THE DESIGN OF AN ELECTRIC ROWING SUPPORT FOR SENIOR ROWERS

Femke Joanne de Gooijer

BIOMECHANICAL ENGINEERING
Prof. Dr. Ir. H.F.J.M. Koopman

EXAMINATION COMMITTEE
Prof. Dr. Ir. G.J. Verkerke
Ir. E.E.G. Hekman
Ir. C.P. Sleutel

August 18, 2016

UNIVERSITY OF TWENTE.

This design report is written at the request of the 'Wetenschapswinkel UT' in consultation with

Ir. E. van Hattem, Martha Bloemberg and Cas Scholten, May 19, 2016.

TABLE OF CONTENT

SUMMARY

Rowing is a popular sport among elderly because it improves the stability of the back and has low impact on the knees. In addition, rowing offers physical and social benefits. Although the electric bicycle is already available for senior bikers, technical support is missing for rowing. A survey was done among senior rowers (>60 years old). Forty percent of the elderly rowers who encounters difficulties during rowing, mentioned to be interested in a technical support. Not only senior rowers are interested. Several rowing organizations specialized in adjusted rowing, mentioned to be interested in this subject as well.

The mechanics of rowing are described together with a physical motion analysis. Both are used to get an understanding of the rowing motion. The difficulties encountered by elderly during rowing where established by a survey. Besides getting in and out the boat, a lack of muscle power was mentioned as a physical effect of aging. It was found that power in rowing has a close relation to the rowing performance. Comparing performance pace times of different rowers of all ages and all around the world showed a relation between the regression in power due to aging. The main function of the design should be the addition of power to the motion of the stroke.

The survey was also used to define the consumer expectations. Having the functions and consumer expectations clear, a list of requirements was made. Four concepts were considered. An evaluation of the four concepts, led to a potential final design. This design consists of an instrumented oarlock for measurement of the force acting on the oar and the oar angular velocity. As a force sensor, four strain gauges were used. For the angular velocity, a magnetic rotary encoder can be placed at the oarlock. The oarlock is driven by a motor, mounted to the pin. The motor and oarlock are coupled using two gearwheels and a belt.

The final design fulfills the requirements that were taken into account. A system was designed that gives the user extra power during on water rowing. The total system is compact, widely applicable and can easily be installed and removed from the boat. Further research should be done to specify the design. A way to calibrate the sensors and the specifications of the motor, gear and battery should be thought of. The integration of a freewheel mechanism can be considered as well as a solution for the rotation of the blade during the stroke. It is recommended to use a prototype to test the on water 'rowing feel', which can only be encountered in practice.

1. INTRODUCTION

Rowing is a widely practiced sport for all ages. It has many health benefits since all major muscle groups are being used. Because of the wide range of motion, flexibility is maintained or even improved. It offers a combination of stimulating the aerobic condition and strength condition at the same time. The great advantages of rowing above other sports are the low impact on the knees and the improvement for the stability of the back. This makes rowing a sport for all ages, in particular for elderly who want to stay fit and cherish social contacts. (1)

Teamwork in rowing is of huge importance; the rowing motion should be made as synchronous as possible to obtain the best results. Therefore, being unable to keep up with the performance of the rest of the boat, leads to difficult situations. It can be a reason for elderly to discontinue their favorite sport. Aging effects the movability and strength of the body. The body gets stiffer, muscles get weaker and the physical condition gets less. For bicycles, an electrical support system is the solution to this problem. It gives the opportunity to keep up with others, by de support of extra electrical power. Nowadays electric bicycles are widely used and the concept is socially accepted. (2) With rowing being a popular sport, especially among elderly, there seems to be a good market for an electrical rowing support. This leads to the main focus of this thesis: designing an electrical support for rowing.

An electric rowing support will not only be beneficial for senior rowers, but will also give disabled the possibility to row at a higher level. The foundation 'Roeivalidatie', located in Rotterdam, provides help to give everybody the opportunity to row. (3) People that use their include patients with Spina Bifida, paralysis, paraplegia, multiple sclerosis, arthrosis, visual disabilities but also mentally disabilities. Creative solutions are used to make rowing more easily; adjusted oars, supporting seats and devices to get easily in- and out the boat. To be able to always return back home safely, small motors are being brought into the boat.

One of the main focuses of this thesis is to establish the needs of the target audience with respect to rowing support technology. Firstly, more information about rowing will be provided. The mechanics of rowing will be discussed as well as the biomechanics; a physical motion analysis of the rowing movement will be done. With this background information, the target audience and the difficulties that they encounter during rowing can be made clear. To do so, a survey will be done among senior rowers and the rowing performance over age will be analyzed. This results in a clearly defined problem. The problem can be translated into the functions the electrical support for rowing should fulfil. The survey is also used to define the consumer expectations. Having the functions and consumer expectations clear, a list of requirements is made. Other requirements, for example safety, costs and applicability, will be taken into account as well. With the motion analyzed, knowing the functions the design should fulfil and having the requirements listed, technical solutions can be obtained. The technical solutions should abate the difficulties encountered by the target audience. Combining the technical solutions will lead to conceptual designs. The conceptual designs can be evaluated on how well they meet the requirements. Eventually, the concept with the most potential can be formed into a final design.

NOMENCLATURE

α_{catch}	angle of oar at the catch	Degree	°
$\alpha_{release}$	angle of oar at the release	Degree	°
α_{total}	total range of angle of oar	Degree	°
$\alpha(t)$	angle of oar as function of time	Degree	°
F_{ba}	force at blade in direction of oar axis	Newton	N
F_{blade}	total force at blade	Newton	N
F_{bn}	force at blade in direction normal to oar axis	Newton	N
F_{boat}	boat drag force	Newton	N
F_{ha}	force at handle in direction of oar axis	Newton	N
F_{handle}	total force at blade	Newton	N
F_{hn}	force at handle in direction normal to oar axis	Newton	N
F_{oa}	force at oarlock in direction of oar axis	Newton	N
$F_{oarlock}$	total force at oarlock	Newton	N
F_{on}	force at oarlock in direction normal to oar axis	Newton	N
$F_{stretcher}$	force at foot stretcher	Newton	N
P	performance power	Watt	W
P_h	power applied at the handle	Watt	W
P_{57}	performance power of rower ages 57	Watt	W
P_{85}	performance power of rower ages 85	Watt	W
R	total actual length of oar	meter	m
R_{in}	actual inboard length oar	meter	m
R_{out}	actual outboard lenght oar	meter	m
V_{ex}	exitation voltage	Volt	V
V_o	output voltage	Volt	V
v_{oar}	velocity of the handle in direction normal to the oar axis	Meter per second	m/s
$\omega(t)$	angular velocity oar	Degree per second	°/s

2. INTRODUCTION TO ROWING

The rowing motion, or *stroke*, can be evaluated in several ways. On one hand by emphasizing the rower's body and on the other hand by the equipment being used. For this study it is important to get an understanding of the action of muscles during the stroke, so a physical motion analysis has been performed. Furthermore, the mechanics of rowing are explained to get an idea of the forces and moments present during rowing. To clarify the mechanics some important parts of the rowing boat are highlighted, some terms are explained and the general motion of the stroke will be illustrated.

2.1 TERMS

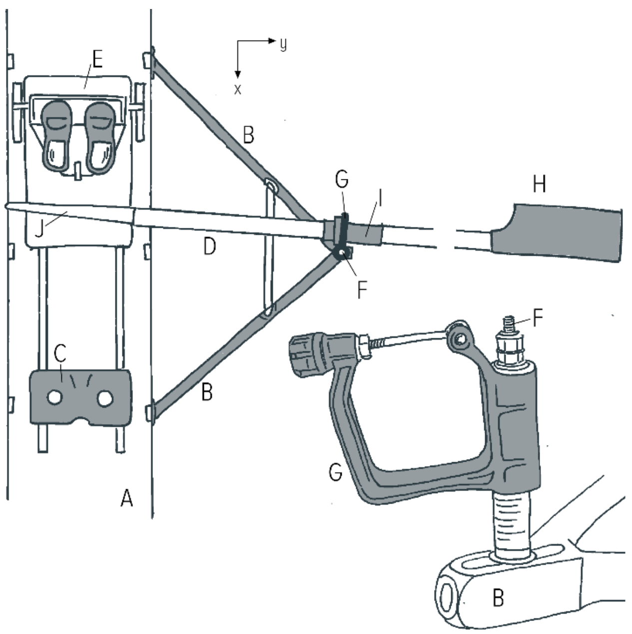


Figure 1. Important parts of the rowing boat. At left a top view of a section of the boat, at right a side view of the oarlock. Indicated are the shell (A), the riggers (B), the seat (C), the oar (D), the foot stretcher (E), the oarlock containing a pin (F) and the gate (G), the blade of the oar (H), the collar (I) and the handle of the oar (J).

Figure 1 shows the most important parts of the rowing boat for this thesis. (4)

Axis and plane

Figure 1 also shows the direction of the x-axis and y-axis. Both in the *horizontal plane*, parallel to the water. The x-axis is increasing in the direction of motion of the boat. The y-axis is perpendicular to the direction of motion of the boat. The z-axis, not shown in figure 1, points outward. The *vertical plane* indicates the plane perpendicular to the motion of the boat, along the y-axis and z-axis.

Types of rowing

There are two types of rowing: *sweep-* and *scull* rowing. In sweep rowing, each rower uses only one oar, held with both hands. Sweep rowing can be done in pairs, with four or with eight rowers. Scull rowing or *sculling*, is rowing using two oars, one in each hand. Scull rowing can also be done solo; so called *skiff rowing*. A general notation is used to indicate the type of rowing. This consists of a number that indicates the number of rowers, combined with a symbol. For sculling without coxswain the symbol 'x' is used. '*' indicates sculling with coxswain, '+' indicates sweep rowing with coxswain and '-' indicates sweep rowing without coxswain.

2.2 THE STROKE

The repetitive movements made during a stroke can be divided into four phases, the catch, the drive, the release or finish and the recovery, see figure 2. (5)

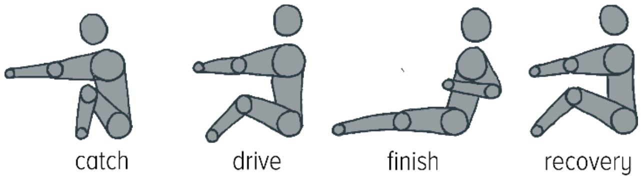


Figure 2. The four phases of the rowing stroke.

The catch

The catch can be regarded as the beginning of the drive. During the catch the trunk is in slightly bent over with the legs fully compressed to the chest. Shins are perpendicular with respect to the water. The arms are fully extended and the fingers are gripped around the handle of the oar. When the shoulders are fully extended, the blade of the oar is entered into the water perpendicularly. This is done at a minimal horizontal angle of the oar, known as the catch angle α_{catch}.

The drive

The drive distinguishes three different smoothly following sequences to move the blade through the water and in this way generate propulsive power. The drive is initiated by the 'leg emphasis', where the legs are driven forward, away from the upper body. The power generated by the legs is transmitted through the contracted shoulders and straight arms into the handle. No power is generated by the upper body jet. Legs engage while the back begins to extend, the 'body swing emphasis'. During extension of the back, the hip is extended, the torso will swing open and the arms engage to pull the handle towards the abdomen. At the end of the drive sequence, the knees are maximally extended and nearly all muscles of the upper body engage, this last part of the drive is called the 'arm pull through'. The oar passes the zero horizontal angle when it is perpendicular to the x-axis.

The release or finish

The movement of the drive ends in the position called the release or finish. Legs are fully extended and make an angle of 110 to 130 degrees with the upper body. When touching the abdomen at the lower part of the sternum, hands tap down to remove the blade from the water. The oar is at a maximal angle, the so called release angle $\alpha_{release}$. Blades are turned horizontally to have as little air resistance as possible.

The recovery

During the recovery the body is brought back in the catch position. The oars are brought in extended position by bringing the arms and torso forward. When the handle passes the extended knees, the legs are bend to slide back into the catch position. This blade is rotated parallel to the water to be as aerodynamic as possible.

3. MECHANICS OF ROWING

For the description of the mechanics of rowing, a simplified model can be used. The rower, oar and boat can be seen as separate bodies where forces are acting on, see figure 3. (6)

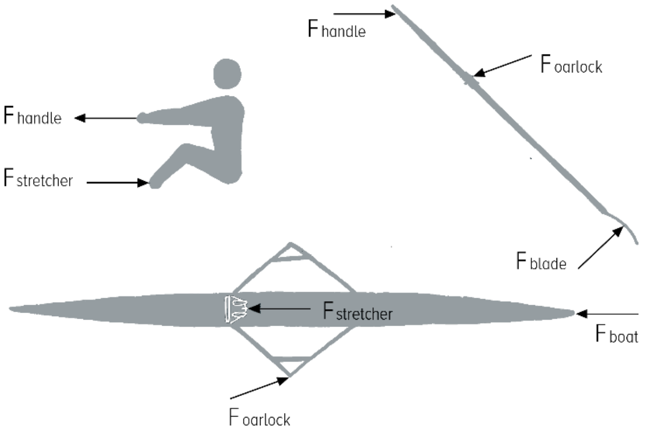


Figure 3. Free body diagrams of the forces acting on the rower, boat and oar.

There are two forces related to the rower; the propulsive force applied by the rower on the oar handle, and the reaction force of the foot stretcher. Both forces acting in x-direction. Forces acting on the oar are the handle force applied by the rower, the force acting on the oar blade and a reaction force at the oarlock. Because the oarlock is attached to the riggers of the boat, this reaction force also acts on the boat. Other forces acting on the boat are the force applied on the foot stretcher and the boat drag force. This is a simplified model; pitching and yawing motions of the boat are neglected as well as air resistance and movement of the water. It is assumed that the rower keeps the boat balanced using zero effort. Because there is no motion in the vertical plane, the normal forces in upward direction are not taken into account.

3.1 OAR ANGLES

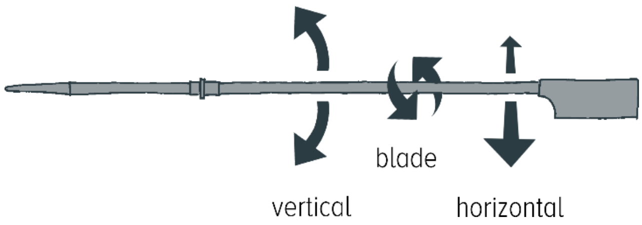


Figure 4. The angles of the oar: the vertical angle, the horizontal angle and the angle of the blade.

The angle of the oar plays an important role in defining the different stroke phases. In total, three oar angles can be distinguished, see figure 4. Firstly one in the vertical plane, the so called vertical oar angle, moving the blade up and down. Secondly the horizontal oar angle, moving the oar parallel to the water. Lastly the angle of the blade, caused by rotation around the axis of the oar. (7)

The start of a stroke is defined during the recovery phase, when the oar passes the point at which it is perpendicular to the x-axis, and therefore defined as $\alpha = 0°$. (8) The total rowing angle α_{total} is now obtained by:

$$\alpha_{total} = \alpha_{release} - \alpha_{catch} \quad \text{(i)}$$

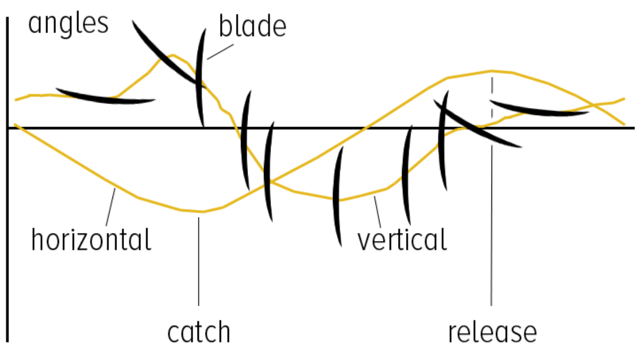


Figure 5. The three oar angles evaluating over time, during one stroke.

