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„The comparison between two mechanical systems of rowing boats "

Sliding seat versus sliding rigger

verfasst von/ submitted by

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Statutory declaration

I hereby declare that the submitted thesis is my own unaided work. I have not used other than the declared sources and I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Vienna, 8/1/2017

Nora Zwillink

Acknowledgment

It is time to say thank you! Without a lot of people this thesis would not have been possible. Some of them I want to thank especially. First of all my supervisor, **Prof. Wolfgang Püschl**. He helped me with his knowledge and gave me input on various occasions.
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Abstract

The following paper discusses the differences in performance between two mechanical systems of rowing boats. One has a sliding seat and a fixed rigger and the other one has a fixed seat and a sliding rigger. In this study the acceleration profiles of both types were measured and the velocity profiles were derived from them. Water drag resistance is dependent on velocity squared. The lower the amplitude of velocity fluctuations, the higher the average drag results. The outcome of the study is that there is indeed an advantage for the sliding rigger boat, because it has much smaller velocity fluctuations during a rowing stroke. These smaller fluctuations originate from less moving mass in the sliding rigger boat. A comparison of power per mass for both systems shows that other influences have to be taken into account as well. Since the sliding rigger boat is forbidden in races, athletes should use it for training to improve their technical skills at a higher velocity.

Kurzfassung

Die folgende Arbeit handelt vom physikalischen Vergleich zweier mechanischer Systeme von Ruderbooten. Das Ziel ist es deren Effektivität zu prüfen um zu beurteilen bei welchem System der/die Sportler/Sportlerin sein/ihr Potenzial besser in Vortrieb umwandeln kann. Der Unterschied in den zwei mechanischen Systemen besteht darin, dass das eine einen Rollsitz und einen fest montierten Ausleger hat und das andere einen festen Sitz und einen beweglichen Ausleger hat. In meiner Arbeit wurden Beschleunigungsverläufe gemessen und daraus Geschwindigkeitsverläufe bestimmt. Denn die Geschwindigkeit spielt eine entscheidende Rolle beim Vergleich von den kennzeichnenden Parametern. Als Resultat erhalte ich, dass es Vorteile für das Rollauslegerboot gibt, denn der Geschwindigkeitsverlauf hat geringere Amplituden als der Geschwindigkeitsverlauf beim Rollsitzboot. Dennoch ist dieses System in Rennen verboten, kann aber für die Weiterentwicklung der Technik bei Athleten und Athletinnen verwendet werden.

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Chapter 1

Introduction

About 30 years ago two different mechanical systems for rowing boats were established in the rowing community. After a short period of time one system was forbidden by the 'World Rowing Federation' (FISA) due to cost reasons [1]. The aim of this thesis is to compare the commonly used system with the rejected one from a physics point of view. Hence, there is the question which of the two systems is more efficient. This means with which of the mechanical systems is it possible, with given power, to run a certain distance in the shortest time [2].

To be able to compare the two mechanical systems properly, it is necessary to consider certain parameters. In the thesis the parameters will be the energy, power averaged over one stroke respectively power per mass averaged over one stroke as well as the average water drag resistance. The energy expended over one stroke is given by

$$E = \frac{1}{2}\rho A c_{\mathrm{D}} \int_0^T v(t)^3 dt \tag{1.1}$$

where E is the energy, ρ is the density of water, A is a characteristic area, c_{D} is a non-dimensional drag coefficient and $v(t)$ is the velocity of the boat [3]. Power is then given as energy per time.

Water drag resistance is the sum of frictional and wave drag. Because of the form of the rowing boat wave drag will not play a major role [4]. Furthermore, air resistance can be neglected in most of the situations because the density of air is much less than the density of water [5]. Discarding wave drag the general law for drag resistance is given by

$$F_{\mathrm{D}} = \frac{1}{2}\rho c_{\mathrm{D}} A v^2 \tag{1.2}$$

where F_{D} is the total drag resistance, ρ is the density of the fluid, c_{D} is the drag coefficient, A is a characteristic area and v is the velocity of the object relative to the fluid. In this law the velocity profile of the object has a major importance because it influences the drag quadratically and not linear.

As the velocity changes continually, so do parameters like power. It turns out that the rower should lay his/her attention on rowing in a way that the velocity stays steady [3].

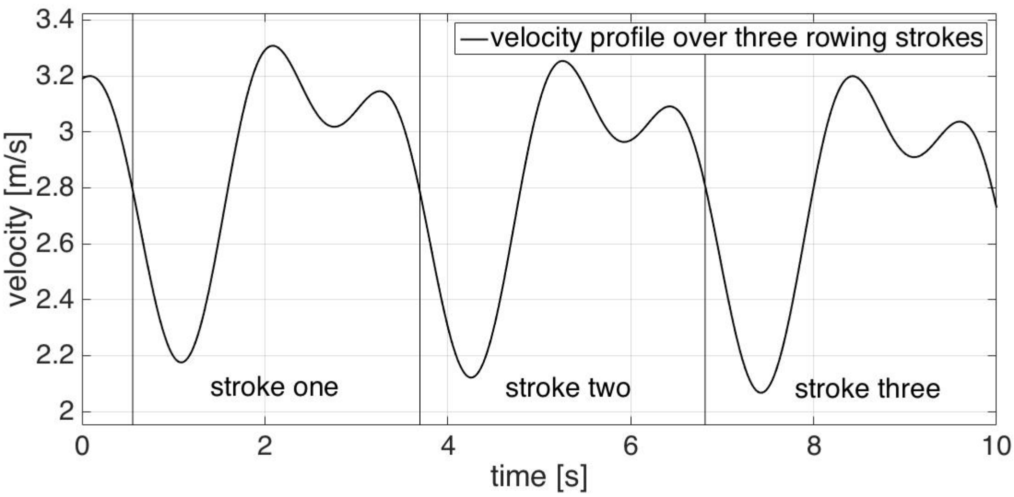


Figure 1.1: Boat velocity over three consecutive strokes in the sliding seat boat.

With regard to the two mechanical systems of rowing boats, the main difference between the two systems is the relationship between hull, rigger and seat. In the commonly used system the rigger is tightly mounted to the hull and the seat is able to slide back and forth (Fig. 1.2a). In the other system this is not the case. Here the seat is fixed and the footstretcher and rigger are a rigidly connected system which is sliding back and forth (Fig. 1.2b). In fact the movements of the rowers will be essentially the same, but the obvious advantage of the sliding rigger system is to shift less mass in the boat. Therefore, there is the expectation for a smoother velocity versus time curve during the rowing stroke. I will subsequently show that this is in fact the case and investigate the

(a)

(b)

Figure 1.2: In 1.2a the sliding seat boat is shown, in 1.2b the sliding rigger boat. In the sliding seat boat the rower moves the whole body with the seat back and forth. In the sliding rigger boat, where the rower moves only the feet back and forth (photo: Nora Zwillink).

consequences thereof.

The method of the experiments was to have five people row in both mechanical systems at two different stroke rates. The first stroke rate is a stroke rate which is used in endurance training. The second, and higher, stroke rate is simulating a rowing race. The acceleration profile of a rowing stroke will be recorded. Afterwards calculations will be done and compared.

The thesis consists of five main parts. First the introduction, followed by an introduction into the sport of rowing with all relevant components. Afterwards the relevant laws of physics will be presented and discussed. In the fourth section the actual experiments will be described and the data will be analysed. In the last section the results of the experiments will be compared to the theoretical statements done in the third section. The advantages of the sliding rigger system and its potential for the rowing community will be considered.

Chapter 2

Introduction to the sport of rowing

In the following chapter the differences and similarities of two alternative mechanical systems of rowing boats will be discussed. On the one hand the commonly used system with a sliding seat and a fixed rigger and on the other hand the system with a fixed seat and a sliding rigger. Furthermore, the types of rowing and the therefore resulting international boat categories are presented. At last, the rowing stroke will be described including the differences in the two mechanical systems.

2.1 Parts of a rowing boat

The biggest part of the boat is the hull, it determines the number of rowers the boat can carry. Typically from one to eight, however some boatbuilders also construct bigger ones (cf. [6]). Older boats are made of wood but today most of the boats are constructed of composite materials. Furthermore, the forward end of the boat is called bow and the other one stern. The right side of the boat is called starboard, the left one is called port. Footstretchers are placed in the boat's hull, which enable the athletes to physically connect to the boat. The last part is the seat, it is placed in the hull.

Another important part of a rowing boat is the rigger. The main part of the rigger is the oarlock, which holds the oar in place. In modern rowing boats the oarlock is typically placed outside of the rowing hull, these riggers are called outriggers. Furthermore, they offer a variety of customizable adjustments in order to adapt the boat's design to the body proportions of the rowers. For example, it is possible to change the height of the

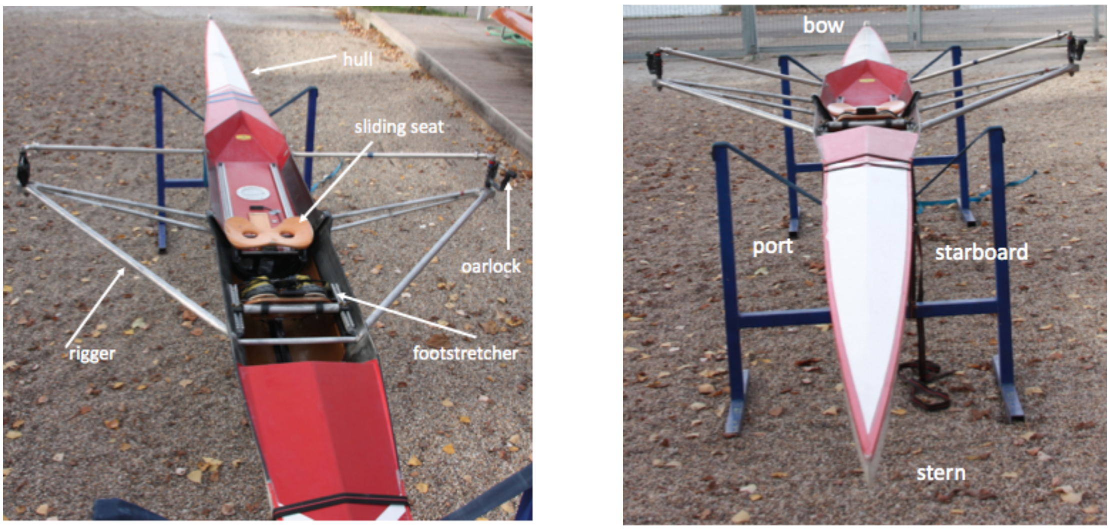


Figure 2.1: In 2.1a the hull, rigger, oarlock, sliding seat and the footstretcher of a sliding seat boat are shown. Furthermore, in 2.1b bow and stern of the boat as well as the sides of the boat, starboard and port are shown (photo: Nora Zwillink).

rigger and the oarlock with the intent of making it easier and more efficient to row. In addition, the oarlock can also be changed in its angle. In Fig. 2.1 all components of the sliding seat boat are shown.

Additionally, there is the need of oars to be able to row. Oars are put together of several parts: shaft, sleeve, button, handle and blade. The button is placed on the sleeve to prevent the oar from slipping through the oarlock towards the water. The rower holds the oar on its handle. Also, there are two different shapes for blades: Macon blades and Hatchet blades. Macon blades are used in rowing races where the rowers are under the age of 15 (not in all countries, but for example in Austria [7]) or sometimes while rowing on flowing water. Figure 2.3 shows the two different blade forms.

Furthermore there are also two typical measurements for oars. The inboard and the outboard length. The inboard length is measured from the handle to the button, the outboard length is measured from the button to the end of the oar. Inboard plus outboard length is the total length of the oar. Figure 2.2 shows the inboard and outboard length as well as the parts of an oar.

