowers are made more similar by moving the rower forward or backward a bit. The underlying mechanism is that half impulse delivery is more simultaneous. This helps a crew to generate maximal effort.

With the conclusion of this thesis, the work is not yet done: the nature of the data that was provided is such that not all energy input and losses could be derived, see fig. 5.1. The exact overview of what happens is incomplete, as the residual work and the axial blade losses are missing, and a set of assumptions was made. Some have more impact on the variance than others. The fact that as well on the work generation side as on the energy losses side of the balance terms are missing, means there is inevitably a lot of unexplained variance. The assumptions in summary:

- For the boat, only forward boat motion was considered, while there are in total 3 possible translations and 3 possible rotations. Newtons equations of motion are applicable in each degree of freedom, so in each of these directions energy may be added or dissipated.
- The oar was considered to only rotate in the x-y plane with the center of mass at the gate, and to be subjected to perpendicular forces solely. This means a large part of the oar dynamics is neglected.
- Power and work are determined using the common proxy, meaning only handle work is considered. The fact that the net work for accelerating the rowers mass is not zero was neglected.
- During the recover, the only force acting on the oar is applied at the handle to rotate it (the respective normal force acts at the gate). In reality, air resistance acts on the blade and the shaft of the oar, and the net work is not negligible.
- All drag losses are considered as viscous drag, with a constant drag coefficient. The drag coefficient is not actually constant, as it consists of hydro- and aerodynamic drag and is subjected to e.g. irregularities in the flow (such as wind gusts) and the frontal surface (movement of the rowers).

Recommendations

Next to the above mentioned assumptions, which are mostly the result of the limitations of the measurement system, a set of recommendations are presented here to improve the reliability of the results:

- The current sampling frequency of the logger is 50 Hz. This is too low compared to the differences in time to half impulse and work. These instances had to be linearly interpolated in the data. A higher sampling frequency would decrease the time over which the interpolation is done, and thus be more accurate. The average Standard Deviation of the Time to Half Impulse c.q. work is about 17 ms, while the used system has a sampling period of 20 ms (50 Hz). So using a system with double the sampling frequency (100Hz, or 10 ms) is recommendable. Such system is available at the VU University.
- Standard Deviation of the Time to Half Impulse was found to be the best working synchronization measure, however, the number of crews and athletes that have been used to get to this result was minimal. It is recommended to repeat the study with more different crews of at least senior level to limit the variation in physical capability. Optionally, performance (Work per Stroke) can be scaled to e.g. the personal average.
- Net foot stretcher work (residual work) is generated because the integral of the foot stretcher power over a cycle is not zero. This means a term of over 10% of energy generation was not included. It is recommended to use an instrumented foot stretcher in future research. First of all for the cause of completeness. Second of all because it can provide insight in how the performance decrease because of kinetic asynchrony works. It is very well possible that when asynchrony increases, the amount of residual work increases, this would be a most interesting continuation of this research.
- The assigned paces during the trials were 30 and 32 SPM. The difference between these paces was reasoned to be negligible. If follow-up studies use data of a larger range of stroke rates, work per stroke is not an ideal measurement of performance. Effort over time, also called intensity, is recommended to be used instead of effort over stroke. Intensity is e.g. average power, calculated as work per stroke times strokes per second.

Besides improving reliability in a follow-up study, it was proposed to validate the individual rigging, as proposed in section 6.3. If this is validated, the effect of peak blade force similarity and segment similarity can also be researched, to achieve a complete advise on all rigging and gearing dimensions. Optionally, a mathematical model could be used to scrutinize the rigging parameters.

Another interesting question is whether there is hysteresis or compensatory behaviour in the relation between synchronization and performance. Does one less synchronized stroke mean that the next one is not so well either, or is the first stroke compensated during the next by e.g. applying more force.

Finally, the statement that rowers generate a fixed force curve shape could be tested specifically, by feeding back the rowers half impulse angles to the rowers. Coker [8] already concluded that rowers are not able to quicken their force build-up, although athletes with a quick build-up are able to adjust themselves automatically to others. So apparently there is some flexibility in the force curve and some sense to adjust it naturally. When specific feedback is provided, one would be able to find out just how flexible the human actually is.

A

Attempted Synchronization Measures

The following Synchronization measures have been incorporated in the report:

- Mean Standard Deviation of the Phase.
- Standard Deviation of the Time to Half Impulse.
- Standard Deviation of the Time to Half Work.
- Standard Deviation of the Half Impulse Angle.