Figure 5 summarizes the total movement of the oar during one stroke. It can be seen that the blade remains perpendicular to the water after entering the water until just before the release. The maximal and minimal oar angles differ per gender, weight and type of rowing. (9) For example; the largest angles at racing rate are reached during men sculling, with a catch and release angle at an average of -66.5 and 43.8 degrees respectively. The smallest angles at racing rate refer to women sweeping, with a catch and release angle at an average of -53.5 and 33.4 degrees respectively. (9)

3.2 OAR VELOCITY

The horizontal angle as function of time $\alpha(t)$ can be used to derive the angular velocity $\omega(t)$ of the oar by differentiating once over time. The distance from the pin to the point where the rower's applied force is acting on the oar is called the actual inner board lever R_{in}. (7) Multiplying the angular velocity with the actual inner board lever gives the linear oar velocity v_{oar} (10) perpendicular to the oar axis:

$$v_{oar}(t) = R_{in}\omega(t) \quad \text{(ii)}$$

3.3 OAR AT ANGLE

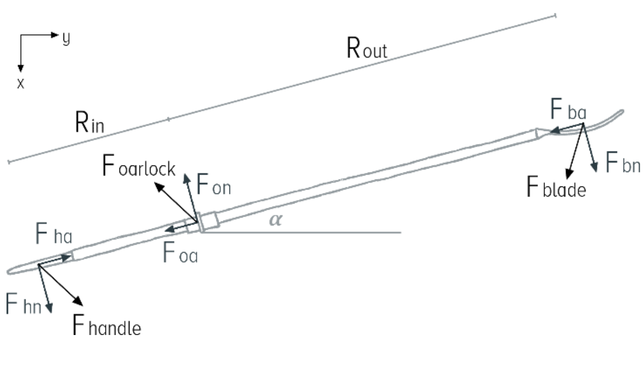


Figure 6. Top view of the oar. Forces acting on the oar when under a horizontal angle.

In figure 6 it can be seen that the handle force F_{handle} applied by the rower on the oar handle, is not always normal to the axis of the oar when under a horizontal angle. Therefore, the force can be dissolved in an axial and normal component, respectively F_{ha} and F_{hn}. (11) The axial component F_{ha} does not play a role as propulsice force. The normal component is given by:

$$F_{hn}(t) = F_{handle}(t)\cos(\alpha(t)) \quad \text{(iii)}$$

The same holds for the blade force:

$$F_{bn}(t) = F_{blade}(t)\cos(\alpha(t)) \quad \text{(iv)}$$

3.4 OAR AS LEVER

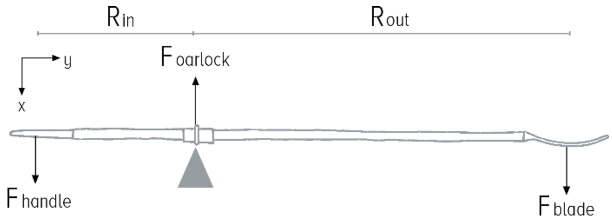


Figure 7. Oar as first class lever.

The oarlock can be seen as pivot point when the oar is assumed as a first class lever, figure 7. When the estimation is made that the oar moves with a constant velocity, the force and moment balance around the oarlock becomes:

$$\Sigma F = F_{hn} + F_{bn} - F_{on} = 0 \quad \text{(v)}$$

$$\Sigma M_o = R_{in}F_{hn} - R_{out}F_{bn} = 0 \quad \text{(vi)}$$

Both balances can be used to obtain an expression (11) for the normal oarlock force as function of the normal handle force or the normal blade force:

$$F_{on} = F_{hn}\frac{R}{R_{out}} = F_{bn}\frac{R}{R_{in}} \quad \text{(vii)}$$

With R the summation of R_{in} and R_{out}. Both distances R_{in} and R_{out} are uncertain, the points where the forces are acting on are not constant during a stroke. Values can be estimated experimentally, see table 1. (9)

Table 1. Total oar length, real inboard length and estimated actual in- and outboard length for different boat types.

	1x	2x	4x	2-	4-	8+
oar length (m)	2.89	2.90	2.91	3.75	3.76	3.77
inboard length (m)	0.89	0.88	0.7	1.16	1.15	1.14
R_{in} (m)	0.85	0.84	0.83	1.03	1.02	1.01
R_{out} (m)	1.76	1.78	1.80	2.30	2.32	2.35

The summation of the normal and axial component of the oarlock force, F_{on} and F_{oa} results in the total oarlock force $F_{oarlock}$. This is the force that is transferred to the pin connecting the oarlock with the riggers.

3.5 POWER

Power is known as the force acting on an object multiplied with its velocity. The rower applies forces at the oar and at the foot stretcher, see figure 3. The force applied at the oar is the force that is acting on the water, transmitted through the oar, and therefor the propulsive force. See figure 6. This propulsive force is closely related (12) with the performance power of the rower by:

$$P_h(t) = F_{hn}(t)v_{oar}(t) \quad \text{(viii)}$$

With P_h the performance power, or the propulsive power applied at the handle, F_{hn} is the force normal to the oar axis, applied on the handle by the rower and v_{oar} is the velocity of the oar at the point of force application, perpendicular to the oar axis. The plots of this three quantities over time form the widely used graphs for evaluating the rower's performance. Figure 8. (10)

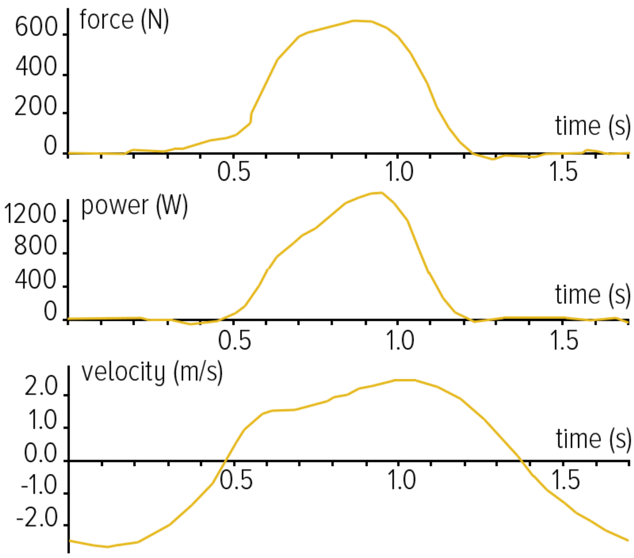


Figure 8. The force, velocity and power at the handle, evaluated over time during one stroke. (10)

4. SSDSDFASDF

The physical motion made by the rower is analyzed in each stroke phase, figure 9. Action of the most important muscle groups is listed point by point. Figures of the human anatomy with used muscles indicated, can be found in appendix I. (5)

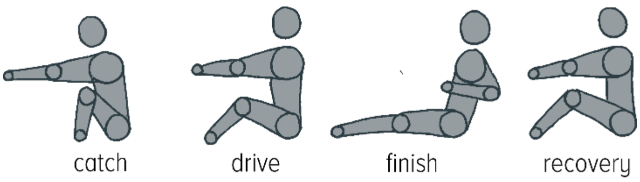


Figure 9. The four phases of the rowing stroke.

4.1 THE CATCH

- Flexion of the trunk by contraction of the abdominal muscles and relaxation of the back.
- Flexion of the pelvis and hips to compress the legs to the chest by contraction of the psoas major, psoas minor and the iliacus.
- Flexion of the pelvis and hips by contraction of the rectus femoris.
- Maximum flexion of the trunk by outward rotation of the thighs, which is provided by contraction of the sartorius.
- Flexion of the knees by contraction of the hamstrings, and gastrocnemius and elongation of the quadriceps.
- Dorsiflexion of the ankles by contraction of the tibialis anterior.
- Extension of the elbows by contraction of triceps brachii.
- Grip on the handle by flexion of the fingers and thumb by contraction of the flexor muscles.

4.2 THE DRIVE

Legs Emphasis

- Extension of the knees by contraction of the quadriceps.
- Plantar flexion of the feet by contraction of the soleus and gastrocnemius.
- Contraction of shoulder muscles: supraspinatus, infraspinatus, subscapularis, teres major, teres minor and the biceps brachii.
- Stabilization of scapula by contraction serratus anterior and trapezius muscles.

Body Swing Emphasis

- Extension of the hip by contraction of the gluteus and hamstrings.
- Extension of the back by contraction of the erector spinae.
- Starting flexion of the elbow by contraction of the biceps, brachialis and the brachioradialis.

Arm Pull Through

- Maximal extension of the knees, plantar flexion of the ankles, hip and back extension is completed.
- Flexion of the elbow by contraction of the biceps, brachialis and the brachioradialis.
- Stabilization and adduction of the wrist by contraction of the flexor capri ulnaris and the extensor capri ulnaris.
- Extension and adduction of the shoulder by the teres minor, posterior deltoid and long head of the biceps.
- Downward rotation of the scapula by the pectoralis minor and backward motion by the trapezius and rhomboid muscles.

- Internal rotation of the upper arm by contraction of the latissimus dorsi and pectoralis major.
- Small extension of the elbows by contraction of the triceps brachii.

4.3 THE RELEASE

- Stabilization of the trunk by contraction of the abdominals.
- Maximal extension of the hips and knees by contraction of i.a. the glutes and quadriceps.
- Adduction of the scapula and stabilization final position by contraction of many back muscles.
- Internal rotation of the upper arm by contraction of the latissimus dorsi.
- Stabilization of final position by contraction of the biceps brachii.

4.4 THE RECOVERY

- Flexion of the torso by the abdominals.
- Full extension of the arms by contraction of the triceps brachii.
- Raising of the arm by contraction of the anterior deltoids, coracobrachialis and biceps brachii.
- Flexion of the knees and hips, dorsiflexion of the angles by contraction of the hamstrings and calves.

5. PROBLEM DEFINITION

To define the problem in this thesis, a survey among senior rowers is done. In total 37 elderly responded, with the youngest respondent being 61 years old and the oldest being 85 years old. The total survey can be found in appendix II.

5.1 TARGET AUDIENCE

The target audience of this study can be compared to the users of an electric supporting bicycle, both devices should give support during recreational exercise. The survey is used to get an idea of the extent of interested senior rowers.

Electric bicycle

The e-bike is mainly used by people who enjoy using bicycles, but who feel hampered by physical limitations. These people are elderly who notice a lack of muscle power, but also vital younger people that need to cover a large distance from work to home. This last group of people will not be part of the target audience for the rowing support; a row boat is not a vehicle used to travel daily distances but mainly used as recreational vehicle. The audience being elderly bikers is much larger than the younger 'work-home' audience, when comparing the data from table 2. This data gives an overview of the percentage of the population in the Netherlands that was in possession of an 'e-bike' in 2012. (2)

Table 2. Percentage of the Dutch population that was in possession of an electrical bike in 2012.

Age	**Men**	**women**	**total**
< 46	1%	1%	1%
46-60	7%	13%	10%
>60	10%	10%	10%
total	4%	6%	5%

Interest

Of the respondents, 20% noticed the rowing motion to get harder caused by aging of the body, 10% indicates having the feeling not being able to keep up with others. Of the respondents who mentioned having physical difficulties caused by aging, 40% would be interested in a rowing support, compared to 30% that said to be interested while not having physical difficulties caused by aging.

Not only senior rowers are interested, the 'KNRB Commission for Adjusted Rowing' and the foundation 'Roeivalidatie' (3) said to have interest in a power support for the rowing motion. Both organizations provide help to give disabled the opportunity to row. The design could be used by people suffering with diseases leading to a lack of muscle power.

5.2 DIFFICULTIES

In the survey, the difficulties mentioned by the senior rowers are a lack of condition and decrease of muscle power. But mostly an overall decrease of flexibility of the body is causing problems. Getting into the boat is seen as one of the hardest parts of rowing, together with getting out again. After accomplishing this task, the rowing movement itself is mentioned to get harder at the end of the drive phase, during the 'arm pull through' and finish phase. In those phases the arms deliver most of the power for the movement, see figure 10. (13) The respondents mentioned noticing a lack of power in the muscles of the arms.

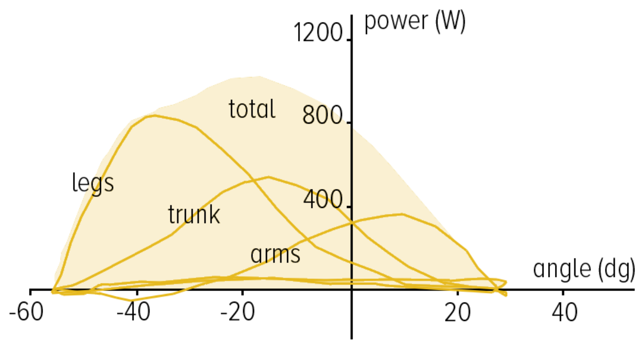


Figure 10. The contribution of three body segments, the legs, trunk and arms, to the total power during one stroke.

Power during a stroke

Although the arms contribute only 23 percent of the total power required for rowing. Most power required is delivered by the legs (45%) and trunk (32%) (13). A logical explanation would be the mentioned increase of stiffness of the body due to aging. Not being able to accomplish total flexion of the trunk, pelvis, hips and knees causing the motion of the legs and trunk to be less powerful. This lack of power during throughout the first half of the drive phase, leads to less speed for swinging the body backwards and bringing the arms to the abdomen during the second half of the drive phase. Therefore, the arms need to deliver more power themselves to pull the handle towards the body.

Power and performance

The lack of muscle strength, flexibility and other physical constraints due to aging, leads to an overall regression of physical power. Physical power is strongly related to rowing velocity, so in rowing a decrease of power means higher pace times. This relation (12) is given by a complex third order polynomial which can be simplified to:

$$P = \frac{1.14 \cdot 10^8}{t^{2.75}} \quad \text{(ix)}$$

Where P is the average power in Watt given by the rower and t the pace time per 500m in seconds. Pace times are good parameters to determine the relation between aging and physical power. The increase of pace times takes all physical constraints that causes power decrease into account. Furthermore, pace times are easily measurable and widely available from databases.

Power regression due to aging

To get a rough idea of the lack of power due to aging, pace times from the Concept II database are being compared. This database collects all performances of amateur and professional rowers worldwide using a Concept II ergometer. (14) Only by Concept II verified results are taken into account of the most recent rowing season from May 1, 2015 till April 30, 2016. The average performance times of the 500m distance of 1583 men and 369 women and of the 2000m distance of 4257 men and 1114 women, ages 19 to 89, are analyzed using MATLAB. Use of the 2000m times is chosen because of the large number of participants, but is divided by 4 to obtain a 500m split time. With the use of equation ix, the performance power is determined. With the 'polyfit' and 'polyval' functions of MATLAB, a trend line is fitted to the raw data to obtain a polynomial expression for power related to age. Previous research has shown that a quadratic relationship between power in rowing and age fits best. (12) The results can be seen in figure 11 and 12.