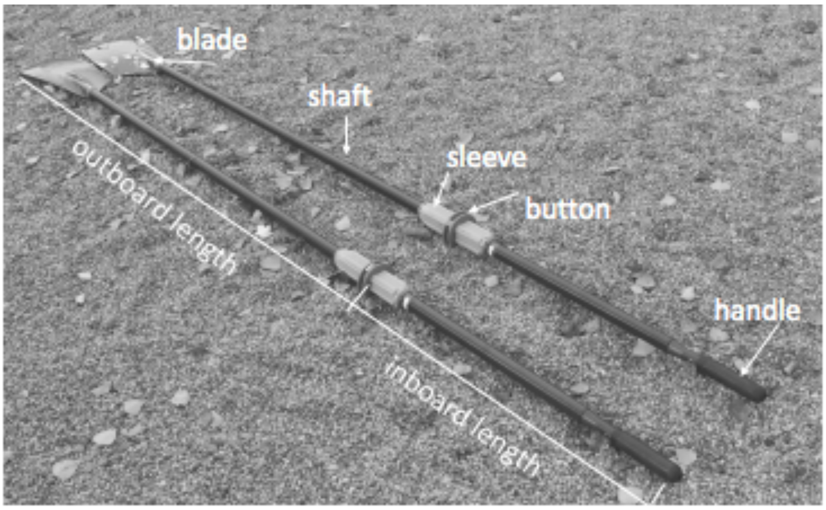


Figure 2.2: All components and typical measurements of two sculling oars are presented. An oar is composed of shaft, sleeve, button, handle and blade. Furthermore these oars have a Hatchet blade (photo: Nora Zwillink).

(a) [8]

(b) [8]

Figure 2.3: 2.3a shows a Hatchet blade which is normally used in race rowing. And 2.3b shows a Macon blade which is used for rowers under the age of 15 or while rowing on flowing water [7].

2.1.1 The sliding rigger boat

The sliding rigger boat is a non-conventional rowing boat system. It was used in races in the years of 1981 and 1982. In 1983 though the system was banned by FISA [1].

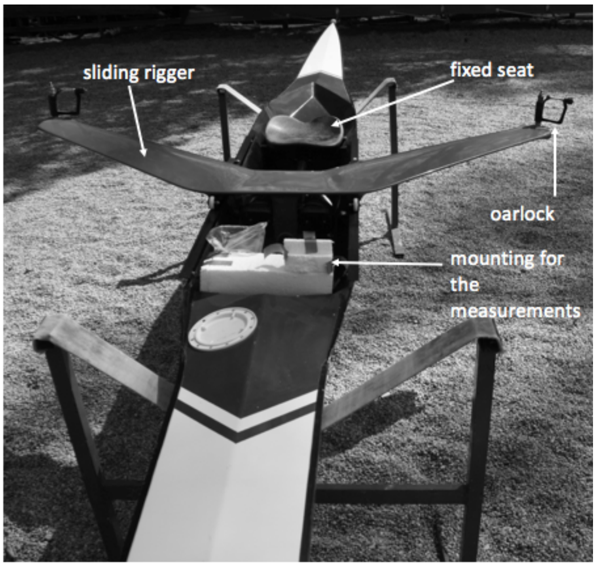


Figure 2.4: The figure shows a sliding rigger boat and its parts. In comparison to the sliding seat boat the seat is fixed and the rigger is much bigger and able to slide. Furthermore the mounting for the measurements is shown (photo: Nora Zwillink).

The system has all the above described parts of a rowing boat, but with a sgnificant difference. The difference is that the rigger is not fixed to the saxboard, therefore it is able to slide, where the seat is fixed in the hull. Additionally the footstretcher is connected to the rigger, so that the rower has the connection to the rigger and is able to push it back and forth. In Fig. 2.4 the parts of a sliding rigger boat are shown.

2.2 Types of rowing

Historically two techniques of rowing have evolved. First, sweep rowing was developed, where rowers have one oar in both hands. Later sculling, where rowers have one oar in each hand. The significant differences between these two oars are that sweep oars have bigger blades than sculling oars and that sweep oars are longer than sculling oars.
In elite rowing the athletes are also classified into two groups according to their weight. There is a lightweight and a heavyweight class. Lightweights are only allowed to have a certain weight and are weighed shortly before their individual races. Women are allowed

a maximum weight of 59kg in the single scull and in a team they are only allowed to have an average weight of 57kg. In comparison, for men the maximum weight is 72.5kg for the single scull and in a team they are only allowed to have an average of 70kg [9].

2.2.1 International boat categories

As mentioned above the boats are classified according to the size of the hull. Together with the different groups of weight and styles of rowing, there exist a lot of different boat classes. In international races boats are only used, where one, two, four or eight people can row, some of them also have a coxswain, who is responsible for steering the boat. In Fig. 2.5 and Fig. 2.6 the international boat classes which are raced at the World Championships are shown. In the Olympic Games Regatta fewer boat classes are raced than in the World Championships. In the Olympic Games in Rio 2016 there were fourteen different boat classes: W1x, W2x, W2-, LW2x, W4x, W8+, M1x, M2x, M2-, LM2x, M4x, M4-, LM4- and M8+, where M is standing for men, W is standing for women, L is standing for the lightweight category, the number for the qunatity of rowers, 'x' for sculling, '-' for without coxswain, '+' for with coxswain (cf. Fig. 2.5 and Fig. 2.6[1]). The racing distance is 2000m [9].

In the Paralympic Games in Rio 2016 there were four different boat classes: ASW1x, ASM1x, TAMix2x, LTAMix4+, where A is standing for arms, S is standing for shoulders, T is standing for trunk, L is standing for legs, 'Mix' is standing for a boat, where men and women row together, the number for the quantity of rowers, 'x' for sculling and '+' for with coxswain[2]. The racing distance is 1000m [9].

[1] see also appendix
[2] see also appendix

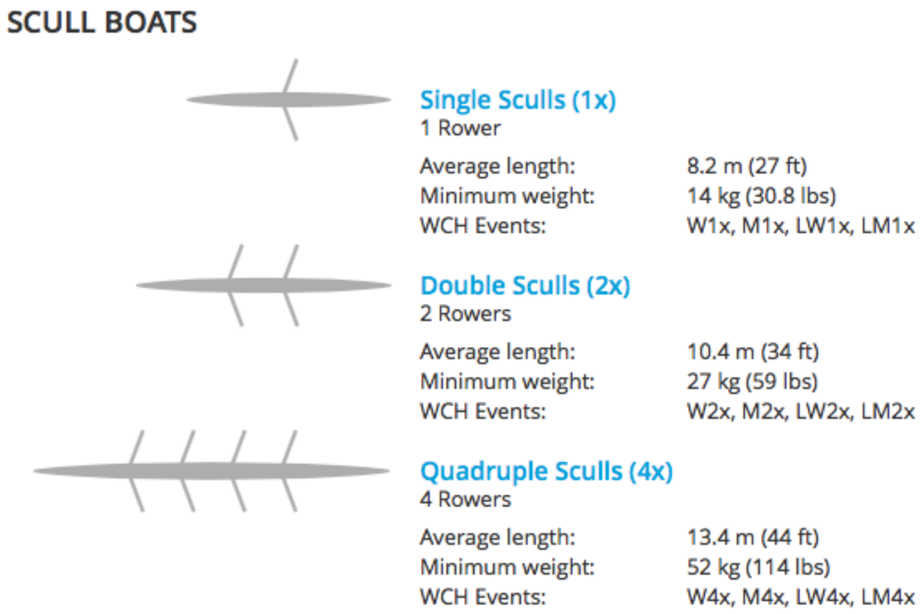


Figure 2.5: The international sculling boat categories are shown. They are all raced at the World Championships. At the Olympic Games Regatta in Rio only the W1x, M1x, W2x, M2x, LW2x, LM2x, W4x and M4x were raced, where M is standing for male, W is standing for female, L is standing for lightweight, the number for the quantity of rowers in the boat and 'x' for sculling (photo: [9]).

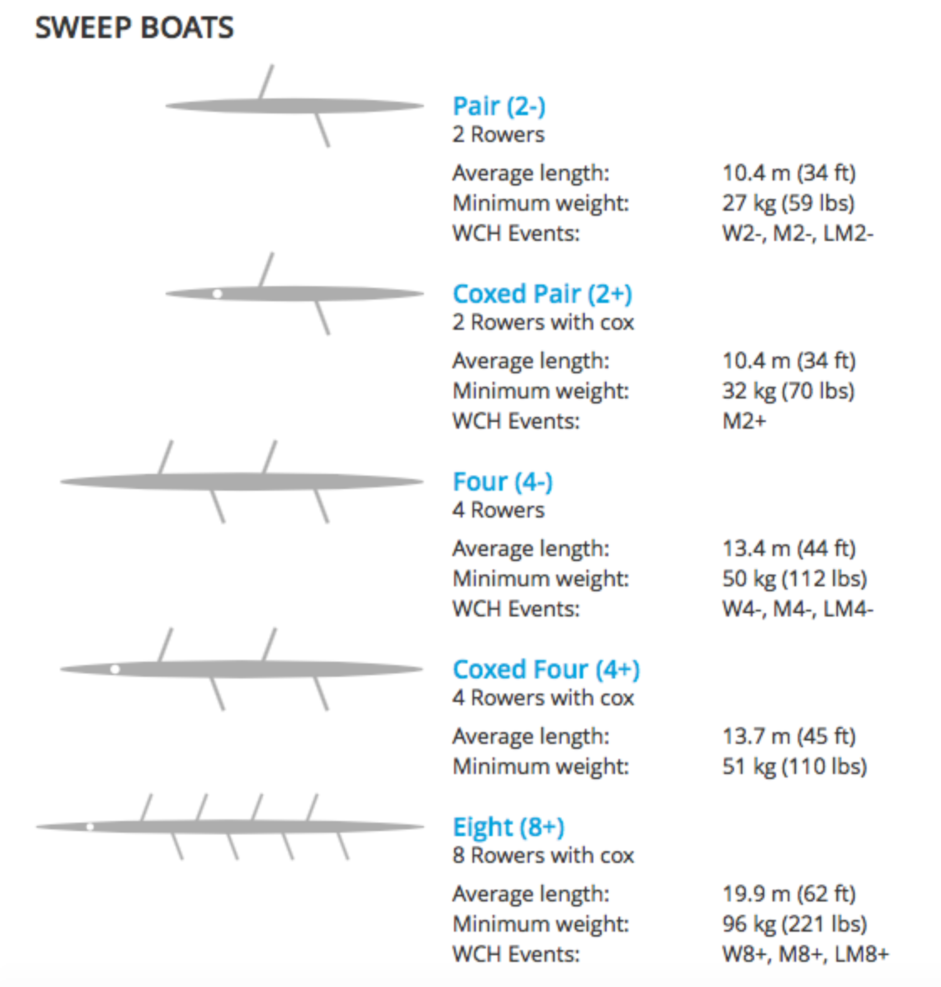


Figure 2.6: The international sweep boat categories are shown. Except for the 'Coxed Four' they are all raced at the World Championships. At the Olympic Regatta in Rio only the W2-, M2-, M4-, LM4-, W8+ and M8+ were raced, where M is standing for male, W is standing for female, L is standing for lightweight, the number is standing for the quantity of rowers in the boat, '-' is standing for 'without coxswain' and '+' is standing for 'with coxswain' (photo: [9]).

2.3 The rowing stroke

After examining the parts of a rowing boat system, I am going to describe the rowing stroke itself. The rowing stroke can be divided into four sections: the catch, the drive phase, the finish and the recovery phase (cf. [10]). The description of the stroke and the similarities and differences between the two mechanical systems are presented in Tab. 2.1. Furthermore the four sections are presented in Fig. 2.7.