In the search for good synchronization measures, three more methods have been attempted. These methods are:

- Standard Deviation of The 30%-70% Force Slope.
- Standard Deviation of The 70% Force Angle.
- Standard Deviation of The Maximal Force Angle.

Of these methods that didn't make it, the standard deviation of the force slope has been worked out mathematically below. The 70% force angle and the maximal force angle are calculated in a similar way as $t_{30\%}$ and $t_{70\%}$: simply by linear interpolation. Therefore, no further mathematical elaboration will be given on these.

Standard Deviation of the Force Slope The force slope was defined as the average gradient between the 30% and 70% of $F_{blade,max}$ points in time. This is usually an almost straight line, as can be seen in fig. A.1. The steepness of this slope, f_{rower}, depends on the maximal force the rower achieves, and how quick after the catch he or she does that. The standard deviation of this slope gives an indication in what extend the athletes 'accelerate the boat together'. This is a term you often hear in rowing, like from Eelco Meenhorst. Blade force per rower was calculated as in eq. (A.1), eqs. (A.2) and (A.3) are used to calculate the standard deviation of the force slopes.

$$F_{blades}(t) = F_{pin,starboard}(t) + F_{pin,port}(t) - F_{handle,starboard}(t) - F_{handle,port}(t) \tag{A.1}$$

$$\bar{f}_{rower} = \text{mean}\left(\frac{\delta F_{blades}(t)}{\delta t}\right) \; \forall \; t \in t_{30\%} \ldots t_{70\%} \tag{A.2}$$

$$\sigma_{slope} = \sqrt{\frac{\sum_{n=1}^{N_{rowers}} \left(\bar{f}_{rower,n} - \mu_{\bar{f}}\right)^2}{N_{rowers}}} \tag{A.3}$$

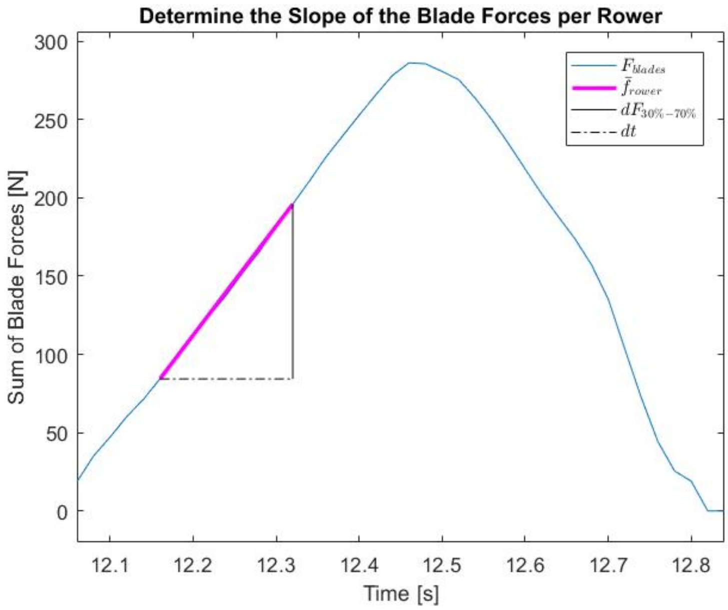


Figure A.1: Typical graph of the handle force. The part between 30% and 70% of F_{max} is approximately a straight line, although sometimes a little convex or concave. The average gradient, $\bar{f}_{rower}$, at this interval represents how quick an athlete was able to generate force. The standard deviation of these values for one stroke is the measure to what extend the rowers 'pick up the boat together'.

Bibliography

[1] A. M. Wing and C. Woodburn. The coordination and consistency of rowers in a racing eight. *Journal of Sport Sciences*, 13:187–197, 1995.

[2] A. Baudouin and D. Hawkins. Investigation of biomechanical factors affecting rowing performance. *Journal of Biomechanics*, 37(7):969–976, 2004.

[3] M. N. Brearley, N. J. de Mestre, and D. R. Watson. Modelling the rowing stroke in racing shells. *The Mathematical Gazette*, 82(495):389–404, 1998.

[4] A. Baudouin and Hawkins D. A biomechanical review of factors affecting rowing performance. *British journal of sports medicine*, 36(6):396–402, 2002.

[5] A. J. de Brouwer, H. J. de Poel, and M. J. Hofmijster. Don't rock the boat: how antiphase crew coordination affects rowing. *PloS one*, 8(1):e54996, 2013.