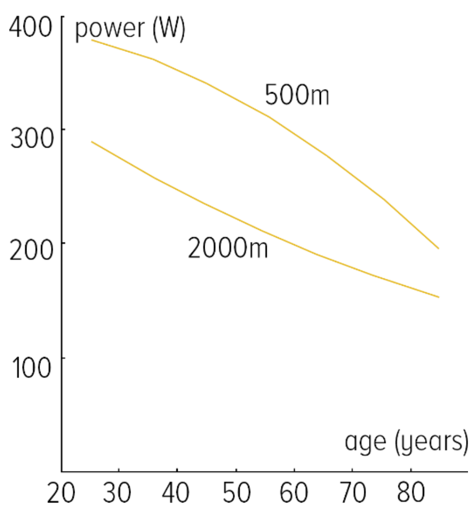


Figure 11. Regression of the performance power of male rowers over age, measured on a distance of 500m and 2000m.

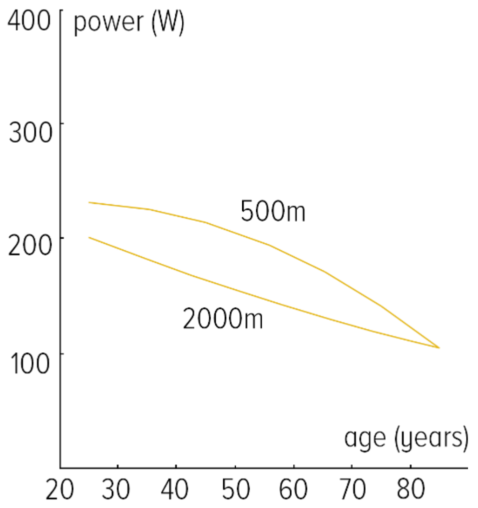


Figure 12. Regression of the performance power of female rowers over age, measured on a distance of 500m and 2000m.

It can be seen clearly, that aging effects the power performance in rowing. The performance power during a distance of 500m is higher compared to the performance power of 500m during a distance of 2000m. Because rowing among elderly is mainly done with recreational purpose, the short distance pace, such as the 500m pace, is not of high importance. Therefore, the power over the 2000m distance will be taken into account for further calculations.

Power to maintain

The respondents of the survey mentioned to start notice physical difficulties due to aging at an average age of 57 years old. This age is therefore chosen as guideline for the required specifications of the design.

Table 3. Comparison of the performance power at an age of 57 and 85 for male and female rowers.

	power age 57 (W)	**power age 85 (W)**	**lack**
women	144.2	104.6	37.9%
men	207.0	154.3	34.4%

The last column of table 3 shows the percentage of power that should be added to the power of an 85-year-old, to maintain the power at the age of 57. This is done using:

$$\left(\frac{P_{57}}{P_{85}} - 1\right) 100\% = lack\ \% \qquad (x)$$

From table 3 it can be seen that an additional 40% of the delivered power will be enough for senior rowers aged 85 to reach the same performance level at the age of 57 years old. Logically, an additional 40% op power must be enough for all ages in between as well. To summarize this findings, a schematic representation of the function the design should fulfil is shown in figure

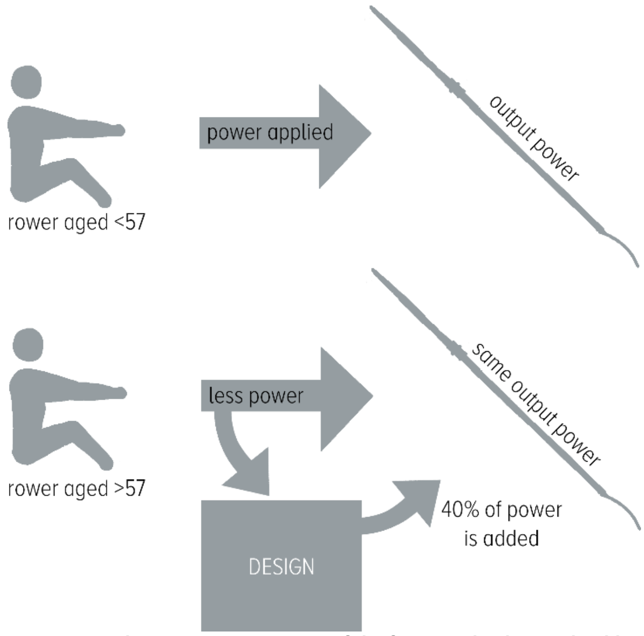


Figure 13. Schematic representation of the function the design should fulfil.

12.

5.3 EXPECTATIONS

As part of the survey, the senior rowers were asked what their expectations and desires were with respect to a support in rowing. All respondents that indicated to have interest in a rowing support, where asked to rate given expectations on their importance. This was done using a scale from 1 to 5, with 1 indicating ‘not important’ and 5 indicating ‘highly important’. Table 4 shows the results, with the average rate of importance in the right column. The expectations with an average rate of 2.5 or higher are taken into account in the full list of requirements.

Table 4. The consumer expectations rated on its importance by senior rowers.

consumer expectation	rate
The design will be invisible for the outside world.	1.9
The design will be making less noise as possible.	3.5
The design will not affect the rowing experience.	4.0
The design will not affect the rowing motion.	3.3
The user will deliver most of the power required to move the boat, not the design.	3.3
The design will not be in contact with the user.	2.6
The design will be applicable on scull and sweep rowing.	1.3
The design will be applicable on every type of boat.	3.0

6. REQUIREMENTS

With the function the design should fulfil known and the expectations of the target audience clear, the requirements of the design can be obtained. The full list of requirement specifications can be found in appendix IV. The most important requirements are listed in table 5. These requirements will be used to evaluate the future concepts. Requirements that specify quantities that are not relevant for the stage of design in this thesis, are left out table 5. For example, requirement FR010 gives the specifications of the battery, which will not be discussed in this study.

Table 5. List of relevant requirements.

number	requirement
GR002	The design will be used to support people who have a lack of physical power.
PR003	The design will not hinder the on water movement of the oar, boat or user.
PR004	The design will not impede getting in our out the boat.
PR006	The design will be as compact as possible.
FR007	The design will deliver an additional 40% of the rowers applied power on the oar handle.
OR001	The design will not affect the rowing experience.
OR002	The design will make less noise as possible.
OR003	The design will not affect the rowing motion for the rower.
OR007	The design will not be in contact with the user.
OR008	The design will be applicable on every type of boat.
OR009	The design will be easily installed and removed from the boat material.
OR010	The design will require only reversible changes to the boat material.
CR001	The cost of the design will be comparable to the cost of an e-bike relative to a normal bike.

7. CONCEPTS

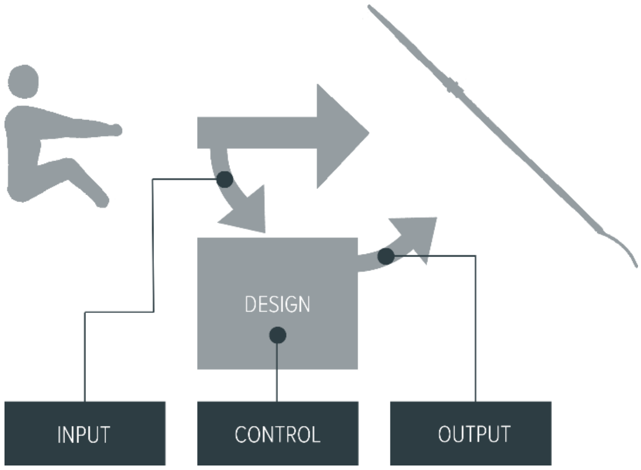


Figure 14. Schematic representation of the function the design should fulfil, separated in three subsystems: the input, control and output.

To create concepts, a closer look at the function the design should fulfil has to be taken. After the analysis done in chapter 6, a schematic overview of the function the design should fulfil was given. As shown in figure 14, the total system should consist of three important aspects to fulfil this function:

- Input: the performance of the rower should be measured using sensors. The sensors provide an input signal that can be used by the control. The input signal should activate the rest of the design.
- Control: the information gathered by the sensors should be processed by the control part of the design. The input signal should be translated into an output signal that is usable for the output of the design.
- Output: the output signal obtained by the control should activate the output of the design. The output should deliver the extra power the user needs.

To generate concepts for the total design, concepts for the separated subsystems of the system are designed. Starting with the last aspect of the system, the output. The output will be the hardware that delivers the extra power to the user. Because the output will be the user interface of the design, it is of great influence on how the total design will operate and its dimensions. It plays an important role in maintaining the safety of the user. Furthermore, the hardware of the output can influence the type of sensors that can be used. How the control will look like, is dependent on both the input and the output.

7.1 OUTPUT CONCEPTS

The output of the system should be a way to deliver the rower extra power during on water rowing. A full list of all the concepts considered can be found in appendix V. For many concepts the change of achieving success was too small, appendix VI, resting four interesting concepts: 1A, 2A, 2C (not shown in figure 15) and 3B, see figure 15.

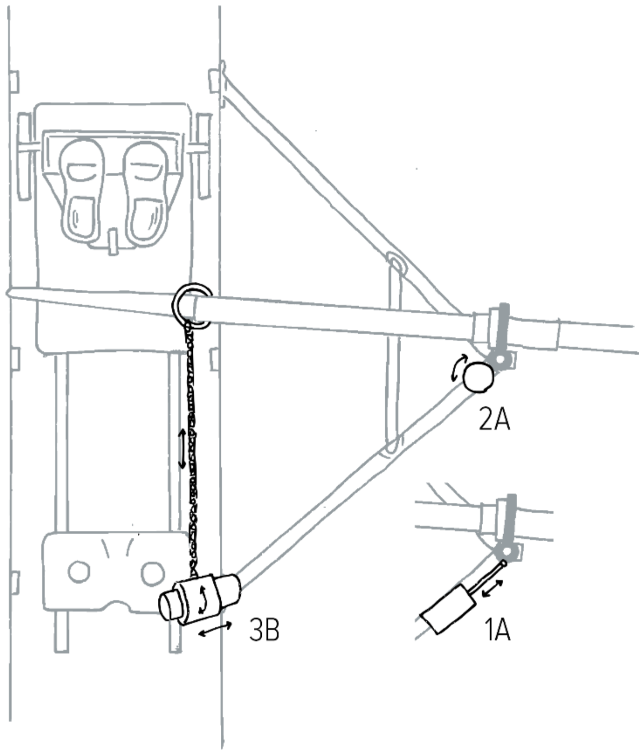


Figure 15. Concept 1A, a linear actuator placed on the rigger and rotating the oarlock. Concept 2A, a rotating motor rotating the oarlock. Concept 3B, a chain winding mechanism. Concept

Concept 1A
This concept uses one or two linear actuators that are both placed on the riggers. By fixing the ends of the actuators to the oarlock, the actuators are able to stimulate the rotation of the oarlock. Through this, the movement of the oar can be supported in the full sequence of the stroke. The exact location can be discussed; by placing the actuators under the riggers, the boat will not be able to come close to the jetty so is will not be favorable.

Concept 2A
Instead of using a linear actuator, AC/DC motors can also be used to rotate the oarlock. The oarlock transfers the supporting power of the motor to the oar. This way, the total movement of the oar can be supported. The motor can be fixed to the riggers or to the pin. To be able to support the stroke motion in only one way, a freewheel mechanic solution could be used. Now the recovery can be done without support.

Concept 2C
This concept is already used in rowing. To be able to always return back home safely, sometimes small motors are being brought into the boat. Extra power is delivered using a motor behind the boat. To maintain a comfortable rowing feeling, the motor can be controlled in a way it imitates the strike of the rower.

Concept 3B
For this concept a vertical rod is placed on the rigger behind the rower. At this rod a motor is placed that can move freely up and down along the rod. The motor controls a winding mechanism. A chain or strep is spanned between the oar and the winding mechanism. Once the mechanism winds up the chain, the chain pulls the oar backwards. During the recovery the chain is unrolled again.

7.2 FINAL OUTPUT DESIGN

To select a concept for the final design, the four remaining concepts (1A, 2A, 2C and 3B) are examine on how they satisfy the requirements. The rate of importance obtained by using the survey, are used for corresponding requirements. Other requirements are assumed to have high importance. High importance is given a rate factor 5, low importance is given a rate factor 1. See table 6. Each of the four concepts are rated from 1 to 5 on how well they satisfy the requirement:

1 = concept does not meet requirement
5 = concept satisfies requirement

It can be seen that the requirements are satisfied best by concept 2A. This concept has the highest score. A great advantage of this concept is that the design is very compact and it is easy applicable on many boat type because it consists only an adjusted oarlock. This concept will be taken into account for the final design.

Table 6. Evaluation of the output concepts. 1 indicating 'design does not satisfy the requirement' and 5 indicating 'design satisfies the requirement'.

Number	Requirement	rate	1A	2A	2C	3B
GR002	The design will be used to support people who have a lack of physical power.	5	5	5	5	5
PR003	The design will not hinder the on water movement of the oar, boat or user.	5	4	4	3	3
PR004	The design will not impede getting in our out the boat.	5	3	5	5	3
PR006	The design will be as compact as possible.	5	4	5	2	3
FR007	The design will deliver an additional 40% of the rowers applied power on the oar handle.	5	5	5	5	5
OR001	The design will not affect the rowing experience.	4	5	5	1	1
OR002	The design will make as little noise as possible.	3,5	3	3	2	1
OR003	The design will not affect the rowing motion for the rower.	3,3	4	4	5	3
OR007	The design will not be in contact with the user.	5	4	4	5	3
OR008	The design will be applicable on every type of boat.	3	2	4	4	3
OR009	The design will be easily installed and removed from the boat material.	5	4	4	5	2
OR010	The design will require only reversible changes to the boat material.	5	2	5	3	1
CR001	The cost of the design will be comparable to the cost of an e-bike relative to a normal bike.	5	5	5	5	5
		total	230	266	230	176

7.3 INPUT CONCEPTS

For measuring input signals, many quantities could be considered. Because this design is based on movement in the horizontal plain, location, velocity and acceleration, this direction should be considered only. The same holds for forces and moments. The two most interesting quantities will therefore be: measuring the forces applied on the oar in horizontal direction and measuring the angle of the oar. Knowing these two quantities, many others can be derived, using chapter 3: 'Mechanics of Rowing'. The location of the measuring device for both force and angle measurements, is of great importance of the type of sensor that could be used.

Location

With the output hardware consisting an adjusted oarlock, it is favorable to locate the sensors in the gate as well. This way the design will be compact; no long cables will be needed and the user only needs to replace the oarlock when using the design.