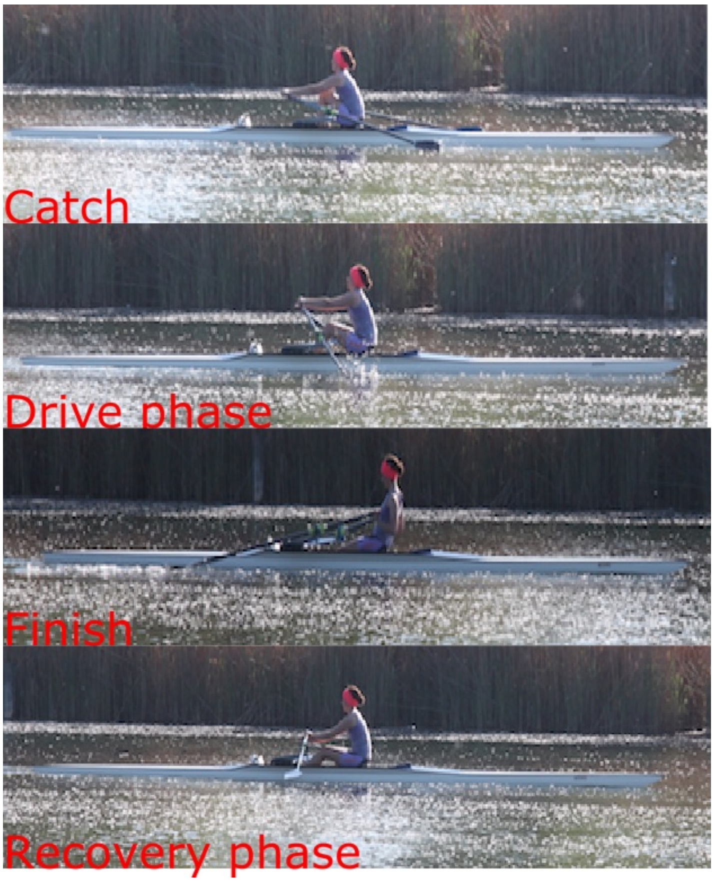


Figure 2.7: The figure shows the four sections of the rowing stroke. The topmost illustration shows the catch position, followed by the drive phase, the finish position and last the recovery phase (photo: Nora Zwillink).

Table 2.1: Description of the rowing stroke

	sliding seat		sliding rigger
Catch	Seat is in the farthest position towards the stern	The knees are bent, arms outstretched, blades are vertically positioned in the water	Rigger is in the farthest position towards the bow
Drive phase		The legs begin to stretch, then the upper body starts to uncoil. At the end of the drive phase the arms are pulled to the upper body.	
Finish	Seat is in the farthest position towards the bow.	The upper body is in a slightly bent backwards position, the legs are stretched, the blades are getting out of the water. The blades get turned from a vertical to a horizontal position.	The rigger is in the farthest position towards the stern.
Recovery phase	The seat is moving towards the stern.	The movement takes place in the opposite direction of the drive phase: the arms are stretched, the upper body is bent forward, the knees start to bend. The blades get turned from a horizontal to a vertical position.	The rigger is moving towards the bow.

Chapter 3

Physics of rowing

In the following chapter the physics behind the rowing motion is described. First, an appropriate coordinate system is defined. Then the relevant forces are introduced and the equations of motion are derived. Finally, power, energy and efficiency are discussed.

3.1 Coordinate system

A coordinate system will be set to describe the rowing motion. Following the cartesian model of [11] and [12], the x-axis is set along the boat's length axis, the y- and z- axis are perpendicular to the x-axis, where the x-y-plane defines the water surface. Furthermore is the z-axis crossing the x-y-plane in the origin chosen at a given starting point at rest relative to the water. In Fig. 3.1 and 3.2 the axes of the coordinate systems are shown. The coordinate system is used for both mechanical systems investigated in this study.

3.2 Forces that are affecting the rowing stroke

In the following section all forces will be discussed which are affecting the rowing motion. The forces are [11]

- Water drag resistance F_{D}
- Shape resistance of the blade F_{B}

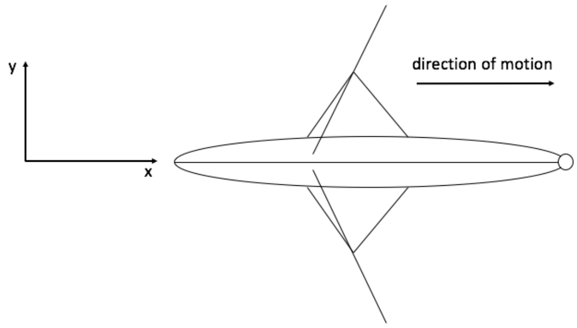


Figure 3.1: The x- and y-axis of the coordinate system are shown. The origin is chosen at a given starting point at rest relative to the water (adapted from [11]).

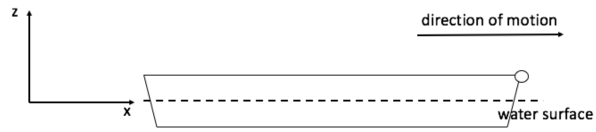


Figure 3.2: The x- and z-axis of the coordinate system are shown. The origin is chosen at a given starting point at rest relative to the water (adapted from [11]).

- Buoyant force of the hull F_{A}
- Gravitational force F_{G}
- Inertia of the total system F_{I} (includes rower, oars and boat)

3.2.1 Water drag resistance $F_{\mathbf{D}}$

The water drag resistance is composed of two main types of resistance. 85% of the total water drag resistance can be dedicated to frictional resistance and only 15% to wave drag resistance [4] [13]. The general water resistance F_{D} is given as [14]

$$F_{\mathrm{D}} = \frac{1}{2}\rho A c_{\mathrm{D}} v^2 \tag{3.1}$$

where ρ is the density of the fluid, c_{D} is the drag coefficient, A is a characteristic area and v is the velocity of the object relative to the fluid. In the case of rowing velocity changes over a stroke. Therefore the average drag resistance F_{D} can be described as

$$F_{\mathrm{D}} = \frac{1}{T}\frac{1}{2}\rho A c_{\mathrm{D}} \int_0^T v(t)^2 dt \tag{3.2}$$

where A is a characteristic surface, c_{D} is the drag coefficient, T is the period time for one stroke and $v(t)$ is the velocity profile over a stroke. Additionally for rowing boats A is not the projected area of the boat normal to the direction of motion, but the wetted surface of the hull [12]. Furthermore, c_{D} is mostly dependent on the boat's shape and the Reynolds number. The Reynolds number is given as

$$\mathrm{Re} = \frac{vL}{\nu} \tag{3.3}$$

where L is a characteristic length, v is the velocity and ν is the kinematic viscosity of the fluid [15]. The Reynolds number is a dimensionless number that characterises fluid flow. It is used in ship design to predict a hull drag force from model testing.
In the following

$$C = \frac{1}{2}\rho c_{\mathrm{D}} A \tag{3.4}$$

is called the prefactor.
The wetted surface of the hull depends on displacement and therefore on the weight of the rower. This surface can be estimated by taking the displaced volume to the two third power, respectively

$$A \propto D^{2/3} \tag{3.5}$$

where A is the wetted surface and D is the displaced volume [12]. Furthermore the displaced volume D can be calculated after Archimedes' law as

$$mg = \rho D g \Leftrightarrow D = \frac{m}{\rho} \tag{3.6}$$

where m is the total mass of the system, g is the gravitational acceleration, ρ is the density of the fluid and D is the displaced volume [16].
As rowing is a cylcic motion, the acceleration and therefore the velocity is varying periodically over the stroke. So it is possible to describe the velocity profile as a Fourier series, namely

$$v(t) = v_0 + \sum_{n=1}^{k} A_n cos(n\omega t) + \sum_{n=1}^{k} B_n sin(n\omega t) \tag{3.7}$$

where $v(t)$ is the velocity profile, v_0 is the mean velocity, A_n, B_n are suitable Fourier coefficients and $\omega = \frac{2\pi}{T}$ where T is the period time for one stroke. To minimise the water drag resistance Eq. 3.2 has to be minimised. As ρ, A and c_D are constants only the integral over the velocity can change. In Eq. 3.7 the Fourier coefficients A_n and B_n characterise the velocity fluctuations. In order to keep drag resistance minimal, the fluctuations of the velocity should be as small as possible [3].

3.2.2 Shape resistance of the blades F_B

Oars are the only connection between the rower-boat system and the propulsion of the boat [13]. When the rower is pulling on the oar handle the blade is moving through the water. Because of Newton's third law there is a force against the occuring one, this one is called the oar blade force F_B [16]. Following the model of [17], the oar blade force can be divided into two components, namely the lift force $F_{\mathrm{B_L}}$ and the drag force $F_{\mathrm{B_D}}$. The lift force $F_{\mathrm{B_L}}$ on the blade can be calculated as

$$F_{\mathrm{B_L}} = \frac{1}{2}\rho A_\mathrm{B} c_{\mathrm{B_L}} v^2_{\text{B-rel}} \tag{3.8}$$

where ρ is the density of water, A_B is the area of the blade, $c_{\mathrm{B_L}}$ is a suitable coefficient and $v_{\text{B-rel}}$ is the resultant blade velocity. Figure 3.3 shows the relationship between the velocity of the blade in x-direction relative to the water and the veolcity of the blade in y-direction. As a result of geometrical relations, the consequent blade velocity can be calculated as

$$v_{\text{B-rel}} = \sqrt{v^2_{\mathrm{B_x-abs}} + v^2_{\mathrm{B_y}}} \tag{3.9}$$

where $v_{\mathrm{B_x-abs}}$ is the velocity of the blade in x-direction relative to the water and $v_{\mathrm{B_y}}$ is the velocity of the blade in y-direction.
Additionally the drag force $F_{\mathrm{B_D}}$ of the blade is given as

$$F_{\mathrm{B_D}} = \frac{1}{2}\rho A_\mathrm{B} c_{\mathrm{B_D}} v^2_{\text{B-rel}} \tag{3.10}$$

where A_B is the area of the blade, $c_{\mathrm{B_D}}$ is the blade drag coefficient and $v_{\text{B-rel}}$ is the velocity of the blade relative to the water.

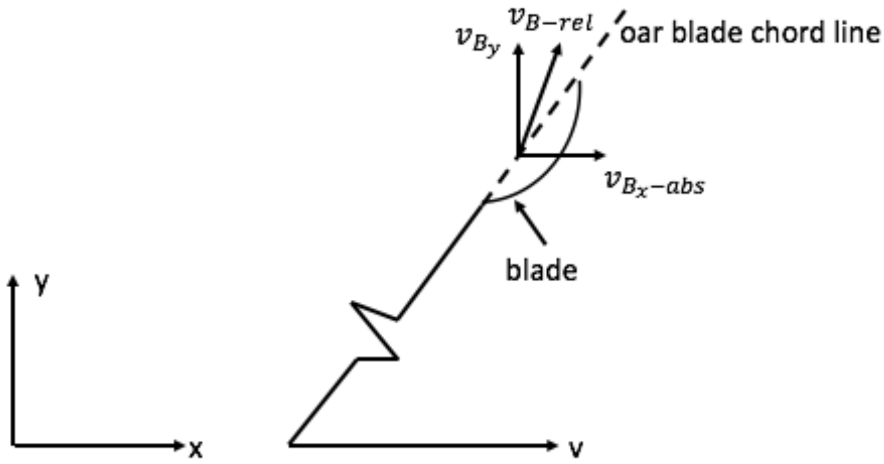


Figure 3.3: The figure shows the relation between the velocity of the blade in x-direction relative to water (v_{B_x-abs}), the velocity of the blade in y-direction (v_{B_y}) and the blade velocity (v_{B-rel}) resulting thereof. v is the velocity of the boat in moving direction (adapted from [17]).

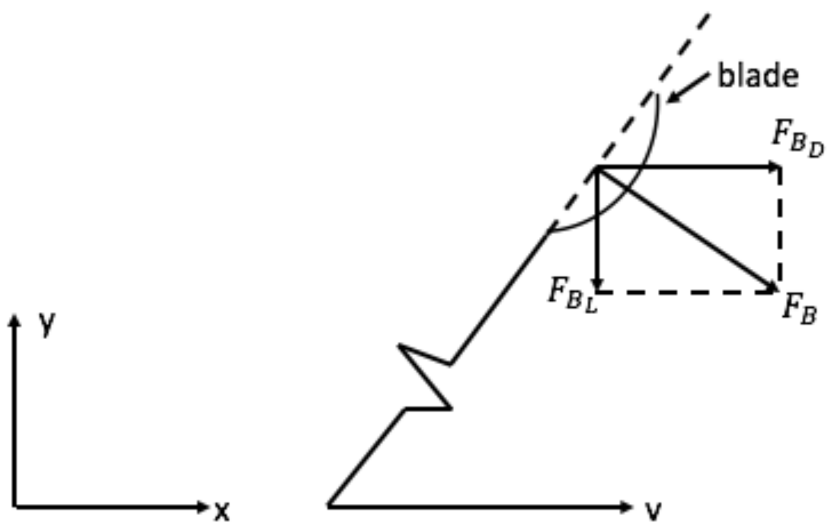


Figure 3.4: The figure shows the relation between the blade lift force ($F_{\mathrm{B_L}}$) the blade drag force ($F_{\mathrm{B_D}}$) and the thereof resulting blade force (F_{B}). v is the velocity of the boat in moving direction (adapted from [17]).