[6] The telegraph. `http://www.telegraph.co.uk/news/2016/08/13/theres-only-one-gold-after-5000ths-of-a-second-divides-dead-heat/`. Accessed: 2017-12-21.

[7] H. Hill. Dynamics of coordination within elite rowing crews: evidence from force pattern analysis. *Journal of Sports Sciences*, 20(2):111–117, 2002. DOI:10.1080/026404102317200819.

[8] J. Coker. *Using a boat instrumentation system to measure and improve elite on-water sculling performance*. PhD thesis, Auckland University of Technology, 2010.

[9] T. Ishiko. *Biomechanics of Rowing in Biomechanics II*. 1971.

[10] J. Warmenhoven, S. Cobley, C. Draper, A. Harrison, N. Bargary, and R.M. Smith. Assessment of propulsive pin force and oar angle time-series using functional data analysis in on-water rowing. *Scandinavian Journal of Medicine & Science in Sports*, 2017. DOI:10.1111/sms.12871.

[11] V. Kleshnev. *Biomechanics of Rowing In: Nolte V, editor. Rowing faster.* Human Kinetics, 2 edition, 2011.

[12] M. J. Hofmijster, A. J. van Soest, and J. J. de Koning. Rowing skill affects power loss on a modified rowing ergometer. *Medicine & Science in Sports & Exercise*, 40:1101–1110, 2008. DOI:10.1249/MSS.0b013e3181668671.

[13] R. M. Smith and C. Draper. Skill variables discriminate between the elite and sub-elite in coxless pair-oared rowing. In *ISBS-Conference Proceedings Archive*, volume 1, 2007.

[14] R. M. Smith and C. Loschner. Biomechanics feedback for rowing. *Journal of Sports Sciences*, 20 (10):783–791, 2002. DOI:10.1080/026404102320675639.

[15] D. H. Lamb. A kinematic comparison of ergometer and on-water rowing. *The American Journal of Sports Medicine*, 17(3):367–373, 1989.

[16] R. G. Dawson, R. J. Lockwood, J. D. Wilson, and G. Freeman. The rowing cycle: Sources of variance and invariance in ergometer and on-the-water performance. *Journal of Motor Behavior*, 30(1):33–43, 1998.

[17] A. C. Ritchie. Dynamic modeling of ergometer and on-water rowing. *Sports Technology*, 1(2-3): 110–116, 2008.

[18] M. Shimoda, T. Fukunaga, M. Higuchi, and Y. Kawakami. Stroke power consistency and 2000 m rowing performance in varsity rowers. *Scandinavian journal of medicine & science in sports*, 19 (1):83–86, 2009.

[19] V. Grigas, A. Domeika, A. Legha, D. Satkunskiene, and R.T. Toločka. Rowing force and its simulation on training facility. In *Solid State Phenomena*, volume 147, pages 712–715. Trans Tech Publ, 2009.

[20] A. J. Greene, P. J. Sinclair, M. H. Dickson, F. Colloud, and R. M. Smith. The effect of ergometer design on rowing stroke mechanics. *Scandinavian Journal of Medicine & Science in Sports*, 23 (4):468–477, 2013.

[21] A. Vinther, T. Alkjaer, I-L. Kanstrup, B. Zerahn, C. Ekdahl, K. Jensen, A. Holsgaard-Larsen, and P. Aagaard. Slide-based ergometer rowing: Effects on force production and neuromuscular activity. *Scandinavian journal of medicine & science in sports*, 23(5):635–644, 2013.

[22] G. Marcolin, A. Lentola, A. Paoli, and N. Petrone. Rowing on a boat versus rowing on an ergometer: A biomechanical and electromyographycal preliminary study. *Procedia Engineering*, 112: 461–466, 2015.

[23] V. Lippens. The temporal and dynamic synchronization of movement in coxless oared shells. *Sport kinetics*, pages 39–44, 1997.

[24] V. Kleshnev. Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 224(1):63–74, 2010.

[25] T. Černe, R. Kamnik, B. Vesnicer, J. Gros, Ž. Jerneja, and M. Munih. Differences between elite, junior and non-rowers in kinematic and kinetic parameters during ergometer rowing. *Human movement science*, 32(4):691–707, 2013.

[26] M. J. Hofmijster, E. H. J. Landman, R. M. Smith, and A. J. van Soest. Effect of stroke rate on the distribution of net mechanical power in rowing. *Journal of sports sciences*, 25(4):403–411, 2007.