Placing sensors at the oarlock has more advantages. It does not change the 'feel' of rowing; when placing the measurement device at the blade, due to long outboard length, a small amount of mass generates a large moment. Placing the measuring device more inboard has also the advantage that it should not withstand tough conditions due to entering the water and high accelerations at the outboard length of the oar. (15)

One disadvantage of having the sensors located at the gate, is less accuracy when determining the applied handle force. (11) With equation (vii) the applied handle force can be determined using the measured gate force. Because the assumption is made that the actual out- and inboard length are constant, which is in reality not the case, the estimated error could be up to 5%. Such errors are not favorable when measuring performances of professional rowers. For this design, the accuracy of the measurement is not of great importance. The inaccuracy will be compensated by the advantages of measuring the force at the gate.

State of art

The instrumented oarlock is not a new discovery; its great advantages are notices by different companies selling measuring systems that include the use of an instrumented oarlock.

Figure 16. First instrumented oarlock by BioRow from 1988 measuring force perpendicular to the oar and the horizontal angle of the oar.

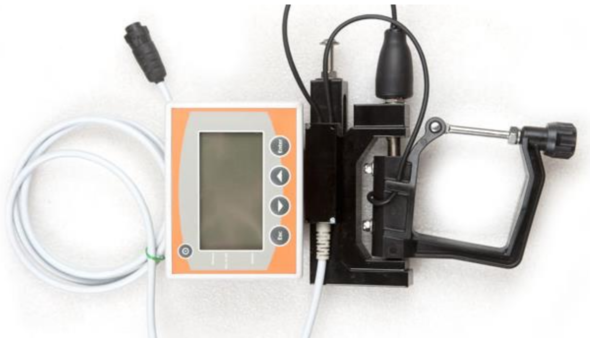


Figure 17. WEBA sport measuring set RowX with at the right the instrumented gate.

Figure 18. The instrumented gate produced by Peach Innovations Limited.

- BioRow was the first to design an oarlock as measuring system in 1988. (16) This design, shown in figure 16, consists of a gate modified to include force and angle sensors. (17) As force sensor, a load cell using strain gauges have been used, measuring the forces applied at the pin of the oarlock. For the angle measurement, a gear mechanism and potentiometer were used. The body of the potentiometer is fixed relative to the pin and the rotor part is mechanically linked to the oarlock. This concept is furtherly improved and used by other companies.
- WEBA sport is one of those companies. (18) They made the instrumented oarlock more light weight and compact, but the conceptual idea remained the same. This oarlock is being sold as part of a total measurement set RowX. Figure 17 shows the WEBA measuring set.
- Peach Innovations Limited created an oarlock with integrated load cell., shown in figure 18. (19) The load cell consists of three concentric tubes, located one inside the other. (20) The tube on the inside provides the contact surface with the supporting pin, the outer tube provides the contact surface where the load of the oar is being supplied on. The oarlock rotates around this outer tube. The middle tube works as load cell that bridges across the two. The deformation of this middle tube is being measured with four strain gauges. For the measurement of the oar angle, a magnet sensing method is used.

7.4 FINAL INPUT CONCEPT

The advantage of the gate designed by Peach Innovations Limited is the more integrated design this device offers. The force and angle measuring system are all pact together. The design seems to be more light weighted and smaller in size as well. Peach Innovations mentions another advantage of their design compared to WEBA sport and that is the fact that its load cell does not rotates which causes no mechanical weak-spot in the flexible cable required to transmit the signals (20). The use of a magnet sensing method is a clever solution looking at the sensors environment.

7.5 CONTROL CONCEPTS

The control should fulfill several functions. Firstly, it should process the information obtained by the sensors. This input signal should be translated into an output signal that is usable for the output of the design. The output signal should control the motor. The systems are designed using Simulink. All systems can be found in appendix VIII. The plotted output signals of the systems can be found in appendix VII.

Input signal

Two input signals can be obtained from the gate force sensor and angle sensor. Both signals can be translated into other quantities; the force applied at the handle and the angular velocity. First both signals can be scaled. To obtain the angular velocity, the derivative of the signal from the angle sensor must be taken. For the handle force the lever equation (vii) is rewritten:

$$\boldsymbol{F_{hn}} = \boldsymbol{F_{on}} \frac{\boldsymbol{R_{out}}}{\boldsymbol{R}} \quad \text{(xi)}$$

Graphs of the handle velocity and the handle force over time can be estimated using the graphs of the velocity and force plotted over time shown in figure 8. Both estimations can be considered as sine functions given by:

$$v(t) = 2\cos\left(\frac{2\pi}{1.7}t - 0.2\right) \quad \text{(xii)}$$

$$F_{hn}(t) = 300\cos\left(\frac{2\pi}{1.7}t\right) + 300 \quad \text{(xiii)}$$

Control system

For the system controlling the desired output power, different options can be considered depending on input signals and complexity. The angular signal, the force signal or both signals can be used as input, and the control can be independent or dependent of the magnitude of this input signal. An overview is given in table 7.

Table 7.

	Independent of input	Dependent of input
Angular signal	IA	DA
Force signal	IF	DF
Angular and Force signal	IAF	DAF

IA and IF system

Both systems use the input signal from the sensors to detect a sense of motion or force application in positive direction, independent of the magnitude. When motion is sensed during the drive, so from catch to release angle, a constant output signal is send to the motor. It is optional to make this constant output signal adjustable using a knob or slider. This way the user is able to choose the amount of supporting power up to, for example, 250 Watt. The output signal is plotted over time using a scope.

IAF system

This system operates like the IA and IF systems, but now uses two input signals instead of only one. Both angular velocity and handle force need to be above a certain threshold to produce an output signal. For this threshold, a knob can be added to adjust this variable. The user needs to find out what threshold gives the most pleasant feel.

DA and DF system

These systems use the applied force, in case or the angular location of the oar to determine an output power. Both relations between oar angle or applied handle force and output power should be estimated. Once the input quantity is translated into power, it can be used to determine the amount of supporting output power, again a knob can be used to adjust this factor. To make sure only the power applied by the rower is taken into account for determining the output power, the output power could be subtracted first.

DAF system

This system uses the product of both signals, force and velocity, to determine the real power measured at the gate instead of using an estimated relation as done in the IAF system. The next step is subtracting the applied power by the system to remain the applied power by the user. This is again gained by an adjustable factor to obtain an output power. The output power signal is only send to the motor when the angular velocity is positive, using a switch in the system.

7.6 FINAL CONTROL CONCEPT

It is important that the feel of rowing remains the same. The use of the design should feel natural and smoothly. To accomplish this, the output signal of the power the support gives over time, should be comparable to figure 19, the graph of the power applied by the rower over time. The plotted output signals, appendix VII, are being compared on how well they match the applied power graph.

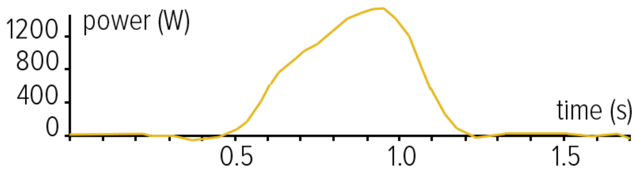


Figure 20. The power applied at the handle, evaluated over time during one stroke. (10)

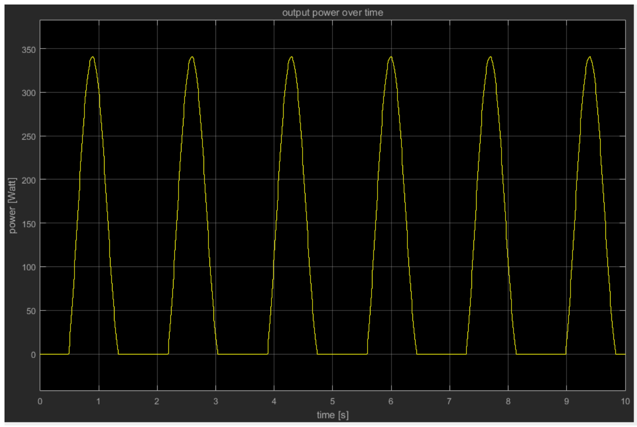


Figure 21. The output signal of the system, likewise the power the motor will apply to the oar over time.

As a result of this comparison, the output signal of the DAF system, figure 20, seems to match the power graph best:

- From 0 s < t < ~0.5 s, the graph remains zero.
- From ~0.5 s < t < ~0.8 s, the graph increases smoothly.
- From ~0.8 s < t < ~1.3 s, the graph decreases smoothly until reaching zero again.

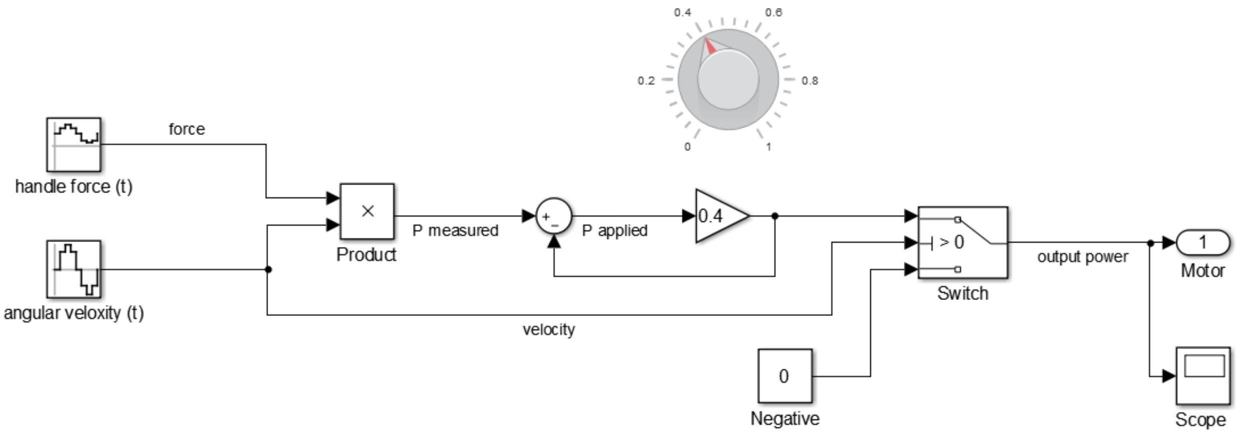
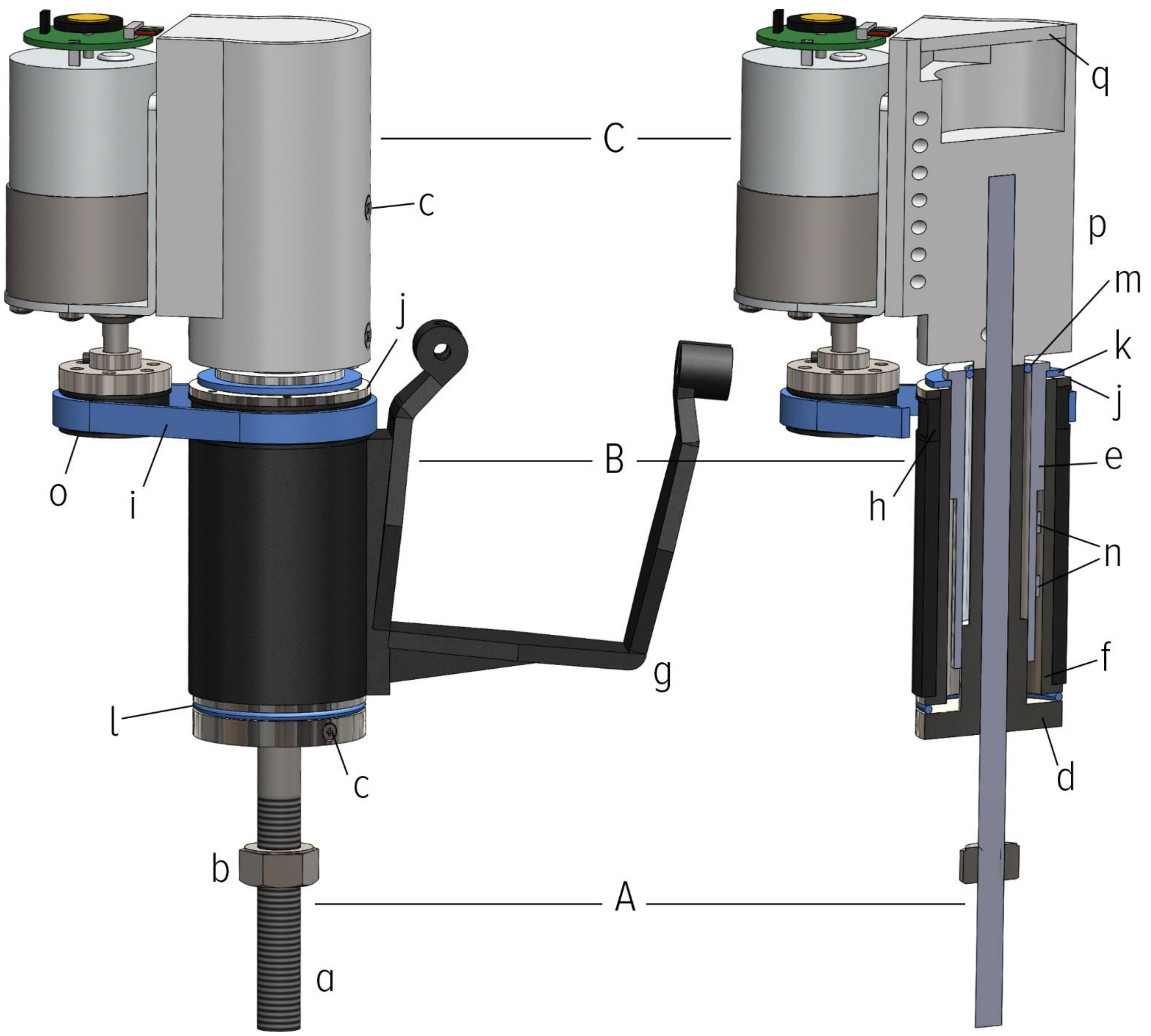


Figure 19. The DAF system uses two input signals; handle force (t) and angular velocity (t) to obtain the power measured. This power is multiplied by a factor that can be adjusted using a knob. The next step is subtracting the applied power by the system to remain the applied power by the user. The angular velocity must be positive to obtain an output signal.

It is therefore chosen to use the DAF controlling system for the final design, shown in figure 19.

8. FINAL DESIGN



the control panel.

Figure 22. The final design, consisting of the pin (A), the instrumented gate (B) and the motor (C). At left, a cross-section of the design is shown.

Combining the final concept of the input, control and output, gives the final design of the total system. This result is drawn using SOLIDWORKS and is shown in figure 22. The final design consists of three separable parts; the pin (A) fixing the design to the boat, the instrumented gate (B) holding the oar and containing the sensors and the motor (C) including its holder and

8.1 THE PIN

The pin is comparable to the pin used for ordinary oarlocks. The lower end consists of screw-thread (a) for mounting the oarlock on the riggers using a bolt (b). The pin goes through the gate part and ends half way in the holder where the motor is being fixed on, the holder rests on this end of the pin. Both parts are being fixed to the pin using screws (c). See figure 23. To be able to lead wiring trough the pin, the inside of the pin can be made hollow.