With the geometrical relations of the drag and lift force of the blade, shown in Fig. 3.4, it is possible to calculate the resulting blade force F_{B} as

$$F_{\mathrm{B}} = \sqrt{F_{\mathrm{B_L}}^2 + F_{\mathrm{B_D}}^2} \tag{3.11}$$

where $F_{\mathrm{B_L}}$ is the blade lift force and $F_{\mathrm{B_D}}$ is the blade drag force [17].

3.2.3 Buoyant force of the hull $F_{\mathbf{A}}$

The buoyant force F_{A} is given by Archimede's principle:

> 'The vertical force of buoyancy on a submerged object is equal to the weight of fluid the object displaces' [18]

Therefore, the vertical equilibrium is achieved through the balancing of the gravitational force F_{G} (cf. Sec. 3.2.4) and the buoyancy force F_{A} [13]. Furthermore a dynamical lift force is acting on the hull [15].

3.2.4 Gravitational force $F_{\mathbf{G}}$

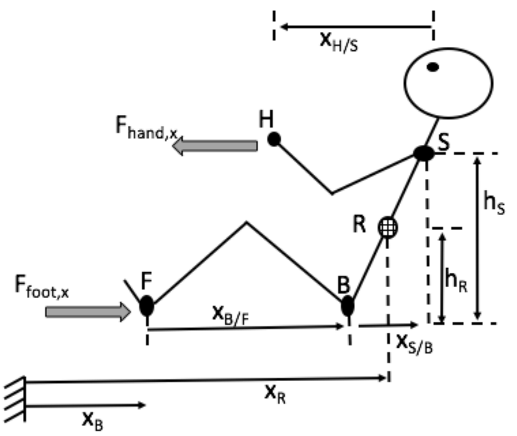
The gravitational force F_{G} is given by [16]

$$F_{\mathrm{G}} = mg \tag{3.12}$$

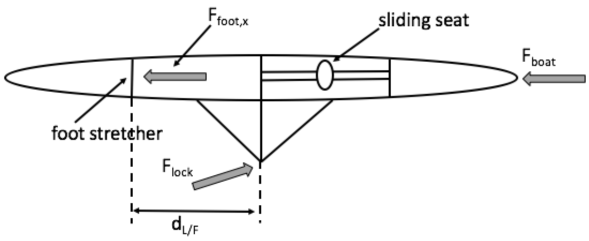
where m is the total mass of the system, which includes the fully equipped boat, the rower and the oars and g is the gravitational acceleration constant with a value of $g \approx 9.81 \frac{m}{s^2}$ for European latitudes [16]. The exact value of the gravitational acceleration depends on latitude, elevation and the geological place.

3.3 Equations of motion

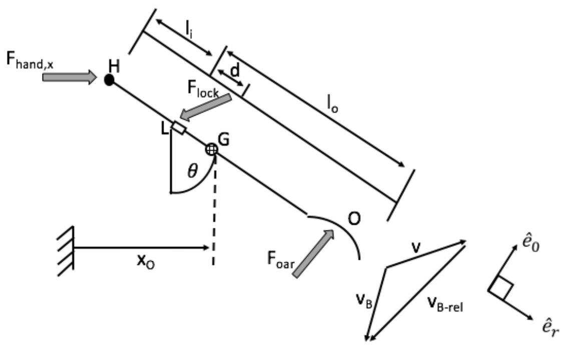
In physics, motions can be described by using appropriate equations which contain all forces acting on the system. The following model describes the rowing motion for a sliding seat boat and is taken from [12]. The model assumes perfect synchronicity on both sides of the boat and does not account for splash and missed water at the catch.



(a) rower



(b) boat



(c) oar

Figure 3.5: In Fig. 3.5a all measurements needed to describe the equations of motion affecting the rower are shown. Furthermore in Fig. 3.5b all measurements are shown for the boat and in Fig. 3.5c for the oar. l_i, l_o, d, h_R, h_S and $d_\text{L/F}$ are geometrical constants. In comparison to x_R, x_B, x_O, $x_\text{B/F}$, $x_\text{S/B}$, $x_\text{H/S}$, Θ, v, v_B, $v_\text{B-rel}$ which are time dependent quantities. For further explanation of the quantities see text respectively the list of symbols in the appendix (adapted from [12]).

Furthermore the model differentiates between the drive and the recovery phase of the stroke. In a first step the motion of the rower, boat and oars will be discussed, followed by the drag on the boat and the oar blade force to reach seven equations in total. All variables and model constants are shown in Fig. 3.5.
Starting with the drive phase of the the stroke. The linear momentum for the rower in x-direction (= moving direction) $F_{\mathrm{R,x}}$ is given by

$$\sum F_{\mathrm{R,x}} = m_{\mathrm{R}}\ddot{x}_{\mathrm{R}} \tag{3.13}$$

$$\text{where } \sum F_{\mathrm{R,x}} = -F_{\mathrm{hand,x}} + F_{\mathrm{foot,x}} \tag{3.14}$$

$$\text{as well as } F_{\mathrm{hand,x}} = F_{\mathrm{hand}} \cos(\Theta) \tag{3.15}$$

where m_{R} is the mass of the rower, x_{R} is the absolute x-position of the rower's center of mass relative to the starting line, $F_{\mathrm{hand,x}}$ is the handle force in x-direction, $F_{\mathrm{foot,x}}$ is the force on the footstretcher in x-direction and Θ is the oar angle.
The linear momentum for the boat in x-direction $F_{\mathrm{B,x}}$ is given by

$$\sum F_{\mathrm{B,x}} = m_{\mathrm{B}}\ddot{x}_{\mathrm{B}} \tag{3.16}$$

$$\text{where } \sum F_{\mathrm{B,x}} = -F_{\mathrm{boat}} - F_{\mathrm{foot,x}} + F_{\mathrm{lock}} \tag{3.17}$$

where m_{B} is the mass of the boat, x_{B} is the absolute x-position of the footstretcher relative to the starting line, F_{boat} is the force acting against the boat and F_{lock} is the force on the oarlock.
And last the linear momentum of the oar in x-direction $F_{\mathrm{O,x}}$ is given by

$$\sum F_{\mathrm{O,x}} = m_{\mathrm{O}}\ddot{x}_{\mathrm{O}} \tag{3.18}$$

$$\text{where } \sum F_{\mathrm{O,x}} = F_{\mathrm{hand,x}} - F_{\mathrm{lock}} + F_{\mathrm{oar}} \cos(\Theta) \tag{3.19}$$

where m_{O} is the mass of the oar, x_{O} is the absolute x-position of the oar's center of mass relative to the starting line and F_{oar} is the force on the oar blade.
Additionally the following relation is valid

$$-F_{\mathrm{hand,x}} l_{\mathrm{i}} \cos(\Theta) + F_{\mathrm{oar}} l_{\mathrm{o}} = m_{\mathrm{O}} d \cos(\Theta) \ddot{x}_{\mathrm{B}} + (I_{\mathrm{G}} + m_{\mathrm{O}} d^2)\ddot{\Theta} \tag{3.20}$$

where l_{i} is the inboard length of the oar, l_{o} is the outboard length of the oar, d is the distance between the oarlock and the center of gravity of the oar and I_{G} is the polar

moment of inertia of the oar blade about its center of mass.
To describe the rower's (x_{R}) and the oar's (x_{O}) center of mass only kinematic relations are used, namely

$$x_{\mathrm{R}} = x_{\mathrm{B}} + x_{\mathrm{B/F}} + r x_{\mathrm{S/B}} \tag{3.21}$$

$$\text{where } r = \frac{h_{\mathrm{R}}}{h_{\mathrm{S}}} \tag{3.22}$$

$$\text{and } x_{\mathrm{O}} = x_{\mathrm{B}} + d_{\mathrm{L/F}} + d \sin(\Theta) \tag{3.23}$$

where $x_{\mathrm{B/F}}$ is the distance between bottom and feet, r is the ratio between the height of the rower's center of gravity ($\mathrm{h_R}$) to the height of the shoulder of the rower ($\mathrm{h_S}$), $x_{\mathrm{S/B}}$ is the distance between shoulder and bottom and $d_{\mathrm{L/F}}$ is the distance between footstretcher and oarlock. After differentiating Eq. 3.21 and Eq. 3.23 twice the result is

$$\ddot{x}_{\mathrm{R}} = \ddot{x}_{\mathrm{B}} + \ddot{x}_{\mathrm{B/F}} + r \ddot{x}_{\mathrm{S/B}} \tag{3.24}$$

$$\ddot{x}_{\mathrm{O}} = \ddot{x}_{\mathrm{B}} + d\ddot{\Theta} \cos(\Theta) - d\dot{\Theta}^2 \sin(\Theta) \tag{3.25}$$

Because the rower has always grip on the oar handle the fore-aft positions of the rower's hand and the oar handle relative to the footstretcher are the same. Therefore the following equation is

$$d_{\mathrm{L/F}} - l_{\mathrm{i}} \sin(\Theta) = x_{\mathrm{B/F}} + x_{\mathrm{S/B}} - x_{\mathrm{H/S}} \tag{3.26}$$

where $x_{\mathrm{H/S}}$ is the distance between hand and shoulder, valid. Furthermore only the movement of the arm in fore-aft position is considered and hence the actual path, which is nearly the arc of a circle, neglected. If Eq. 3.26 is differentiated twice the result is

$$l_{\mathrm{i}} \ddot{\Theta} \cos(\Theta) = \ddot{x}_{\mathrm{H/S}} - \ddot{x}_{\mathrm{B/F}} - \ddot{x}_{\mathrm{S/B}} + l_{\mathrm{i}} \dot{\Theta}^2 \sin(\Theta) \tag{3.27}$$

For the recovery phase the equations are the same except for the fact that the force on the oar blade is zero (air resistance is neglected). As stated in Sec. 3.2.1 the drag force can be written as Eq. 3.1 or rewritten as

$$F_{\mathrm{D}} = C v^2 \tag{3.28}$$

where F_D is the water drag resistance, C is the prefactor and v is the velocity of the boat relative to the water. In addition the oar blade force F_{oar} is given by [19] as

$$F_{oar} = C_B(v_O\hat{e}_\Theta)^2 = C_B(l_o\dot{\Theta} + \dot{x}_B\cos(\Theta))^2 \tag{3.29}$$

where C_B is the blade coefficient given as $C_B = \frac{1}{2}\rho c_B A_B$ where ρ is the density of water, c_B is a suitable coefficient and A_B is the area of the blade and $v_0\hat{e}_\Theta$ is the oar blade velocity in $\hat{e}_\Theta$-direction.

Summarising Eq. 3.13-Eq. 3.29, there is a system of seven equations with ten unknowns. In order to be able to solve this system three variables must be determined. The equations can be written into a matrix system

$$[M]z = b \tag{3.30}$$

where

$$M = \begin{pmatrix} m_R & 0 & 0 & 0 & 0 & 0 & 0 & 1/\cos(\Theta) & -1 & 0 \\ 0 & m_B & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & m_O & 0 & 0 & 0 & 0 & -1/\cos(\Theta) & 0 & 1 \\ 0 & m_O d\cos(\Theta) & 0 & 0 & 0 & 0 & I_G & s & 0 & 0 \\ -1 & 1 & 0 & 1 & r & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & d\cos(\Theta) & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -1 & l_i\cos(\Theta) & 0 & 0 & 0 \end{pmatrix}$$

$$z = \begin{pmatrix} \ddot{x}_R & \ddot{x}_B & \ddot{x}_O & \ddot{x}_{B/F} & \ddot{x}_{S/B} & \ddot{x}_{H/S} & \ddot{\Theta} & F_{hand,\Theta} & F_{foot,x} & F_{lock,x} \end{pmatrix}^T$$

$$b = \begin{pmatrix} 0 & -F_{boat} & F_{oar,\Theta} & l_O F_{oar,\Theta} & 0 & d\dot{\Theta}^2\sin(\Theta) & l_i\dot{\Theta}^2\sin(\Theta) \end{pmatrix}^T$$

3.3.1 Equations of motion for the sliding rigger boat

The model described above was developed for the sliding seat rowing boat system. The question to raise is what changes if the model is adapted for the sliding rigger boat. In the sliding seat boat x_B is the absolute x-position of the footstretcher relative to the starting line and is therefore fixed to the boat. In the sliding rigger system this point is not fixed to the boat. Furthermore $d_{L/F}$ is the distance between the footstretcher and the oarlock. Because the rigger is moving in the sliding rigger boat, this quantity is moving its position, but not its magnitude. It can now be shown that no relative quantities change. Therefore the equation system described above (Eq. 3.30) can as well be used for the sliding rigger boat.