[27] R. Anderson, A. Harrison, and G. M. Lyons. Rowing: Accelerometry□based feedback□can it improve movement consistency and performance in rowing? *Sports Biomechanics*, 4(2):179–195, 2005.

[28] T. Korner. Background and experience with long-term build-up programmes for high performance rowers. *FISA-Coach*, 49(3):1–6, 1993.

[29] P. Schwanitz. Applying biomechanics to improve rowing performance. *FISA coach*, 2(3):1–7, 1991.

[30] V. Kleshnev. Rowing biomechanics newsletter. Jul 2001.

[31] M. R'Kiouak, J. Saury, M. Durand, and J. Bourbousson. Joint action of a pair of rowers in a race: Shared experiences of effectiveness are shaped by interpersonal mechanical states. *Frontiers in psychology*, 7, 2016.

[32] L. S. Cuijpers, F. T. J. M. Zaal, and H. J. de Poel. Rowing crew coordination dynamics at increasing stroke rates. *PloS one*, 10(7):e0133527, 2015.

[33] L. S. Cuijpers, P. J. M. Passos, A. Murgia, A. Hoogerheide, K. A. P. M. Lemmink, and H. J. de Poel. Rocking the boat: does perfect rowing crew synchronization reduce detrimental boat movements? *Scandinavian Journal Of Medicine & Science In Sports*, 2016. DOI:10.1111/sms.12800.

[34] M. J. Hofmijster, L. L. Lintmeijer, P. J. Beek, and A. J. van Soest. Mechanical power output in rowing should not be determined from oar forces and oar motion alone. *Journal of sports sciences*, accepted 2018, to be published. https://doi.org/10.1080/02640414.2018.1439346.

[35] V. Kleshnev. Rowing biomechanics newsletter. Mar 2015.

[36] C. S. Tay and P.W. Kong. Consistency in stroke synchronisation patterns of crew-boat (k2) sprint kayaking over a four-week period. *Paper presented at 34th International Conference on Biomechanics in Sports, Tsukuba, Japan*, 34(1):1051–1054, 2016.

[37] V. Kleshnev. Rowing biomechanics newsletter. May 2014.

[38] U.S.R. Triton standaardwaarden voor afstellen. `https://usrtriton.nl/roeien/standaardwaarden-voor-afstellen/`. Accessed: 2017-09-14.

[39] BioRow Ltd. rowing speed & rigging chart. `http://www.biorow.org.uk/RigChart.aspx`. Accessed: 2017-09-14.

[40] Croker Oars sculling oars. `https://www.crokeroars.com/sculling-oars`. Accessed: 2017-09-14.

[41] EmPower Oarlock - the most effective training tool in rowing. `http://www.nkhome.com/rowing-sports/empower-oarlock`. Accessed: 2017-09-21.

[42] D. Cabrera, A. Ruina, and V. Kleshnev. A simple 1+ dimensional model of rowing mimics observed forces and motions. *Human movement science*, 25(2):192–220, 2006.

[43] Peach Innovations tour. `http://www.peachinnovations.com/Tour.htm`. Accessed: 2017-11-19.

[44] Nielsen Kellerman Australia how moving water affects your speedcoach. `https://www.nk.com.au/cms.cfm?Section=moving_water`. Accessed: 2017-10-30.

[45] mattymanuel's Blog gps (global positioning system) in sport. `https://mattymanuel.wordpress.com/2014/02/04/gps-global-positioning-system-in-sport/`. Accessed: 2017-11-02.

[46] V. Kleshnev. Estimation of biomechanical parameters and propulsive efficiency of rowing (unpublished). *Australian Institute of Sport*, 1998.

[47] M. J. Hofmijster, J. J. de Koning, and A. J. van Soest. Estimation of the energy loss at the blades in rowing: Common assumptions revisited. *Journal of sports sciences*, 28(10):1093–1102, 2010.

[48] H. Hill and S. Fahrig. The impact of fluctuations in boat velocity during the rowing cycle on race time. *Scandinavian journal of medicine & science in sports*, 19(4):585–594, 2009.

[49] V. Kleshnev. Propulsive efficiency of rowing. In *ISBS-Conference Proceedings Archive*, volume 1, 1999.

[50] Statistics - worldrowing.com. `http://www.worldrowing.com/events/statistics/`. Accessed: 2017-11-23.

[51] K. Affeld, K. Schichl, and A. Ziemann. Assessment of rowing efficiency. *International journal of sports medicine*, 14(S 1):S39–S41, 1993.