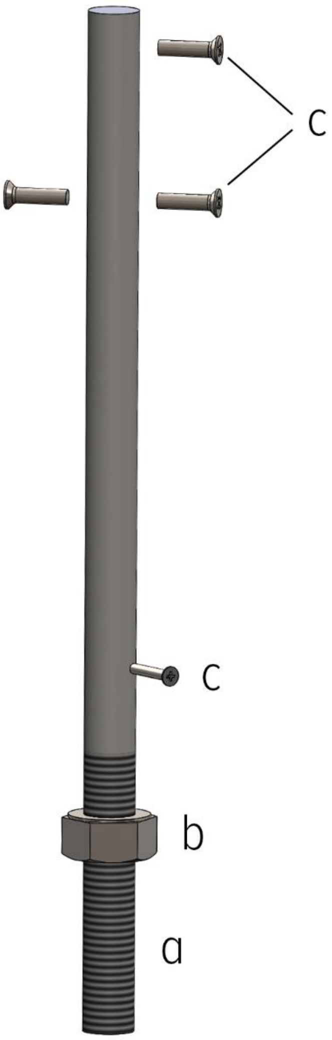


Figure 23. Screw-thread (a) to mount the pin on the riggers using a bolt (b). Screws (c) hold the gate- and motor part in place.

8.2 THE INSTRUMENTED GATE

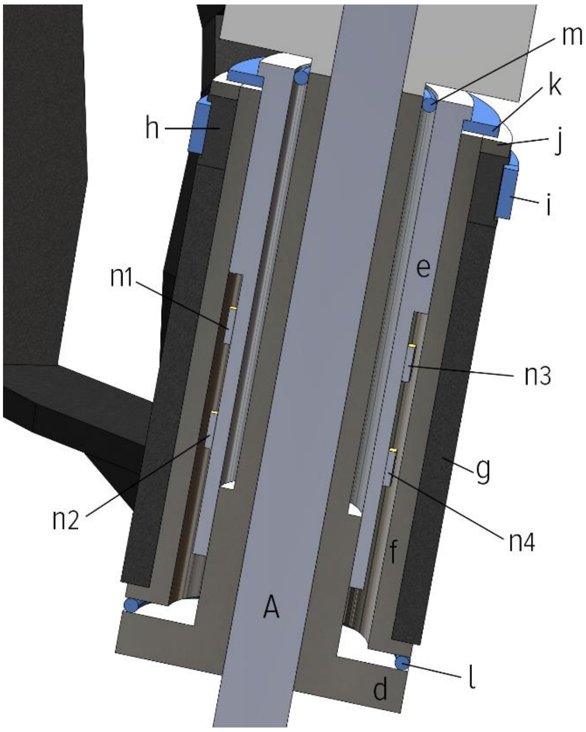


Figure 24. Section view of the instrumented gate (B) to show the four tubes (d) (e) (f) (g), the four strain gauges (n) and the pin (A) centered.

Figure 25. Zoomed in on the two Hall sensors (r) located at the bottom of the holder (p). The rotation is measured using the magnetic field of a magnetic ring (j).

The instrumented gate consists of four tubes (d) (e) (f) (g) with the pin located at the center (A). The outer tube

(g) is the ordinary gate. The gate rotates around the other tubes, creating friction between the surfaces. This should be taken into account choosing the material for the gate. The gate transfers the torque from the motor to the oar and therefore the material should be able to withstand high stresses. The material should be water resistant and light weighted as well.

The gate is connected to a gearwheel (h), which is driven by a belt (i). The connection between the gearwheel, gate and belt gives the opportunity for a mechanical solution to allow rotation of the motor in one direction only. On top of the gearwheel a magnetic ring (j) is placed to provide a magnetic field for measurement of the gate angle.

The inner three tubes form the load cell. (20) The outer tube (f) of the load cell has two functions. It holds the gate in place and provides a contact surface for the load applied by the oar on the gate. The middle tube bridges between the outer tube and the inner tube (d). Four strain gauges (n_1) (n_2) (n_3) (n_4) are places on the middle tube to measure the deformation of the middle tube caused by the load. Because this is the only mechanical linkage between the inner and outer tubes, all force applied to the outer tube will passes through the middle tube and are being sensed. The inner tube (d) is fixed to the pin using a screw (c). The material used for the tubes should be water resistant and light weighted.

The wiring needed to provide a connection between the strain gauges (n) and the control panel in de holder (p), can be leaded trough the pin (A) to reach the measuring sensors.

A plastic circlip (k) is places to hold the gate in place, but allows the ability to remove the gate and rotation of the gate. Two soft gaskets (l)(m) are placed at top and bottom of the tubes to seal the spaces between the tubes so the strain gauges will stay dry.

Rotary magnetic encoder

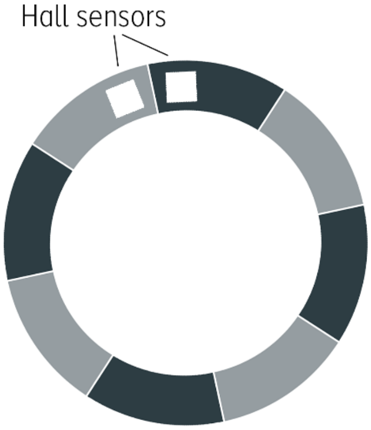


Figure 26. Poles of the magnetic ring (j) with the Hall sensors separated 22.5 degrees.

The angle measurement is done using a rotary magnetic encoder. A magnetic ring (j) is mounted on the rotating gate. The ring contains eight equally spaced poles, alternating north and south, as shown in figure 26. The strength of the resulting magnetic field can be measured using two Hall sensors. The Hall sensors are placed on the bottom of the holder, and should be placed 22.5 degrees apart, exactly half a pole. This way, one of the sensors obtains a sine wave, while the other sensor obtains a cosine. By comparing the two signals, the angle can be estimated. Because the oar will rotate in a range of 110 degrees, using an eight pole magnet will be sufficient. (20)

Strain gauge load cell

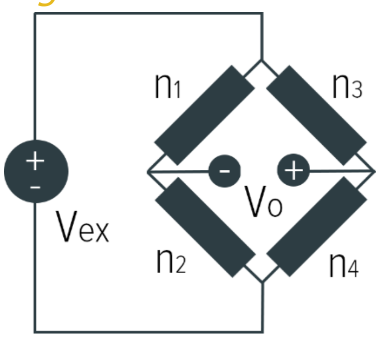


Figure 27. The four strain gauges (n) are connected using a Wheatstone bridge to measure the change in resistance.

As mentioned, the load applied at the gate is measured using strain gauges. (n_1) (n_2) (n_3) (n_4) Strain gauges are used to convert the load applied at the gate into electrical signals. The electrical resistance of a metal is known to increase when the metal is mechanically elongated. (21) By fixing strain gauges to a material that will deform due to the application of load, the resistance of the strain gauges will change proportionally to the deformation of the material. To measure the resistance of the strain gauge, a Wheatstone bridge circuit is used, figure 27. Using a full-bridge configuration, meaning that all four resistors of the Wheatstone bridge circuit are being replaced by strain gauges, the effect of temperature is minimized; all four strain gauges are at the same temperature and mounted on the same material, so the ratio of their resistances does not change due to temperature.

Looking in the design, strain gauge n_1 and n_4 will be under compression, while n_2 and n_3 will be measuring tension. An excitation voltage across n_1-n_3 and n_2-n_4 is compared to the output voltage measured between n_1-n_2 and n_3-n_4 using:

$$\boldsymbol{V_o} = \left(\frac{\boldsymbol{n_4}}{\boldsymbol{n_4}+\boldsymbol{n_3}} - \frac{\boldsymbol{n_2}}{\boldsymbol{n_2}+\boldsymbol{n_1}}\right)\boldsymbol{V_{ex}} \quad \text{(xiv)}$$

The change of the resistance of the strain gauges is proportional to the radial force applied at the oar.

8.3 THE MOTOR

The motor (C) is combined with a suitable gear to obtain enough torque. This torque is translated to a gearwheel (o) that rotates a belt (i). The belt or gear belt should be made of a material that is strong but flexible, water-resistant and that does not slip to transfer the rotation to the gearwheel of the gate (h). The motor is powered by a chargeable battery, which is placed inside the shell of the boat.

The motor is fixed to a holder (p) made of light weighted, water resistant material. This holder does not only function as connection between pin (A) and motor (C), but has two other functions as well. It serves as protection of the control panel that can be stored inside the holder. The control panel is easily accessible by lifting the cover (q), see figure 28. It second function is to hold two Hall sensors (r) that are located at the bottom of the holder, see figure 25. Figure 25 also shows one of the three screws (c) that holds the holder and motor in place.

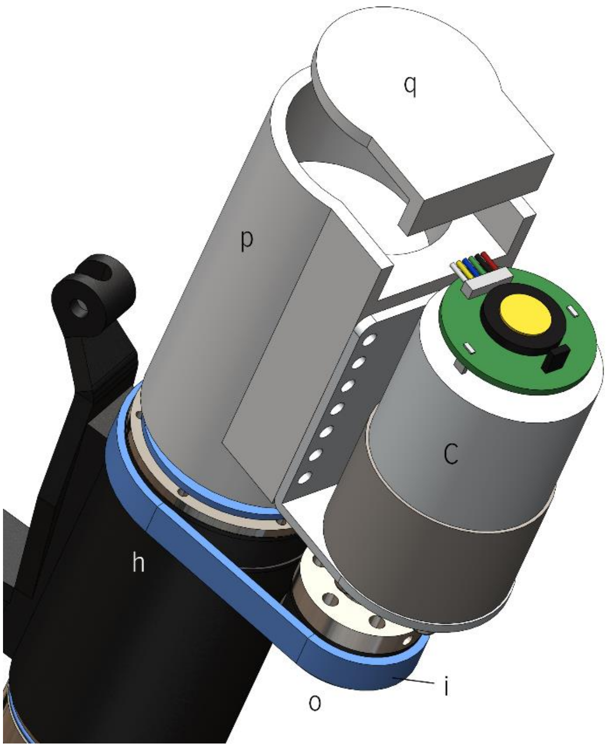


Figure 28. The motor (C) with its holder (p) and the cover (q) lifted. A gearwheel (o) is rotated by the motor. This rotation is transferred to another gearwheel (h) using a belt (i).

9. CONCLUSION AND RECOMMENDATIONS

Rowing is a popular sport among elderly because it improves the stability of the back and has low impact on the knees. In addition, rowing offers other physical and social benefits. With the electric bicycle available for senior bikers, such a support was missing in rowing. 40% of the senior rowers who encounters difficulties during rowing, mentioned to be interested in a support for rowing. Not only senior rowers are interested. Several organizations providing help for disabled, giving disabled the opportunity to row again, mentioned to be interested in this study as well.

One of the main focusses of this thesis was to establish what the difficulties are being encountered by senior rowers. Especially, physical difficulties due to aging of the body. To do so, a survey among senior rowers, aged >60 years old, was done. Besides getting in and out the boat, a lack of muscle power was mentioned in this survey. The survey has also been used to obtain the expectations of the target audience.

It was found that power in rowing has a close relation to the rowing performance. Comparing performance pace times of different rowers of all ages, all around the world showed a relation between the regression in power due to aging.

The final design fulfills the requirements that were taken into account. A system is designed that gives the user extra power during on water rowing. The total system is compact, widely applicable and can easily be installed and removed from the boat. It will not hinder getting in our out the boat, nor it will be in contact with the user.

In this study, as target audience, senior rowers were taken into account. Future studies can broaden this audience by obtaining the needs and expectations of other disabled rowers. For example, rowers suffering with diseases leading to muscle weakness.

The relationship found between the rowing performance over age, was done using pace times from Concept II. These pace times were obtained during rowing contests, which leads to higher performance levels than would be obtained during recreational rowing. On the other hand, the device is designed for recreational rowing. To be more specific about the performance of the target audience, the pace times should be measured during longer distances of recreational rowing.

Not all requirements were taken into account for this study. The full list can be found in appendix IV. This list can be made more specific and be developed further. For example, costs were mentioned shortly, but are not specified jet.

Some aspects of the design should be further specified. The material used for the gate for example. This material should be strong enough to transfer the power from the motor onto the oar. The motor, gear and battery used should also be specified. Appendix III contains calculations on the maximum power the motor should be able to deliver.

Strain gauges and Hall effect sensors are both commonly used sensing techniques. It should be figured out how both sensors can be calibrated to make the design function properly.

One of the requirements was to deliver power only during the drive phase of the stroke. This requirement was fulfilled by the control of the system, only giving an output signal when the angular velocity is positive. The user should be able to rotate the gate backwards again during the recovery. It would be favorable if the gate can be uncoupled of the motor, while being rotated backwards in the recovery. A freewheel mechanism can be used to fulfill this. Figure A shows the basic concept of a freewheel mechanism. The driving part is the outer ring, which can rotate both counterclockwise and clockwise. Only when the outer ring rotates in counterclockwise direction, the inner part will follow. This mechanism is used in bicycles to let the user paddle backwards without moving in backwards direction. Further research can be done to find a mechanical mechanism that completes this task for this design.

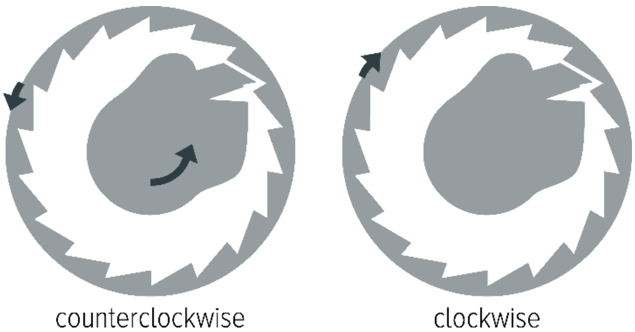


Figure 29. The principle of a freewheel mechanism.

Another point of discussion is the rotation of the blade during the stroke. Rotation around the axis of the oar is not taken into account designing the concepts. In de final design, the gate pushes the oar, letting it rotate around the pin. The force applied by the gate on the oar due to the support could affect the rotation of the oar around its axis.

A prototype could be used to test if the design affects the rowing motion or the rowing experience. Those requirements seem to be fulfilled by placing the support at the oarlock. Doing this, no moment is created on the oar, all mass is carried by the pin and thus riggers. Testing the prototype will obtain the real ‘rowing feel’ the design gives. This experience should be encountered in practice.

REFERENCES

1. **Wells, Steve.** *Benefits of Rowing*. Foss Rowers, 2005. [Cited: August 10, 2016.] http://www.fossrowers.org/Benefits_of_Rowing.html.

2. **Boggelen, Otto van.** *Feiten over de elektrische fiets.* Fiets Beraad, 2013, Vol. 1, 24.

3. **Stichting Roeivalidatie**. *Verwijzer?* 2016. [Cited: August 10, 2016.] http://www.roeivalidatie.nl/professionele-verwijzers/.

4. **CWNC CREW** *Glossary of Rowing Terms*. 2016. [Cited: 20 July 2016.] http://www.nccrew.com/terms.html.

5. **Concept2**. *The Biomechanics of Rowing*. [Cited: July 20, 2016.]

6. **Cabrera, D.** A simple 1+ dimensional model of rowing mimics observed forces and motions. Human Movement Science. April, 2006, Vol. 25, 2.

7. **Baudouin, A.** A biomechanical review of factors affecting rowing performance. British Journal of Sport Medicine. December, 2002, 36.

8. **Kleshnev, Valery.** *Moving the Rowers, biomechanical background*. Australian Institute of Sport, 2002.

9. **Kleshnev, Valery**. *Rowing Biomechanics*. Rowing Science Consultant, 2011.