3.4 Power of rowing

The rowing stroke is a periodical cycle with changing velocities of the boat relative to the water. The power of the rowing motion is affected by three major factors. First the power generated by the rower, then the drag forces against the boat and third the efficiency of power utilization considering the technical skills of the rower and the rigging of the rowing boat [20] [3].
Reffering to the Encyclopaedia Britannica [21] power is stated as:

> Power in science and engineering, time rate of doing work or delievering energy, expressible as the amount of work done W, or energy transferred, divided by the time intervall t- or W/t. [...] Units of power are those of work (or energy) per unit time, such as foot-pounds per minute, joules per second (or watts)[...]. Power is expressible also as the product of the force applied to move an object and the speed of the object in direction of the force [...]. In the International System of Units power is measured in newton metres per second.

As we want to know how much power is needed on average during a rowing stroke we need to have first a look at how much energy is needed. The energy dissipated in one stroke cycle, where the boat has travelled the distance X is given by [3] as

$$E = \int_0^X F_{\mathrm{D}} dx \tag{3.31}$$

where E is the energy, F_{D} is the water drag resistance and X is the distance travelled. Because of $v = \frac{dx}{dt}$ Eq. 3.31 can also be written as

$$E = \int_0^T F_{\mathrm{D}} v dt \tag{3.32}$$

where T is the period time of the stroke and v is the velocity of the boat. T is taken in a way that it is relating to X as $X = \int_0^T v dt$. Furthermore F_D is given in Sec. 3.2.1 and can be substituted into Eq. 3.32

$$E = \int_0^T \frac{1}{2}\rho A c_\mathrm{D} v(t)^2 v(t) dt \Leftrightarrow E = \frac{1}{2}\rho A c_\mathrm{D} \int_0^T v(t)^3 dt \tag{3.33}$$

Using the prefactor C Eq. 3.33 can also be written as

$$E = C \int_0^T v(t)^3 dt \tag{3.34}$$

The goal is to minimise the energy dissipation. This is the case when v is constant. Still in the rowing motion there are always velocity fluctuations. Therefore rowers should pay attention to minimise the boat velocity changes through a rowing stroke [3].

3.5 Wave effects

As mentioned in section 3.2.1 the total water resistance is composed of the frictional drag and the wave drag. Waves are produced when the pressure on a surface is changing. This is the case when a boat is moving through the water surface and therefore disturbs the general equilibrium [4]. An important parameter dealing with wave effects is the Froude number. It is a dimensionless number and given as

$$\mathrm{Fr} = \frac{v}{\sqrt{gL}} \tag{3.35}$$

where v is the velocity of the boat, g is the gravitational acceleration and L is the length of the waterline [15]. It determines the relationship between the wave length of the generated waves and the waterline length of the boat. For boatbuilders it is necessary to find the optimal balance between the frictional and the wave drag resistance. Because low frictional resistance requires a minimum of the wetted surface of the hull. Therefore the boat length can be reduced, but with reducing the boat length the wave drag increases [4].

3.6 Efficiency of rowing

The standard definition for the efficiency η of a system is given as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{3.36}$$

where P_{out} is the power output and P_{in} is the power input [16]. Equally to that Kleshnev [22] states the efficiency for the rowing system (η_{sys}) as the product of the efficiency of the boat (η_{B}), the blade (η_{BL}) and the rower (η_{R}). The efficiency of the boat can be calculated as

$$\eta_{\text{B}} = \frac{P_{\text{min}}}{P_{\text{prop}}} \tag{3.37}$$

where P_{min} is the minimal power required for propelling the boat and rower with a constant speed equal to the average boat velocity and P_{prop} is the propulsive power at the blade. Furthermore is the efficiency for the blade η_{BL} given as

$$\eta_{\text{BL}} = \frac{P_{\text{prop}}}{P_{\text{mech}}} \tag{3.38}$$

where P_{mech} is the total mechanical power. Last, the efficiency of the rower η_{R} can be calculated as

$$\eta_{\text{R}} = \frac{P_{\text{mech}}}{P_{\text{met}}} \tag{3.39}$$

where P_{met} is the consumed metabolic power. Resulting of that the efficiency of the system can be calculated

$$\eta_{\text{sys}} = \eta_{\text{B}}\eta_{\text{BL}}\eta_{\text{R}} \tag{3.40}$$

using Eq. 3.37- 3.39 the efficiency of the system η_{sys} can now be stated as

$$\eta_{\text{sys}} = \frac{P_{\text{min}}}{P_{\text{met}}} \tag{3.41}$$

where P_{min} is the minimal power required for propelling the boat and rower with a constant speed equal to the average boat velocity and P_{met} is the consumed metabolic power.

Chapter 4

Experiments

The following chapter is about the experimental part of my thesis. The goal is to compare both mechanical systems under real circumstances. I had five rowers, of different gender, row in both boats. Starting with a stroke rate for an endurance training followed by a stroke rate that imitates a rowing race. The measurements took place on the Old Danube river in Vienna. The Old Danube is a former part of the Danube and is now a lake with no current. Afterwards the data was prepared in order to enable a comparison of certain stroke rates and get information about the efficiency of both mechanical systems. In addition one proband rowed with a GPS watch[1] for measuring the average velocity during the rowing process.

4.1 The measuring system

The measuring system consisted of two boats (one for each of the mechanical systems), a 'Sony Xperia' smartphone[2] and a mounting device for the smartphone in the boats. The 'Sony Xperia' was used to record the acceleration during the rowing stroke. The inertial acceleration sensor has an accuracy of $0.05 m/s^2$. Furthermore the 'Accelerometer Data Recorder' App was used to memorise all the data. The smartphone was placed in both boats at the same position as well as perpendicular to the water surface. To ensure that the position of the smartphone would not change during a series of measuring it

[1] Garmin fenix 3
[2] Sony Xperia MT27i

Table 4.1: Dimensions of the boat

	sliding seat	sliding rigger
total length	(8.155 ± 0.001)m	(7.835 ± 0.001)m
maximum width of the hull	(0.283 ± 0.001)m	$(0.283 \pm 0.001)m$
total mass (= fully rigged shell including the measuring system)	(15.6 ± 0.05)kg	(19.15 ± 0.05) kg

was fixed to an adapted styrofoam mounting. A 'Toledo' scale[3] was used to weigh all included parts. The scale has an accuracy of $0.05kg$. For helping the rowers keep on the right stroke rate a 'Stroke Coach'[4] was placed in the boat.

4.1.1 The boats used

The boats were both built by the Austrian boatbuilder M. Schellenbacher[5]. They are approximately for the same weight category of rowers. In Tab. 4.1 the boats are compared in their measurements.

4.1.2 The oars used

The same oars were used for both types of the boats. They were 'Concept 2' oars[6], with specifications that they had a Skinny shaft, smoothie blade, vortex edge and Medflex. The oars had the measurements of:

- Inboard length $l_\mathrm{i} = (0.880 \pm 0.001)m$
- Outboard length $l_\mathrm{o} = (2.850 \pm 0.001)m$
- Mass of one oar $m_\mathrm{O} = (1.55 \pm 0.05)kg$

[3]Tolede scale, model number 8140, max. 150kg, min 1kg, accuracy $\pm 0.05kg$
[4]Stroke Coach with surge rate, SKU:0125, Nielsen-Kellerman, 21 Creek Circle Boothwyn, PA 19061
[5]Schellenbacher GmbH, 4020 Linz, Am Winterhafen 15
[6]'Concept2' c/o Gebrüder Weiss GmBH, 6800 Feldkirch, Reichsstraße 149

4.1.3 Selection of the rowers

The rowers were selected according to the following criteria:

- They should be experienced in rowing a single scull.
- They should be male and female.
- They should have different sizes and mass.

After that selection I did my measuring process with five rowers. Four of them were female and one was male. Furthermore only rower C was experienced in rowing in a sliding rigger boat. The others have never rowed in this system. In Tab. 4.2 the specifications of the rowers are listed.

Table 4.2: Rowers

rower	mass of rower [kg]	gender	wind conditions during the measuring
A	88.65 ± 0.05	female	no wind
B	67.65 ± 0.05	female	head wind
C	56.90 ± 0.05	female	down wind
D	82.50 ± 0.05	female	down wind
E	70.60 ± 0.05	male	head wind

4.1.4 Measuring process

The measuring process started with weighing all components of the included material, as well as measuring the dimensions of the boats. The rowers were weighed and then started to row first in the sliding seat boat. To warm up and get familiar with the boat they rowed to a certain starting point, where the actual measuring started. After arriving at the starting point they rowed five minutes with a stroke rate of 20. Then they stopped rowing and turned the boat to get back to the starting point. Followed by five minutes of rowing but now with a stroke rate of 28. Afterwards they changed to the sliding rigger boat and made the same sequence again.

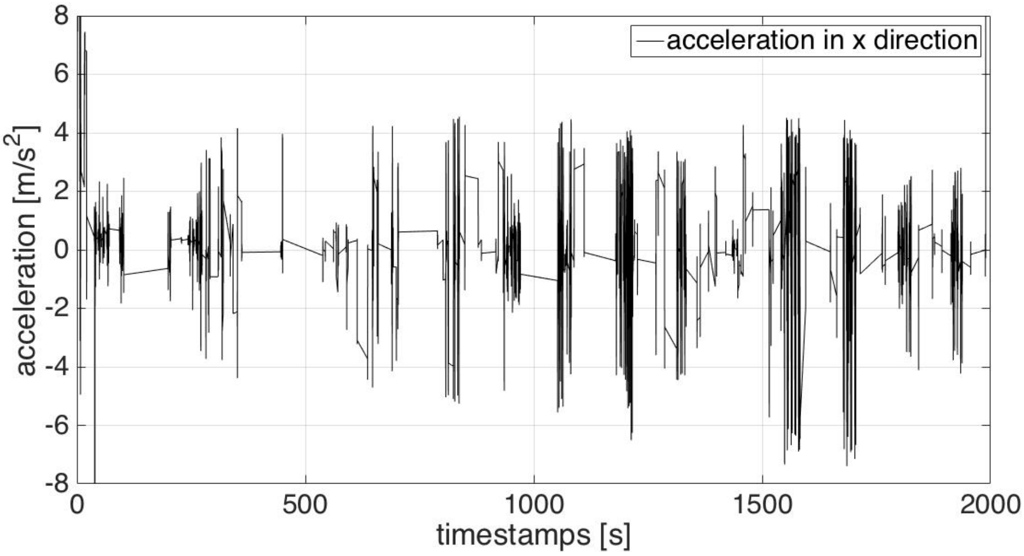


Figure 4.1: The diagram shows the whole measuring period of rower C in the sliding seat boat. The acceleration in moving direction is plotted against the time. The data is really noisy and some data points are missing (horizontal lines).

4.2 Preparation of data

The following section is about the preparation of the data gained during the measuring process. This was done with Matlab[7].
Figure 4.1 shows a typical data set of a whole measuring process. The acceleration of the boat in moving direction is plotted against the time. The data shows on one hand that it is really noisy and on the other hand that data points are missing. Where data points are missing the diagram shows horizontal lines. The intervals with missing data are probably due to temporal failure of the measuring system.
Therefore it was necessary to prepare the data. This was done in three steps.