10. **Kleshnev, Valery**. *Force and Power in Rowing.* Rowing Biomechanics Newsletter. March, 2014, 156.

11. **Kleshnev, Valery**. *Q&A*. Rowing Biomechanics Newsletter. March, 2010, Vol. 10, 108.

12. **Seiler, K.S.** *Gender differences in rowing performance and power with aging.* Medicine and Science in Sports and Exercise . January, 1998, Vol. 1, 30.

13. **Kleshnev, Valery.** *Power in Rowing.* Australian Insitude of Sport, 2000.

14. **Concept2**. *Rankings database*. [Cited: June 24, 2016.] https://log.concept2.com/rankings.

15. **In Motion Software & Sports Technology**. *Designing a Measurement System for Rowing: Force and Power on the Oar.* Rowing Motion, 2014. https://www.rowinginmotion.com/designing-measurement-system-rowing-force-power-oar/

16. **Kleshnev, Valery** *A brief history of our developments in force measurement area.* BioRow, 2011.

17. **Kleshnev, Valery.** *Device for power measurement in rowing.* SU1650171, 1988.

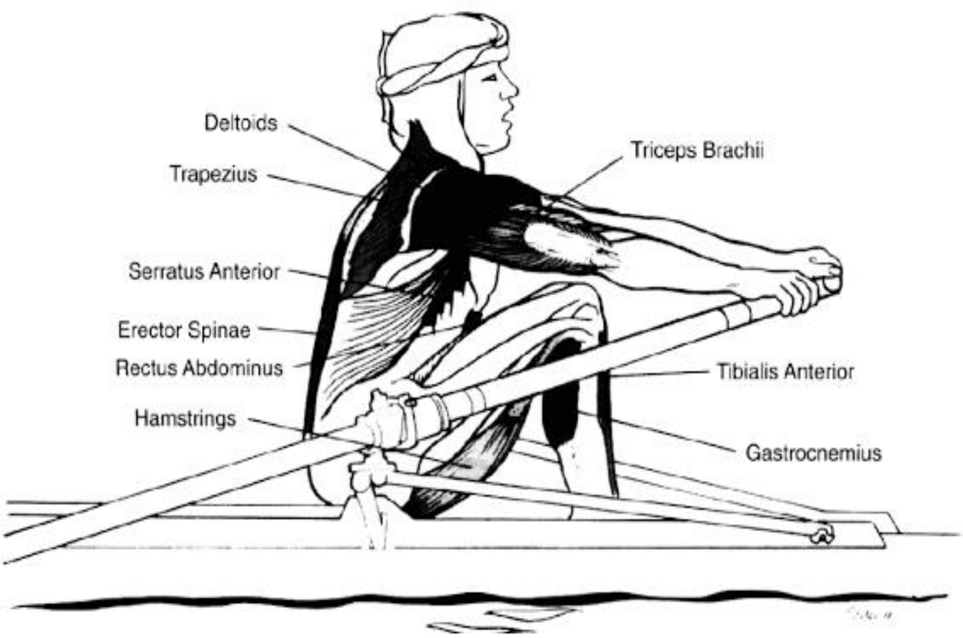
18. **WEBA sport.** *Product RowX-outdoor*. 2014. [Cited: August 1, 2016.] http://www.weba-sport.com/en/products/rowx-outdoor

19. **Peach Innovations.** *Instrumented Oarlocks.* [Cited: August 2, 2016.] http://www.peachinnovations.com/touroarlocks.htm.

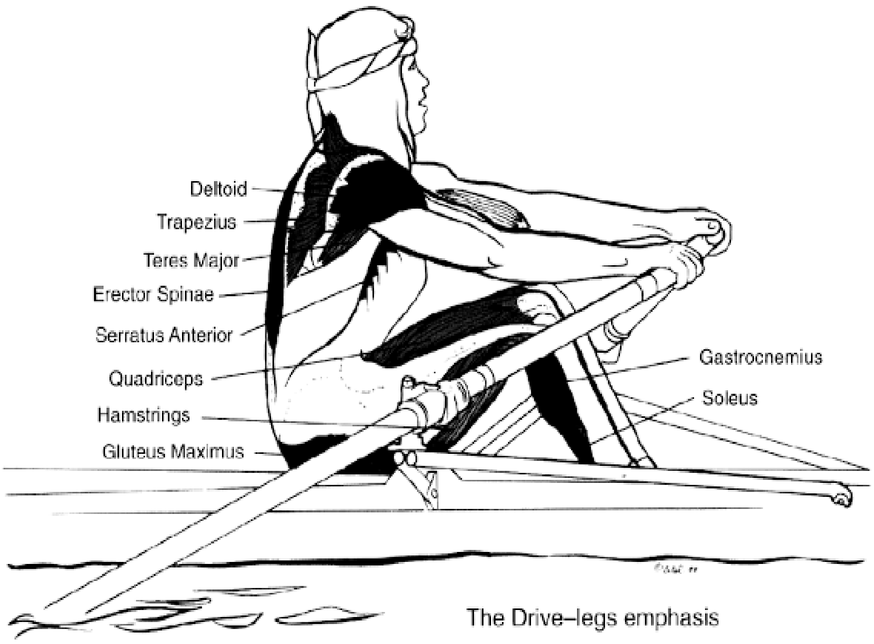
20. **Haines, Paul**. *Force sensing system.* US7114398, September 10, 2003.

21. **National Instruments.** *How Is Temperature Affecting Your Strain Measurement Accuracy?* 2016. [Cited: August 10,2016.] http://www.ni.com/white-paper/3432/en/ .

THE CATCH

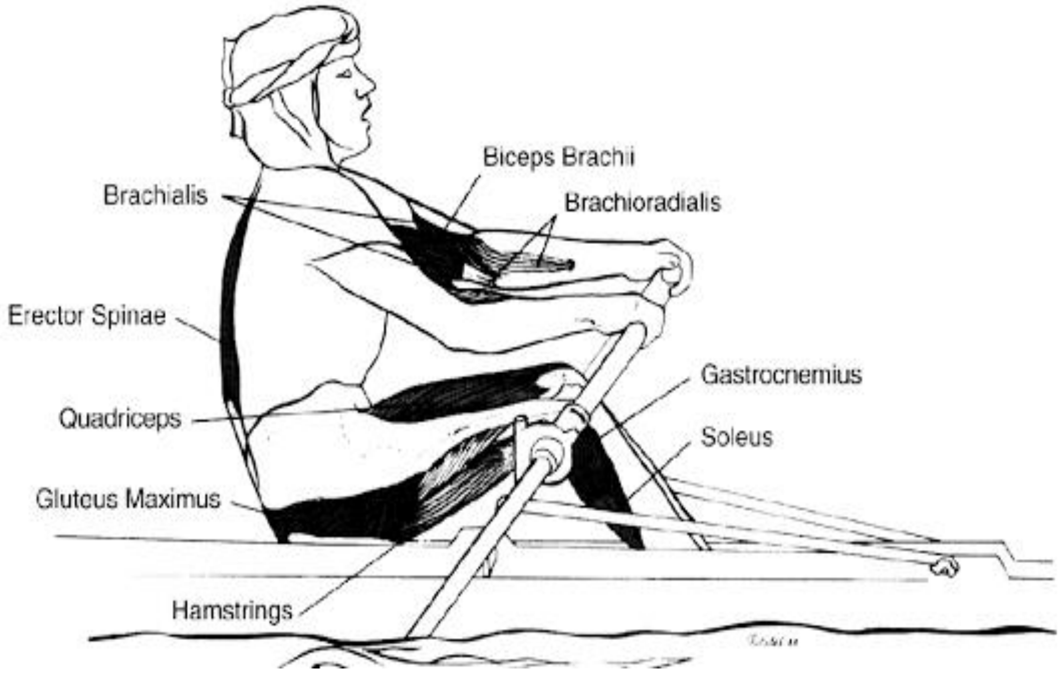


THE DRIVE – LEGS EMPHASIS

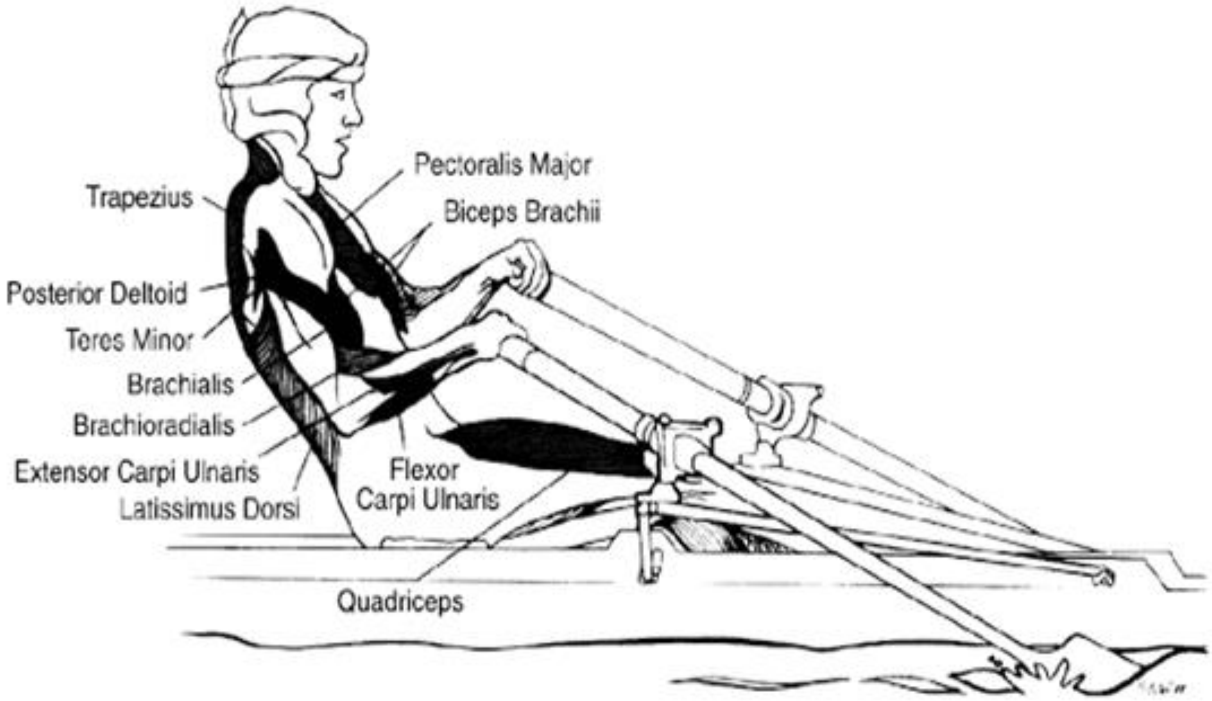


The Drive–legs emphasis

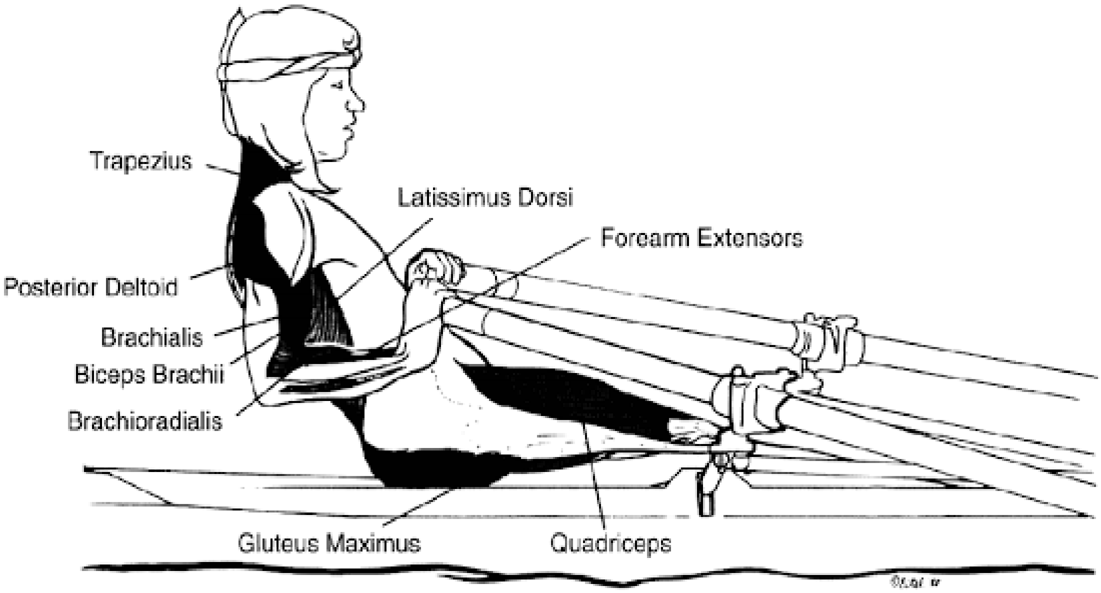
THE DRIVE – BODY SWING EMPHASIS



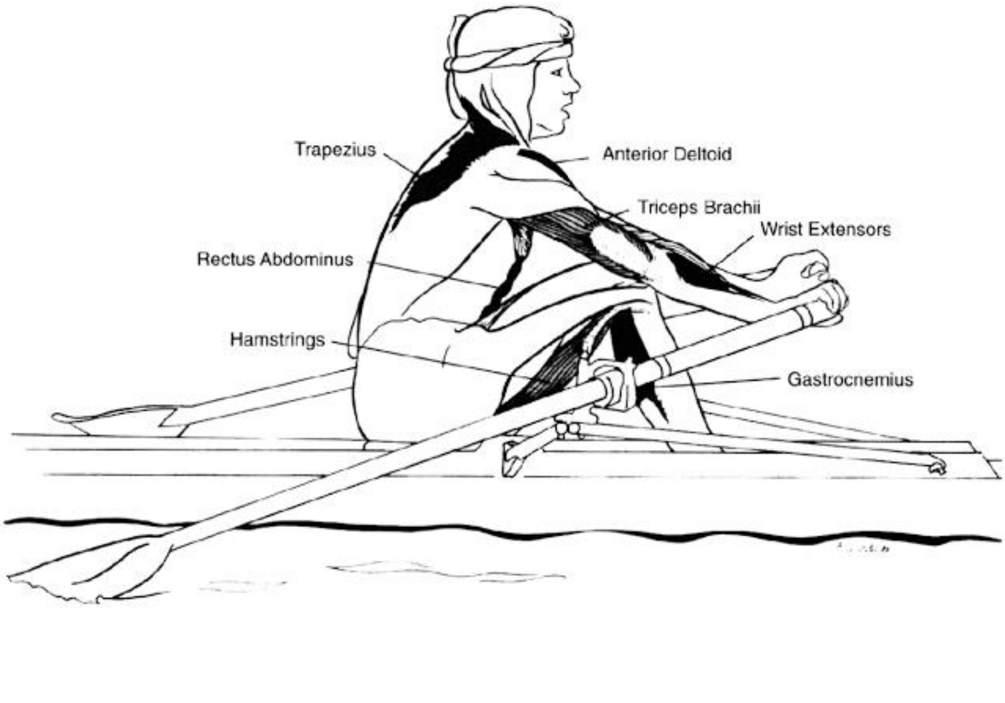
THE DRIVE – ARM PULL TROUGH



THE RELEASE



THE RECOVARY



APPENDIX II SURVEY

Enquête e-row

Beste roeier,

Mijn naam is Femke de Gooijer en ik ben derdejaars student Biomedische Technologie aan de Universiteit Twente. Momenteel ben ik bezig met mijn bachelor thesis en wil ik kijken naar de mogelijkheden voor een ondersteuning bij het roeien.

Door veroudering van het lichaam gaat bewegen soms niet zo makkelijk meer als vroeger. Gelukkig bestaan er al veel technische oplossingen, neem bijvoorbeeld de e-bike die ondersteuning biedt voor fietsers op leeftijd. Helaas voor roeiers bestaat zo'n soort oplossing nog niet en dat is waar deze thesis om de hoek komt kijken.

U kunt mij hiermee helpen door deze enquête in te vullen. Het zal u ongeveer 10 minuten tijd kosten en de antwoorden die u geeft zullen geheel anoniem blijven. De antwoorden zullen gebruikt worden om te achterhalen wat de eisen en wensen zijn om rekening mee te houden bij het ontwerpen van een 'e-row'.

Alvast hartelijk dank voor uw tijd en moeite!

* Required

Algemeen

1. **Wat is uw geboortedatum? ***

   Example: December 15, 2012

2. **Wat is uw geslacht?**

   Mark only one oval.

   - ( ) man
   - ( ) vrouw
   - ( ) Other: ____________

Algemeen

3. **Hoeveel jaar roeit u al? ***

   ____

4. **In wat voor een type boot roeit u voornamelijk?** *

Mark only one oval.

- Wh1* - single wherry
- Wh2* - dubbel wherry
- C1x - C-een
- C2x - C-dubbeltwee
- C2* - C-dubbeltwee met stuur
- C2+ - C-twee met stuur
- C3x - C-dubbeldrie
- C4* - C-dubbelvier
- C4+ - C-vier
- Ov1x - Overnaadse skiff
- Ov2+ - Overnaadse twee
- Ov4+ - Overnaadse vier
- 1x - Skiff
- 2x - Dubbeltwee
- 2- - Twee zonder
- 2+ - Twee met
- 4x - Dubbelvier
- 4* - Dubbelvier met
- 4- - Vier zonder
- 4+ - Vier met
- 8+ - Acht

5. **Wat is uw splittijd van 500m tijdens een standaard haal? (in min:seconden)**

Hoelang zou u doen over 500 meter wanneer u een langere afstand roeit?

6. **Heeft u soms het gevoel dat u niet meer goed kunt meekomen met andere roeiers van vergelijkbare leeftijd?** *

Bijvoorbeeld dat u het idee heeft dat andere ploeggenoten extra kracht moeten leveren om u te compenseren, dat u het tempo van de groep niet kunt bijhouden, etc.

Mark only one oval.

- Ja, ik heb (soms) het gevoel dat ik minder goed mee kom.
- Nee, dit gevoel heb ik niet.

7. **Tijdens het maken van de roeibeweging, merkt u dat dit lastiger gaat t.o.v. vroeger door veroudering van uw lichaam?** *

Mark only one oval.

- Ja, de roeibeweging maakt ik minder makkelijk dan vroeger.
- Nee, ik merk geen verschil. *Skip to question 12.*

Lichamelijke hinder

U heeft aangegeven dat het maken van de roeibeweging lastiger is geworden door veroudering van uw lichaam. De volgende vragen gaan hier dieper op in.

8. **1. Wanneer ervoer u voor het eerst lichamelijke hinder door ouderdom tijdens het roeien?** *

Example: December 15, 2012

9. **2. Op welke manier(en) merkt u dat het roeien lastiger geworden is?** *
Meerdere antwoorden zijn mogelijk.
Check all that apply.

- [ ] Ik merk dat ik minder kracht heb in mijn spieren.
- [ ] Ik merk dat mijn spieren sneller vermoeit raken.
- [ ] Ik merk dat mijn lichaam stijver is geworden.
- [ ] Ik merk dat ik minder conditie heb gekregen.
- [ ] Ik ervaar pijn tijdens het roeien.
- [ ] Other:

Last van uw spieren tijdens het roeien

De volgende vragen hoeft u alleen in te vullen als u bij de vorige vraag één van onderstaande heeft aangevinkt:

- Ik merk dat ik minder kracht heb in mijn spieren.
- Ik merk dat mijn spieren sneller vermoeit raken.

Voor de volgende vraag onderscheiden we 7 stappen in de roeibeweging:


1. Eerste deel van de herstelfase


2. Tweede deel van de herstelfase


3. De inpik


4. Eerste deel van de arbeidsfase


5. Tweede deel van de arbeidsfase


6. Het einde van de haal


7. De uitpik

10. **Kunt u aangeven bij welke stappen van de roeibeweging u last ervaart en in welke spiergroepen u deze last ervaart?**
Bijvoorbeeld: "Ik merk dat ik minder kracht heb in de spieren van mijn bovenarm tijdens stap 5 (tweede deel arbeidsfase)" Onderscheiden spiergroepen: onderarm, bovenarm, schouders, bovenste rugspieren, onderste rugspieren, borst, buik, bil, bovenbeen en onderbeen.

11. **Zou u geïnteresseerd zijn in ondersteuning tijdens het roeien?** *
Dit gaat om een ondersteuning bij het roeien vergelijkbaar met de ondersteuning van een e-bike bij het fietsen.
Mark only one oval.

- Ja *Skip to question 14.*
- Nee *Skip to question 13.*

Geen lichamelijke hinder

U heeft aangegeven geen last te ervaren door het verouderen van uw lichaam, fijn!

12. **Zou u wel interesse hebben in een roei-ondersteuning als u last begint te ervaren?** *
Dit gaat om een ondersteuning bij het roeien vergelijkbaar met de ondersteuning van een e-bike bij het fietsen.
Mark only one oval.

- Ja *Skip to question 14.*
- Nee *Skip to question 13.*

Geen interesse

U heeft aangegeven niet geïnteresseerd te zijn in ondersteuning tijdens het roeien.

13. **Kunt u uitleggen waarom u niet geïnteresseerd bent?**

Stop filling out this form.

Wensen

De volgende vragen zijn bedoeld om een beeld te krijgen van wat de wensen zijn wanneer het gaat om een ondersteuning voor tijdens het roeien.

14. **In hoeverre vindt u het belangrijk dat de ondersteuning niet zichtbaar is voor de buitenwereld?**
Mark only one oval.

	1	2	3	4	5	
Niet belangrijk						Heel erg belangrijk

15. **In hoeverre vindt u het belangrijk dat de ondersteuning geluidarm is?**
Mark only one oval.

	1	2	3	4	5	
Niet belangrijk	◯	◯	◯	◯	◯	Heel erg belangrijk

16. **In hoeverre vindt u het belangrijk dat de roei-ervaring hetzelfde blijft?**
Mark only one oval.

	1	2	3	4	5	
Niet belangrijk	◯	◯	◯	◯	◯	Heel erg belangrijk

17. **In hoeverre vindt u het belangrijk dat u zelf de grootste kracht levert om de boot te laten bewegen?**
Mark only one oval.

	1	2	3	4	5	
Niet belangrijk	◯	◯	◯	◯	◯	Heel erg belangrijk

18. **In hoeverre vindt u het belangrijk dat de ondersteuning op elke roeiboot toepasbaar is?**
Mark only one oval.

	1	2	3	4	5	
Niet belangrijk	◯	◯	◯	◯	◯	Heel erg belangrijk

19. **In hoeverre zou u het als vervelend ervaren wanneer uw lichaam in direct contact staat met de ondersteuning?**
Mark only one oval.

	1	2	3	4	5	
Niet vervelend	◯	◯	◯	◯	◯	Heel erg vervelend

20. **In hoeverre zou u het als vervelend ervaren wanneer u met de ondersteuning uw roeibeweging moet aanpassen?**
Mark only one oval.

	1	2	3	4	5	
Niet vervelend	◯	◯	◯	◯	◯	Heel erg vervelend

21. **In hoeverre zou u het als vervelend ervaren wanneer u met de ondersteuning enkel nog zou kunnen scullen?**
Mark only one oval.

	1	2	3	4	5	
Niet vervelend	◯	◯	◯	◯	◯	Heel erg vervelend

22. **Heeft u nog verdere ideeën, wensen of opmerkingen die u kwijt zou willen als het gaat om een ondersteuning voor tijdens het roeien?**

Powered by
Google Forms

RELATION POWER APPLIED BY THE ROWER AND DESIGN

A relation between the power applied by the rower on the handle, and the power the design should give as a support is obtained. A distinction is made between the normal handle force applied by rowers having no lack of power F_{hn1} and the normal handle force applied by rowers that do have a lack of power F_{hn2}. Resulting in:

$F_{hn2} < F_{hn1}$

Combining this with the moment balance around the oarlock equation (vi) leads to an unbalanced summation of moments:

$\sum M_o = R_{in}F_{hn2} - R_{out}F_{bn} = M_{res}$

With M_{res} the resultant moment at the oarlock. To balance this, the design should deliver M_{res} to compensate the lack of power at the handle. Rewriting the expression:

$M_{res} = R_{in}F_{hn1} - R_{in}F_{hn2}$

Expressions for these forces can be found using equation (viii):

$F_{hn1} = P_{h1}/(R_{in} * \omega(t))$ and $F_{hn2} = P_{h2}/(R_{in} * \omega(t))$

It is stated that the design must result in an additional power of 40% experienced by the rower. From this follows:

$P_{h1} = 1.4P_{h2}$

Combining above equations:

$M_{res} = R_{in}*(1.4P_{h2} \;/(R_{in} * \omega(t))) - R_{in}*(P_{h2}/(R_{in} * \omega(t))) = 0.4P_{h2}/\ \omega(t)$

From this, a relation between the power delivered by the rower and the power delivered by the support can be obtained:

$P_{add} = 0.4P_{h2}$ Watt

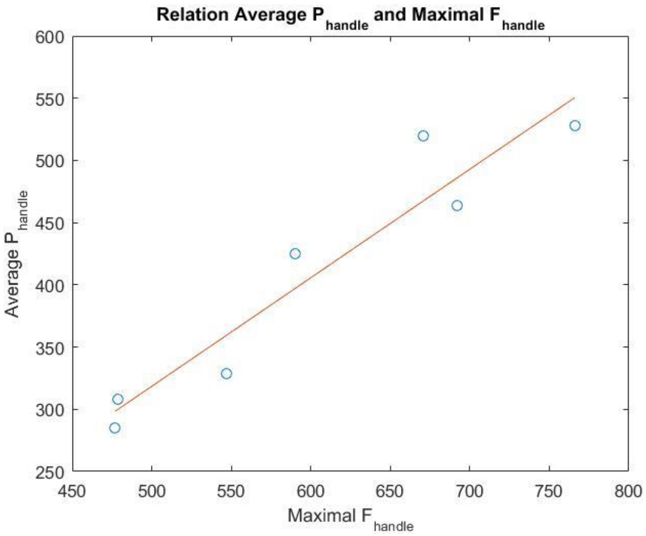
MAXIMAL HANDLE POWER, VELOCITY AND FORCE

In this section, the maximal power the design should be able to deliver is obtained. With the relation found in previous section, it can be seen that the maximal power applied by the rower needs to be found. With use of equation (ix) the average applied power $P_{h,avg}$ by the rower can be determined using the average boat velocity $v_{b,avg}$. To determine the maximal applied power, the maximal handle velocity and the maximal applied handle force can be used. The maximal handle velocity has a strong correlation (r=88)[1] with the average boat velocity, given by:

$v_{h,max} = 0.32\ v_{b,avg} + 0.87$ for sweep rowing
$v_{h,max} = 0.36\ v_{b,avg} + 0.75$ for sculling

To find the maximal power applied by the rower $P_{h,max}$ a relation is obtained between the average power and the maximal applied handle force by analyzing data[2] in MATLAB, see figure 1.

[1] Reference: **Kleshnev, Valery.** *Facts, did you know that…* Rowing Biomechanics Newsletter. June, 2003, Vol. 3, 6
[2] Reference: **Kleshnev, Valery**. *Rowing Biomechanics*. Rowing Science Consultant, 2011.



Appendix figure 1. Relation between the average applied handle power and the maximal applied handle force.

The assumption is made, that this relation is valid to use to get a rough indication of the power needed:

$P_{h,ave} = 0.8723 * F_{h,max} - 117.6723$

From (viii) it is stated that:

$P_{h,max} = v_{h,max} * F_{h,max}$

Looking at figure 8 it can be seen that the relation this relation is not exact, the value of $P_{h,max}$ will be lower because both the applied force and the velocity of the handle are not maximal when the maximal power is reached. Because the actual value of the maximal power will be lower, the calculated maximal power is a valid value to use for obtaining the required maximal power the support must deliver. Using above equations, the maximal velocity and power for sweep and scull rowing is determined and listed in appendix table 1.

Appendix table 1. Average boat velocity, average power applied at handle, maximal handle velocity and maximal power applied at handle for women and men both for 500m and 2000m.

		$v_{b,ave}$ [m/s]	$P_{h,ave}$ [Watt]	$v_{h,max}$ [m/s]		$P_{h,max}$ [Watt]	
age				sweep	scull	sweep	scull
57	Women 2000m	3.7106	144.2	2.0574	2.0858	617.65	626.18
	Men 2000m	4.1841	207.0	2.2089	2.2563	700.13	702.51
85	Women 2000m	3.1596	104.6	1.8811	1.8874	562.86	574.93
	Men 2000m	3.6101	154.3	2.0252	2.0496	631.44	639.05

Note that during scull rowing, the applied power is divided over two oars. Taking this into account, the maximal additional powers the support is required to deliver for men aged 85 are given in appendix table 2.

Appendix table 2. Maximal additional power that will be needed.

$P_{add,max}$ Sweep rowing	252.58 Watt
$P_{add,max}$ Scull rowing	80.70 Watt

APPENDIX IV LIST OF REQUIREMENTS

GENERAL REQUIREMENTS

Number	Requirement	Explanation
GR001	The design is for recreational use and revalidation in rowing.	The design cannot be used in professional rowing.
GR002	The design will be used to support people who have a lack of physical power.	The design will compensate this lack of power for elderly and disabled rowers.

PHYSICAL REQUIREMENTS

Number	Requirement	Explanation
PR001	The design will be as light as possible.	Extra mass will decrease the performance of the rower.
PR002	The design will not unbalance the boat.	Balance is a hard task in rowing, therefore unstabilizing the boat is not favorable.
PR003	The design will not hinder the on water movement of the oar, boat or user.	The full rowing movement must be made.
PR004	The design will not impede getting in our out the boat.	Getting in and out of the boat is mentioned as difficult by the target audience, this should not be made more complicated.
PR005	The design will be applicable on most commonly used types of boats.	To make the design more widely usable.
PR006	The design will be as compact as possible.	To make the design less obtrusive and increase the ease of use.

ENVIRONMENTAL REQUIREMENTS

Number	Requirement	Explanation
ER001	The design will be resistant to an environment temperature between -40°C and 60°C.	Taken outdoor conditions into account.
ER002	The design will be able to handle direct sunlight.	Taken outdoor conditions into account.
ER003	The design will have a water resistance of level 4 established by the Ingress Protection rating. However, up to level 7 is desired.	Level 4 provides protection against splashing of water, but with the change of tipping over, lever 7 is desired to provide protection against immersion up to 1 m depth.
ER004	The design will provide protection to hazardous parts by level 2.	Level 2: effective against fingers or similar objects. Established by the Ingress Protection rating.