1. First step was to sort the data in sections where consecutive strokes were recorded. For example, Fig. 4.2 shows the acceleration data of six strokes in the sliding rigger boat at a stroke rate of twenty.

[7] mathworks.org, USA

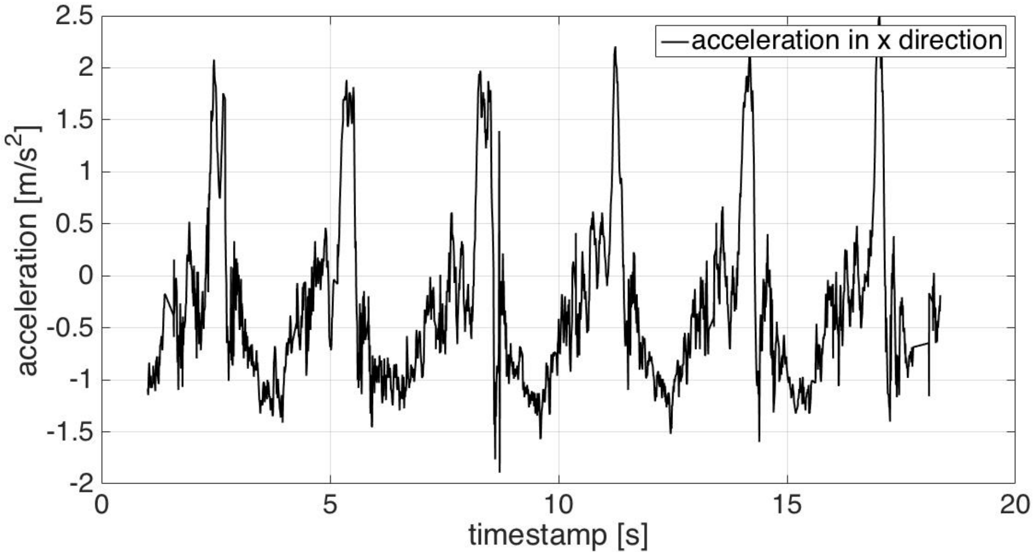


Figure 4.2: The diagram shows a section of consecutive strokes of rower D in the sliding rigger boat at a stroke rate of 20. The acceleration in moving direction is plotted against the time.

2. Second step was to use a moving average filter over the obtained sections. The moving average filter is a typical filter used in digital signal processing and it reduces random noise to retain a sharp step response. It operates by averaging a certain number of points from the input signal to produce each point in the output signal. The number of points of averaging can be set independently for every section [23].

3. Last the filtered data was fitted with a Fourier function. The fourier function in general form is given as

$$f(t) = a_0 + \sum_{n=1}^{k} a_n cos(n\omega x) + \sum_{n=1}^{k} b_n sin(n\omega x) \quad (4.1)$$

   where $\omega = \frac{2\pi}{T}$ and T being the period time for one stroke. For example, Fig. 4.3 shows on the one hand the filtered data gained in step two (black line) and the corresponding Fourier fit (red line) of rower E in the sliding rigger boat.

As a result there are now datasets of acceleration over a certain amount of rowing strokes in the sliding seat and the sliding rigger boat as well with the different rowers.

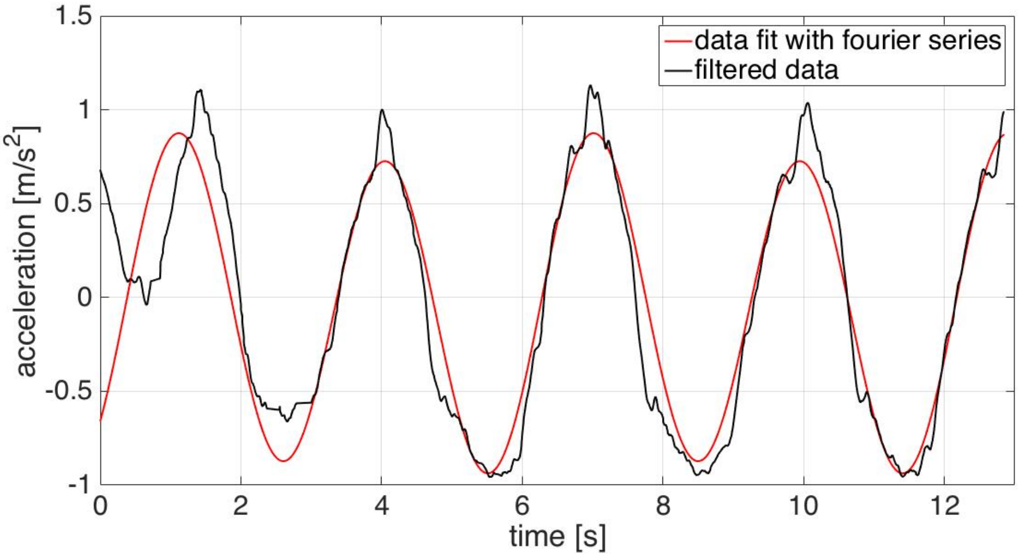


Figure 4.3: The diagram shows the acceleration of four strokes in the sliding rigger boat of rower E. The black line is the filtered data and the red line is the Fourier fit of it.

Now it is possible to extract data for further calculations such as the velocity profile or the required energy.

4.3 Different acceleration profiles of the rowers

The following section shows some acceleration profiles for different rowers and stroke rates. In Fig. 4.4 and Fig. 4.5 a stroke rate of 20 is shown. And Fig. 4.6 shows a stroke rate of 27. It can be observed that the plots for the sliding seat boat have higher peaks than the ones for the sliding rigger boat.

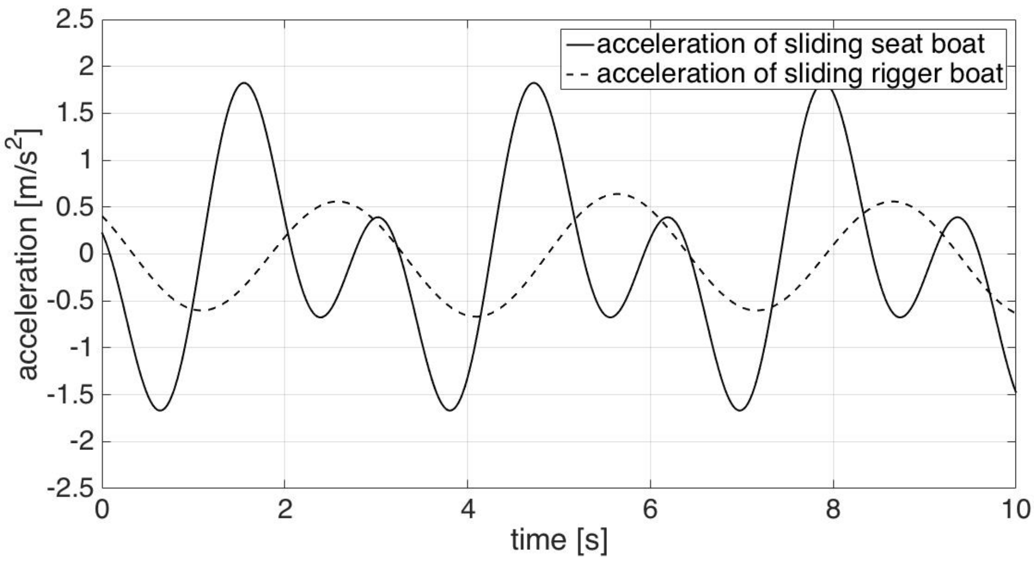


Figure 4.4: The diagram shows the acceleration of the sliding seat boat (black line) and the sliding rigger boat (dashed black line) at a stroke rate of 20 of rower A.

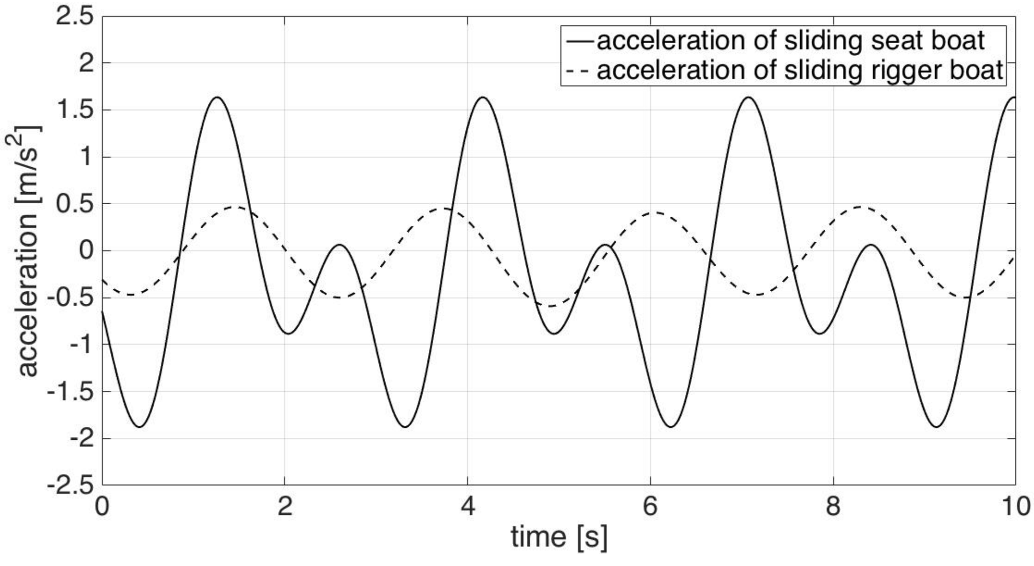


Figure 4.5: The diagram shows the acceleration of the sliding seat boat (black line) and the sliding rigger boat (dashed black line) at a stroke rate of twenty of rower C.

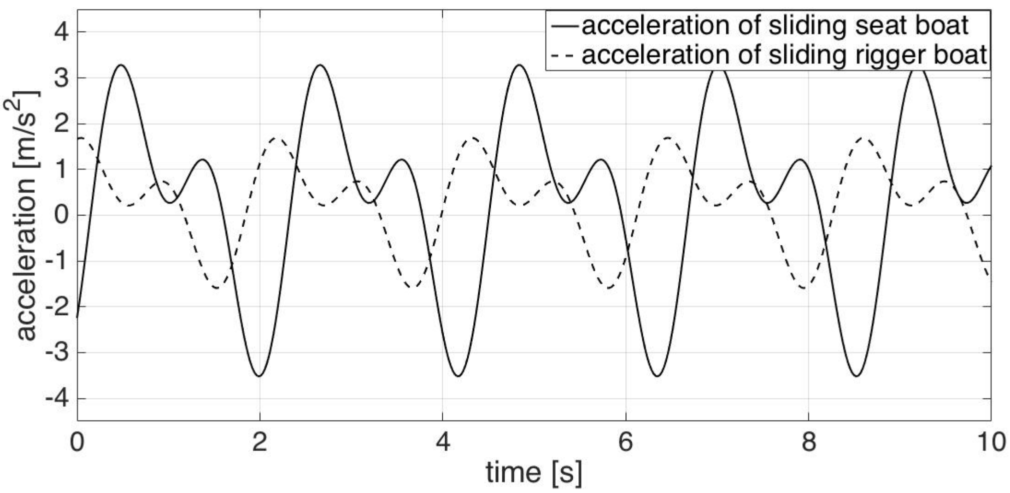


Figure 4.6: The diagram shows the acceleration of the sliding seat boat (black line) and the sliding rigger boat (dashed black line) at a stroke rate of twentyseven of rower E.

4.4 Calculations

In the following section the calculations for rower A will be done. Starting with some preparations to be able to determine all important facts. The goal in rowing is to cover a certain distance in the shortest time or to maintain a given speed with a minimum amount of power.

4.4.1 Preliminary work for calculations

The first step in the precalculations is to determine the velocity profile over the rowing stroke. $v(t)$ can be found as the integral of the Fourier series which describes the acceleration of the boat, namely:

$$\int a(t)dt = v^*(t) + v_0 = v(t) \tag{4.2}$$

where $a(t)$ is the acceleration of the boat, $v^*(t)$ is the integrated acceleration function without the integration constant, v_0 is the average velocity of the rowing boat during the stroke and $v(t)$ is the resulting velocity of the boat. v_0 was measured with a GPS

Table 4.3: Measurements of v_0 of rower A

boat type	stroke rate $[min^{-1}]$	$v_0[m/s]$
sliding seat	20	2.81
	26	3.33
sliding rigger	20	3.25
	26	3.70

capable Garmin watch[8], in Tab. 4.3 the measurements of v_0 are listed.
We should make sure that the velocity profile over one stroke satisfies the following equation:

$$\int_0^T (v(t) - v_0)dt \equiv 0 \tag{4.3}$$

where T is the period time for the stroke. This equation provides that the average velocity of the boat is staying constant over a longer period of time. Figure 4.7 shows the velocity profile of rower A at a stroke rate of 20 in the sliding seat boat.
As mentioned in Sec. 3.2.1 the prefactor C has to be determined. To determine this factor the method of Cabrera [12] is used. Cabrera writes the total drag F_D as

$$F_\mathrm{D} = Cv^2 \tag{4.4}$$

$$\text{where } C = 1.07\frac{1}{2}\rho D^{2/3} c_\mathrm{D} \tag{4.5}$$

where v is the velocity of the boat relative to water, ρ is the density of water, D is the displaced volume and therefore $D^{2/3}$ is proportional to the wetted surface of the hull and c_D is the drag coefficient [12]. Comparing to Eq. 3.4 a factor of 1.07 was added. This factor should account for the additional drag (=wave drag) caused by the deformation of the water surface [19].
According to Archimedes' law the displaced volume D can be calculated as

$$mg = \rho D g \Leftrightarrow D = \frac{m}{\rho} \tag{4.6}$$

[8]Garmin fenix 3

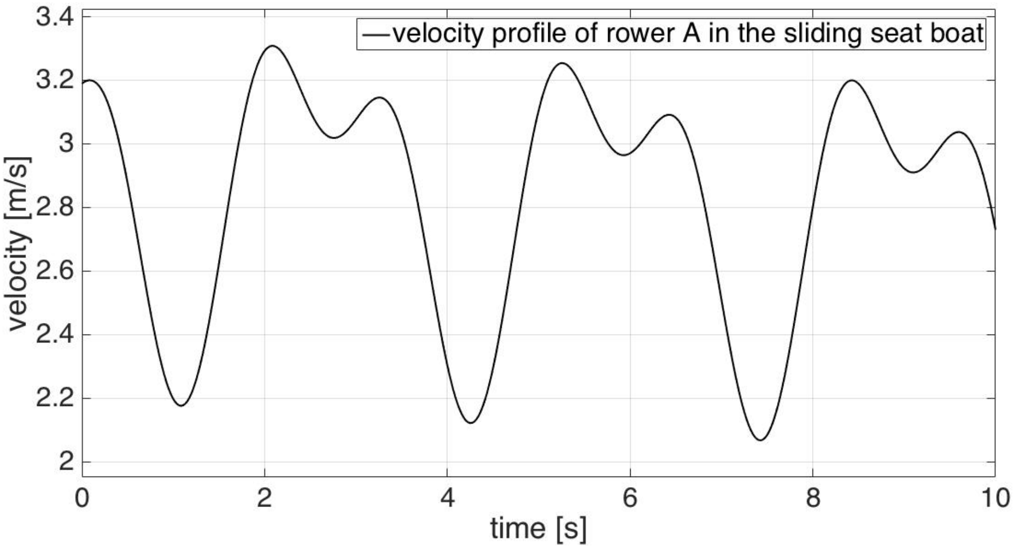


Figure 4.7: The diagram shows a velocity profile for rower A at a stroke rate of 20 in the sliding seat boat.

Table 4.4: Total mass m and displaced volume D for rower A

rower A	total mass [kg]	displaced volume $[m^3]$
sliding seat	107.35 ± 0.15	0.1070 ± 0.0012
sliding rigger	110.90 ± 0.15	0.1109 ± 0.0013

where m is the total mass and g is the gravitational acceleration constant [16]. The total mass m is calculated as

$$m = m_\mathrm{B} + 2m_\mathrm{O} + m_\mathrm{R} \tag{4.7}$$

where m_B is the mass of the boat, m_O is the mass of one oar and m_R is the mass of the rower. In Tab. 4.4 the values for the total mass and the displaced volume for both mechanical systems are listed for rower A.
Furthermore Cabrera [12] suggests the prefactor for a sliding seat single scull boat with a value of $C_\mathrm{S} = 3.16\frac{kg}{m}$. With that knowledge it is possible to determine the value of c_D

as

$$C_{\mathrm{S}} = 1.07\frac{1}{2}\rho D^{2/3}c_{\mathrm{D}} \Leftrightarrow c_{\mathrm{D}} = \frac{C_{\mathrm{S}}}{1.07\frac{1}{2}\rho D^{2/3}} \tag{4.8}$$

where C_{S} is the prefactor for the sliding seat boat, ρ is the density of water, D is the displaced volume and c_{D} is the drag coefficient. c_{D} will then be taken as a constant. This can be done, because both types have approximately the same shape, due to the same length-width-relation [17]. As a result c_{D} has a value of $c_{\mathrm{D}} = (0.0262 \pm 0.0005)$. To determine the prefactor for the sliding rigger boat C_{R} Eq. 4.5 can be used. As a result the prefactor for the sliding rigger boat C_{R} for rower A is $C_{\mathrm{R}} = (3.23 \pm 0.04)\frac{kg}{m}$.

4.4.2 Calculation of energy and power

As stated in Sec. 3.4 power is given as energy per time. Therefore the first step is to calculate the energy. As stated in Eq. 3.31 the energy E can be calculated as

$$E = C\int_0^T v(t)^3 dt \tag{4.9}$$

where C is the prefactor, T is the period time for one stroke and $v(t)$ is the velocity of the boat. In Tab. 4.5 the values for the energy for rower A are listed. Afterwards it is possible to calculate the power P namely as

$$P = \frac{E}{T} \tag{4.10}$$

In Tab. 4.6 the values of the power for rower A are listed. Because the energy is dependent on the displaced volume, which again is dependent on the mass of the rower it is hard to compare the values of the calculated power directly between the different rowers. Consequently to that a new quantity will be introduced, namely power per mass (P_m), the values for that quantity are listed in Tab. 4.7. This is a commonly used parameter in the rowing community [24] [25].

4.4.3 Calculation for water drag resistance

As stated in Sec. 3.2.1 the average water drag resistance can be calculated as

$$F_{\mathrm{D}} = C\frac{1}{T}\int_0^T v(t)^2 dt \tag{4.11}$$

Table 4.5: Energy E for rower A

stroke rate	sliding seat [J]	sliding rigger [J]
20	232.94 ± 6.99	360.53 ± 10.82
25	281.23 ± 8.44	431.99 ± 12.96

Table 4.6: Power P for rower A

stroke rate	sliding seat [W]	sliding rigger [W]
20	73.35 ± 2.20	121.53 ± 1.66
25	120.28 ± 3.61	168.66 ± 5.06

where F_{D} is the water drag resistance over one stroke, C is the prefactor, T is the period time for one stroke and $v(t)$ is the velocity profile. In Tab. 4.8 some values for the total drag over one stroke are listed. It can be observed that the values for the sliding rigger system are higher than the values for the sliding seat system.

4.4.4 Froude number

As mentioned in Sec. 3.5 the characterising number for wave effects is the Froude number (Fr). To calculate the Froude number Eq. 3.35 is used. The velocities will be taken from rower A at a stroke rate of 20.

Froude number for the sliding seat boat

$$\mathrm{Fr_S} = \frac{v}{\sqrt{gL_{\mathrm{S}}}} \Leftrightarrow \mathrm{Fr_S} = \frac{2.81}{\sqrt{9.81 \cdot 7.855}} = 0.3201 \tag{4.12}$$

where $\mathrm{Fr_S}$ is the Froude number for the sliding seat boat, v is the velocity, g is the gravitational acceleration and L_{S} is the length of the waterline for the sliding seat boat.

Table 4.7: Power per mass P_m for rower A

stroke rate	sliding seat [W/kg]	sliding rigger [W/kg]
20	0.83 ± 0.03	1.37 ± 0.04
25	1.36 ± 0.04	1.90 ± 0.06

Table 4.8: Average drag over one stroke F_D

stroke rate	sliding seat [N]	sliding rigger [N]
20	26.81 ± 1.61	34.79 ± 2.09
25	34.52 ± 2.07	47.68 ± 2.86

Froude number for the sliding rigger boat

$$\mathrm{Fr_R} = \frac{v}{\sqrt{gL_\mathrm{R}}} \Leftrightarrow \mathrm{Fr_R} = \frac{3.25}{\sqrt{9.81 \cdot 7.535}} = 0.3780 \tag{4.13}$$

where $\mathrm{Fr_R}$ is the Froude number for the sliding rigger boat, v is the velocity, g is the gravitational acceleration and L_R is the length of the waterline for the sliding rigger boat.

4.5 Improvements of the measuring system

The next section is about the discussion of the occuring errors and the therefore consequential improvements for the measuring system in future studies. The occuring errors can be classified into two main groups, the group 'phone' and the group 'rowers'.
Starting with the group 'phone'. As it was observed the data series had a lot of additional peaks. These peaks could probably be reduced if the smartphone is not mounted directly to the styrofoam, but damped with a cellular material. This would had lead to less vibration transfer to the phone. This additional vibration transfer might be generated by turning the blade at the finish position and during the recovery phase.
Another point in the 'phone' section is that there occured some problems with the app used. The app should have recorded with a constant frequency of 40Hz, but instead it was irregular over a measuring period. There were sections in which more data points were recorded (e.g. 100 points per second) and then there were sections with less data points. This instance made it difficult to get useful data in some parts of the measuring period. It would possibly have been better to use another app to record the data or to use another phone with more advanced software.
The second group of improvements regards the rowers. The rowers were of completly different sizes and mass. As already mentioned, rowing boats are classified into groups

according to the weight of the rower. Therefore some rowers had difficulties to do their best rowing, because the measurements of the boat did not fit perfectly. A solution could be to use different boats. However the usage of different boats would made the comparison more complex, because of additional changing parameters. But if I would have used different boats it would be more complex to compare the data, because then there would have been more changing parameters. The solution for future studies could be to lay the attention only on one weight group and do more research in the differences of male and female.

Additionally it would be helpful to include biometric measurements of the rowers, such as the heart rate. This could lead to minimisation of the error between the two different mechanical systems. In order to do that there should be a cooperation with a biomechanical engineer.

The last point for improvement would be to transfer the measurements from a natural environment into an indoor tank. Then some of the problems would not have occured, such as swans crossing the rowing path or macrophytes which got into the fin of the boat and caused more drag resistance.

4.5.1 Aspects which should not be changed

In this short section I want to discuss the characteristics which should not be changed in the measuring system. Since they have proven to be valuable for the analysis of data. Starting with the measuring period for each stroke rate. The length of the measuring period is long enough to receive adequate results. Although the data was not recorded regularly there are enough complete stroke cycles for analysing. Since all the athletes had no difficulties adapting to the sliding rigger system, it was possible for them to row well at higher stroke rates with both rigger systems. The amount of time spent by the probands was long enough to get good results. However the time needed was short enough to find a good number of very experienced athletes.

4.6 Results

The next section is about the comparison of all significant measurements in the two mechanical systems of rowing boats. The first aspect I want to compare is the acceleration profile in moving direction. If the absolute distance between the maximum and minimum of the profile is compared, it can be observed that the distance in the sliding seat boat is about the double of the one in the sliding rigger boat (cf. Fig. 4.4-Fig. 4.6). Resulting from this difference the velocity profile in the sliding seat boat is much smoother. This has a major influence on the following calculated quantities. As stated in Sec. 3.2.1 the rower should try to minimise theses fluctuations [3].

Next the power over one stroke in the different systems will be compared. As power is dependent on the mass of the system it is more appropriate to compare the values of power per mass. As stated in Tab. 4.7 the values for the sliding rigger boat are about 1.5 times bigger than the values for the sliding seat boat. Furthermore it can be observed that the values for power per mass are less than values found in the literature (cf. [25]). This can be the reason, because rower A is not a professional (compared to the study of [25]) and therefore does not have the same technical skills and muscular potential. The measurements of the other study were taken at a much higher stroke rate and therefore at a higher velocity and power.

Another issue is to have a look at is the comparison of the values for the average water drag resistance of one stroke. As listed in Tab. 4.8 the values of the sliding rigger boat are higher than the ones of the sliding seat boat. This appears first a little bit irritating compared to the power per mass values. But it gets evident when it is compared to the law of the water drag (cf. Eq. 3.2). Here, the velocity influences the water drag by square and since you reach higher velocities in the sliding rigger boat the drag has to be higher.

Chapter 5

Conclusion

The previous chapters dealt with the physics of rowing and the measurements done with two mechanical systems of rowing boats. In the last chapter I want to highlight all important facts and focus on the advantages and disadvantages of the two mechanical systems for the rowing community.
In all parts of the rowing community there is the general goal to improve their rowing performance. Baudouin and Hawkins [2] state

> Rowing performance can be improved by two basic mechanisms: increasing the propulsive impulse and decreasing the drag impulse applied to the system during a stroke cycle. Current rowing practices should be critically evaluated with these ideas in mind and based on fundamental physical and physiological principles. Characterising the interactions between the mechanical system (the rowing shell and oar) and the biological system (the rower) will lead to refinements in rower selection and pairing, rigging setup, and rowing strategy that will increase rowing performance.

The focus of this study is on the matters of the mechanical system and not the rower. A future study could include if and how the rower's body is affected differently by rowing with the two mechanical systems.
As the results show in Sec. 4.6 there is an advantage for the sliding rigger system. Because the athletes are able to generate more power per mass values as well as higher average velocities in the sliding rigger system. This at the same stroke rate as in the

sliding seat boat. One reason for that is that there is less pitching movement in the sliding rigger system than in the sliding seat system. Pitching is when a boat has an angular rotation [26]. In the case of rowing pitching should be observed to reduce energy loss through hydrodynamic drag [27]. As stated in [27] pitching can be measured as changes in the vertical displacement of the bow of the boat. The vertical displacement changes when mass is moving back and forth during the rowing stroke. Therefore the difference of moving mass in both mechanical systems has to be considered. In the sliding seat boat the mass of the rower moves contrary to the sliding rigger system where only the rigger and the legs of the rower move. Therefore there is less moving mass in the sliding rigger system than in the sliding seat. Consequently the changes in the vertical displacement are reduced in the sliding rigger boat.
Additionally Willimczik [14] states four principles to improve performance in watersports. First, he states that 'for an effective propulsion in watersports there is the need to maximise the path of the area of impulsion in the water' [14]. This principle should be implemented approximately the same for both mechanical systems, except for little changes from the rowers themselves, because they are probably more used to row in the commonly used system. Second, he states that 'an effective execution of movement is characterised in a way, that the vertical movements of the center of gravity of the system is minimised' [14]. This principle could be analysed in future studies. It would be interesting to see if there is a significant difference in the vertical movement of the center of gravity of the rower. Third, he states that 'the minimisation of the horizontal acceleration of mass segments of the center of gravity through one moving cycle leads to an effective technique' [14]. For my research this is the most important principle, because it discusses the different acceleration respectively velocity profiles over a stroke. As seen in Fig. 4.4-Fig. 4.6 the acceleration profile for the sliding rigger is smoother than the one for the sliding seat boat. And last, he states that 'the athlete has to minimise the water drag resistance of the floating body with appropriate actions' [14]. This principle, however, is not considered in this study.
Nevertheless the sliding rigger system is banned from rowing races by the International Rowing Federation [9]. Still the system can be useful in some parts of the rowing community. First, it can be considered from a recreational point of view [28] because the boat is easier to handle and has transport advantages. Second, there is a sliding rigger

construction for stand up paddle boards. Here, the rigger gets fixed onto the board [29]. These circumstances make it interesting for the community, because it is then possible to perform two different sports with nearly the same equipment.
In addition the sliding rigger system is also useful in training for elite athletes. As discussed the average velocity is higher in the sliding rigger boat, therefore athletes could use this system to improve their technical skills at higher velocities. The improvement of the technical skills will lead to more efficiency of the rowing motion. If the costs of the system will be decreased and the advantages for the athletes will be emphasised, the system might find its way back to the field of race rowing.

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Appendix

List of symbols

$a(t)$	acceleration of the boat in moving direction
a_0	average acceleration
A	(characterstic) area
A_{B}	area of the blade
B	bottom
C	prefactor
C_{R}	prefactor of the sliding rigger boat
C_{S}	prefactor of the sliding seat boat
$c_{\mathrm{B_D}}$	blade drag coefficient
$c_{\mathrm{B_L}}$	blade lift coefficient
c_{D}	drag coefficient
D	displaced volume
d	distance between the oarlock and the center of gravity of the oar
$\mathrm{d_{L/F}}$	distance between footstretcher and oarlock
E	energy
η	efficiency
η_{B}	efficiency of the boat
η_{BL}	efficiency of the blade
η_{R}	efficiency of the rower
η_{sys}	efficiency of the system
F	force on the system
F	feet
F_{A}	buoyant force
F_{B}	shape resistance of the blades
F_{boat}	force on the boat

$F_{\mathrm{B_D}}$	blade drag force
$F_{\mathrm{B_L}}$	blade lift force
F_{D}	drag resistance
$F_{\mathrm{foot,x}}$	force on the footstretcher in x-direction
F_{G}	gravitational force
$F_{\mathrm{hand,x}}$	handle force in x-direction
F_{I}	inertia of the system
F_{lock}	force on the oarlock
F_{oar}	force on the oar blade
Fr	Froude number
$\mathrm{Fr_R}$	Froude number for the sliding rigger boat
$\mathrm{Fr_S}$	Froude number for the sliding seat boat
G	center of gravity of the oar
g	gravitational acceleration
H	hand
$\mathrm{h_R}$	height of the center of gravity of the rower
$\mathrm{h_S}$	height of the shoulder of the rower
L	length of waterline
L_{R}	length of waterline of the sliding rigger boat
L_{S}	length of waterline of the sliding seat boat
l	length of the boat
l_i	inboard length of the oar
l_0	outboard length of the oar
m	total mass
m_{B}	mass of boat
m_{O}	mass of oar
m_{R}	mass of rower
ν	kinematic viscosity of water
O	oar blade
P	power
P_{in}	total power input

P_m	power per mass
P_{mech}	mechanical power
P_{met}	metabolic power of the rower
P_{min}	minimal power required for propelling the boat and rower with a constant speed equal to the average boat velocity
P_{out}	total power output
P_{prop}	propulsive power of the blade
R	center of gravity of the rower
r	ratio between the height of the center of gravity of the rower (h_R) and the height of the shoulder (h_S)
Re	Reynolds number
ρ	density of water
S	shoulder
SR	stroke rate
T	period time of one stroke
T_{R}	period time of the sliding rigger boat
T_{S}	period time of the sliding seat boat
Θ	oar angle
$v(t)$	velocity of the boat
$v^*(t)$	integrated function of the acceleration without integration constant
v_{B}	velocity of the blade
$v_{\text{B-rel}}$	resultant blade velocity
$v_{\text{B}_\text{x}-\text{abs}}$	velocity of the blade in x-direction relative to the water
v_{B_y}	velocity of the blade in y-direction
v_0	average velocity
v_{R}	velocity of the sliding rigger boat
v_{S}	velocity of the sliding seat boat
x_{B}	absoulte x-position of the foot stretcher relative to the starting line
$x_{\text{B/F}}$	distance between bottom and feet

$x_{\mathrm{H/S}}$	distance between hand and shoulder
x_{O}	absolute x-position of the oar's center of mass relative to the starting line
x_{R}	absoulte x-position of the rower's center of mass relative to the starting line
$x_{\mathrm{S/B}}$	distance between shoulder and bottom

Glossary

blade	part of the oar that is flat and is used to generate resistance in the water to propel the boat
boat's length axis	axis through the middle of the boat in moving direction
bow	forward end of the boat
button	is placed on the sleeve and prevents the oar from slipping through the oarlock
coxswain (or cox)	person who is steering a boat
fin	small metal plate which is mounted on the bottom of the boat in order to help the rower stay in a straight way
FISA	World Rowing Federation
footstretcher	rower is placing his feet there to physically connect to the boat
handle	on the handle the rower holds the oar
hull	main part of the boat, includes rigger, seat and footstretcher
inboard length	length of the oar, measured from the handle to the button
lightweight	class in rowing where the rowers are only allowed to have a certain weight
oar	oar is being used from the rower to propel the boat
oarlock	the oar is placed in the oarlock, which is mounted to the rigger
outboard length	length of the oar, measured from the button to the end of the blade
port	left side of the boat in moving direction
rigger	either sliding or fixed, is mounted to the hull and includes the oarlock
rower	person who is rowing
saxboard	is the side wall of the hull
sculling	rowing, where the rower has one oar in each hand
seat	either sliding or fixed, on the seat the rower is sitting in the hull
shaft	long part of the oar

sleeve	part of the oar where the button is placed
starboard	right side of the boat in moving direction
stern	end of the boat opposite the bow
sweep rowing	rowing technique where the rower has one oar in both hands

International boat categories

Sculling boats	
W1x	Women's Single Scull
M1x	Men's Single Scull
LW1x	Lightweight Women's Single Scull
LM1x	Lightweight Men's Single Scull
W2x	Women's Double Scull
M2x	Men's Double Scull
LW2x	Lightweight Women's Double Scull
LM2x	Lightweight Men's Double Scull
W4x	Women's Quadruple Scull
M4x	Men's Quadruple Scull
LW4x	Lightweight Women's Quadruple Scull
LM4x	Lightweight Men's Quadruple Scull

Sweep boats	
W2-	Women's Pair
M2-	Men's Pair
LM2-	Lightweight Men's Pair
M2+	Men's Coxed Pair
W4-	Women's Four
M4-	Men's Four
LM4-	Lightweight Men's Four
W8+	Women's Eight
M8+	Men's Eight
LM8+	Lightweight Men's Eight

International Para-Rowing boat categories

ASW1x	AS Women's Single Sculls
ASM1x	AS Men's Single Sculls
TAMix2x	TA Mixed Double Sculls
LTAMix2x	LTA Mixed Double Sculls
LTAmix4x	LTA Mixed Coxed Four

Abstract

The following paper discusses the differences in performance between two mechanical systems of rowing boats. One has a sliding seat and a fixed rigger and the other one has a fixed seat and a sliding rigger. In this study the acceleration profiles of both types were measured and the velocity profiles were derived from them. Water drag resistance is dependent on velocity squared. The lower the amplitude of velocity fluctuations, the higher the average drag results. The outcome of the study is that there is indeed an advantage for the sliding rigger boat, because it has much smaller velocity fluctuations during a rowing stroke. These smaller fluctuations originate from less moving mass in the sliding rigger boat. A comparison of power per mass for both systems shows that other influences have to be taken into account as well. Since the sliding rigger boat is forbidden in races, athletes should use it for training to improve their technical skills at a higher velocity.

Zusammenfassung

Die folgende Arbeit handelt vom physikalischen Vergleich zweier mechanischer Systeme von Ruderbooten. Das Ziel ist es deren Effektivität zu prüfen um zu beurteilen bei welchem System der/die Sportler/Sportlerin sein/ihr Potenzial besser in Vortrieb umwandeln kann. Der Unterschied in den zwei mechanischen Systemen besteht darin, dass das eine einen Rollsitz und einen fest montierten Ausleger hat und das andere einen festen Sitz und einen beweglichen Ausleger hat. In meiner Arbeit wurden Beschleunigungsverläufe gemessen und daraus Geschwindigkeitsverläufe bestimmt. Denn die Geschwindigkeit spielt eine entscheidende Rolle beim Vergleich von den kennzeichnenden Parametern. Als Resultat erhalte ich, dass es Vorteile für das Rollauslegerboot gibt, denn der Geschwindigkeitsverlauf hat geringere Amplituden als der Geschwindigkeitsverlauf beim Rollsitzboot. Dennoch ist dieses System in Rennen verboten, kann aber für die Weiterentwicklung der Technik bei Athleten und Athletinnen verwendet werden.

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