FUNCTIONAL REQUIREMENTS

Number	Requirement	Explanation
FR001	The design will measure the power the user applies on the handle when pulling the handle from catch to release angle.	The power the user applies on the handle is the propulsive power of the system during the drive phase.
FR002	The design will be able to measure a maximal power of 800 Watts.	Table A
FR003	The design will be able to measure a maximal handle velocity of 2,5 m/s.	Table A
FR004	The design will be able to measure a maximal handle force of 400 N.	Table A
FR005	The measuring system will have an error of 10% or less.	High accuracy is not required for the design.
FR006	The measuring system will have a sample frequency of 50Hz.	This sample rate is used in adjusted gate measuring systems. bron C
FR007	The design will deliver an additional 40% of the rowers applied power on the oar handle.	Table A – lack of power
FR008	The design will deliver the additional power when the oar moving in direction of motion of the boat.	This is during the drive phase, when the user applies most power on the system.
FR009	The design will deliver a maximum power of 250 Watts and 80 Watts in sweep and scull rowing respectively.	Table B – lack of power
FR010	The design will be usable for 3 hours without battery charging.	This is comparable to the battery time of electric bicycles.

OPERATIONAL REQUIREMENTS

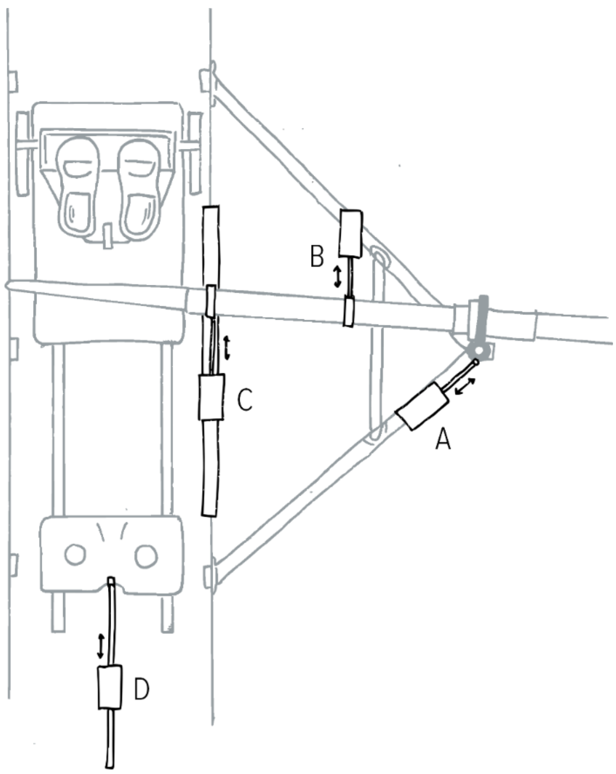
Number	Requirement	Explanation
OR001	The design will not affect the rowing experience.	A comfortable feeling during a stroke must maintain.
OR002	The design will make less noise as possible.	Rowing is considered as relaxing, hard noise will not be comfortable.
OR003	The design will not affect the rowing motion for the rower.	The user does not need to adjust his or her rowing technique to make use of the design.
OR004	The user will deliver most of the power required to move the boat, not the design.	Using the design must feel natural. This requirement will automatically be fulfilled if the design meets FR005.
OR005	The design will follow the movement of the user with a delay as small as possible.	A small delay is required to ensure the safety of the user; the handle should stop when the user stops pulling. Also, only a small delay will lead to a more natural feeling.
OR006	The design will deliver the additional power only when the oar is pulled on by the rower in direction of motion of the boat.	The oar cannot be given power when the rower does not need it, to safe security of the rower. The oar cannot be driven into contrary direction of the users movement, this will lead to dangerous situations.
OR007	The design will not be in contact with the user.	To ensure the safety of the user.

OR008	The design will be applicable on every type of boat.	To make the design more widely usable.
OR009	The design will be easily installed and removed from the boat material.	A trained user should be able to complete this task in less than 20 minutes.
OR010	The design will require only reversible changes to the boat material.	To reduce the cost of the design, and to make the design widely usable.

COST

Number	Requirement	Explanation
CR001	The cost of the design will be comparable to the cost of an e-bike relative to a normal bike.	This price range is known as acceptable for the target audience.

1. USE OF LINEAR ACTUATORS



A. From riggers to oarlock

This concept uses one or two linear actuators that are installed on both riggers. The exact location can be discussed. By fixing the ends of the actuators to the oarlock, the actuators are able to rotate the oarlock. Through this, the movement of the oar can be supported in the full sequence of the stroke.

B. From riggers to oar

This concept uses the same essential idea as 1a, but now the ends of the actuators are fixed to the oar instead of the oarlock. The actuators can support the drive and recovery by pushing and pulling the oar in direction of motion.

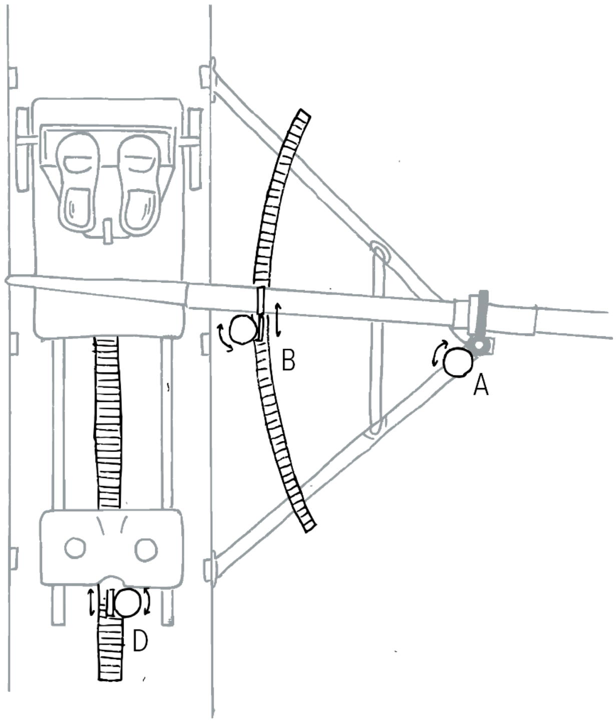
C. From rod to oar

In this concept the actuator is placed on a special rod made in the boat to unload the riggers. The ends of the actuator are connected to the oar again to support the movement.

D. From boat to bench

Instead of supporting the movement of the oar, the sliding of the chair is supported in this concept. This is done by mounting the actuator in the shell and fixing it ends to the chair. This way, the movement of the chair is supported during the leg extension of the drive.

2. USE OF ROTATING MOTOR



A. Rotation of oarlock

Instead of using a linear actuator, also AC/DC motors can be used. In this concept the rotation of the oarlock is being supported. The oarlock transfers the supporting power of the motor to the oar. This way, the total movement of the oar can be supported. To be able to support the stroke motion in only one way, a freewheel mechanic solution could be used. Now the recovery can be done without support.

B. From rail to oar

A special bended rail on the riggers is created to direct the oar’s movement controlled by a motor. Again a freewheel can be used to uncouple the support during the recovery.

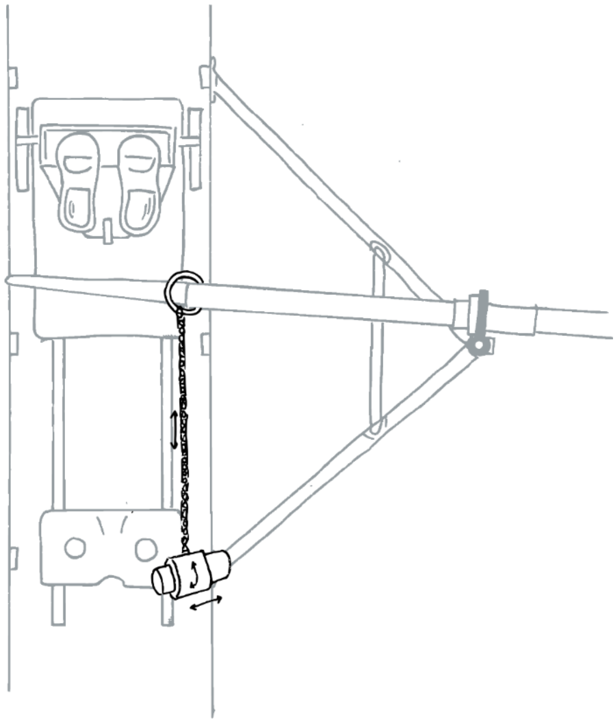
C. Behind boat

Extra power is delivered using a motor driven boat. The motor can be controlled in a way it imitates the strike of the rower.

D. On bench

Concept 1d can be applied the other way around, placing a motor at the chair that moves over a rails in the shell. This way the movement of the bench is being supported.

3. USE OF MOTOR AND CHAIN OR STREP



A. Rotating chain

For this concept two vertical rods are placed on each rigger. On one of the rods, a motor is placed that can move freely up and down along the rod. A chain or strep is spanned around both rods, connected to the motor. When the motor starts to rotate, the chain is being rotated as well. Connecting the chain to the oar, will lead to a support of the oar movement. Again freewheel mechanics can be used to make the support working in one way.

B. Winding mechanism

Instead of placing two rods, only one rod is places on the rigger behind the rower. Now the motor is not rotating the chain but controls a winding mechanism. Once the mechanism winds up the chain, the chain pulls the oar backwards. During the recovery the chain is unrolled again.

4. USE OF EXOSKELETON

A. Full body

The movement of the full body is supported by a robotic exoskeleton.

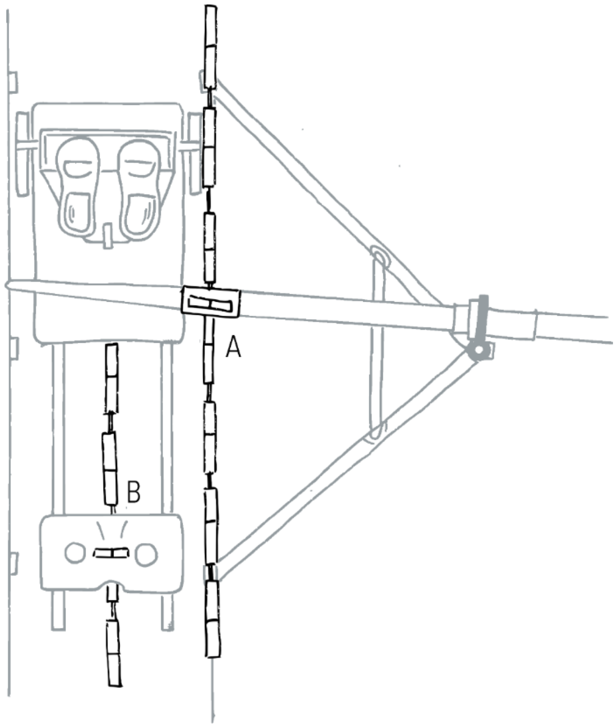
B. Only arms

Only the arms are being supported by an exoskeleton.

C. Only legs

Only the legs are being supported by an exoskeleton.

5. USE OF ELECTROMAGNETIC FIELD



A. Magnets in edge of boat

Electromagnets are places in the edge of the boat and half way the inboard length of the oar. The drive is being supported by magnetic forces pulling or pushing the oar towards the rower.

B. Magnets in rails under bench

Instead of supporting the oar, the bench is supported using the same mechanism as described in 6a. Electromagnets are placed in the bottom of the shell and under the chair. This way the leg extension during the drive is supported.

6. COUPLINGS

A. Between chairs

The two, four or eight chairs are coupled to each other, resulting in support of the chair of the enabled rower by the other rowers. By moving the chair, the movement of the lower body is supported during the whole sequence.

B. Between oars

Instead of the chairs, the oars of all rowers are coupled to each other. This way, the movement of the oar is supported.

7. ADAPTED BLADE*

This concept uses blades with holes in it. This way the blades go more easily trough the water, and therefore less power is needed during the drive. A motor described in 2b can be used to obtain enough speed.

8. USE OF SPRING*

Springs are used to save power during the recovery which can be used in the drive.

A. From riggers to oarlock
B. From oar to actuator
C. From boat to bench

* as addition to other concept

APPENDIX VI EVALUATION OF FIRST OUTPUT CONCEPTS

The concepts from previous section can be rated using three categories:

- Positive: succeed of the concept is guaranteed. This often means that the concept includes a proven technology.
- Interesting: succeed of the concept is achievable, the concept will be considered as potential final design.
- Negative: succeed of the concept is not achievable, it can be seen that important requirements are not fulfilled. The concept will no longer be taken into account as potential final design.

An overview of the requirements that are not being fulfilled by the concept and therefore labeled as negative can be found in appendix table 3. Explanation is given below.

Appendix table 3. Overview of the requirements that are not being fulfilled by the concept.

	1				2				3		4			5	6	7*			8*		
	a	b	c	d	a	b	c	d	a	b	a	b	c	a	b	a	b		a	b	c
GR002	-			x	-		-	x		-				x	x	x		-		-	
PR003	-	x	x		-		-			-						x	x	-		-	
PR004	-				-		-			-								-		-	
PR006	-				-		-			-								-		-	
FR007	-				-		-			-								-	x	-	x
OR001	-				-		-			-						x	x	-		-	
OR002	-				-		-			-								-		-	
OR003	-			x	-		-	x		-								-		-	
OR007	-	x	x		-		-		x	-	x	x	x					-		-	
OR008	-				-		-			-								-		-	
OR009	-				-		-			-								-		-	
OR010	-				-		-			-						x	x	-		-	
CR001	-				-		-		x	-	x	x	x	x	x			-		-	

* as addition to other concept

POSITIVE

Concept 2c is considered positive because the idea of placing a motor behind a boat is already existing.

Concept 7 is already being used in validation. Therefore, this additional concept is considered positive as well.

INTERESTING

Concepts 1a and 2a are very likely to succeed. Rotating the oar by using linear actuators or by a servo motor will result in a supporting force in the horizontal direction.

Concept 3b is likely to succeed as well. It is a more complex design, but due to the motion of the chain up and downward as well, the additional force will be applied in horizontal direction only.

Concepts 8b is an addition on other concepts. Therefore, it could be interesting to investigate the effect of this concepts on the final design.

NEGATIVE

Concepts 1b and 1c are both considered negative by the fact that the technique used will be comparable to the technique of the concepts 1a and 2a but harder to apply. Addition of a connection between the boat and the oar is not favorable. Furthermore, concept 1c will be in the way of the rower's movement. [OR001][PR003]

The technique of using an exoskeleton in concept 4 is very complicated and therefore considered negative. Likewise, existing exoskeletons are very expensive and it is not favorable that the user is in contact with the design. [CR001][OR007]

Concepts 1d, 2d, 5c and 6a are all considered negative because supporting the movement of the bench, will only support the 'leg emphasis' during the drive. This is not favorable because the created power must be transferred trough the trunk, shoulders and arms as well. If those body parts are not capable of transferring this power, the user could end up with injuries. [GR002][OR003]

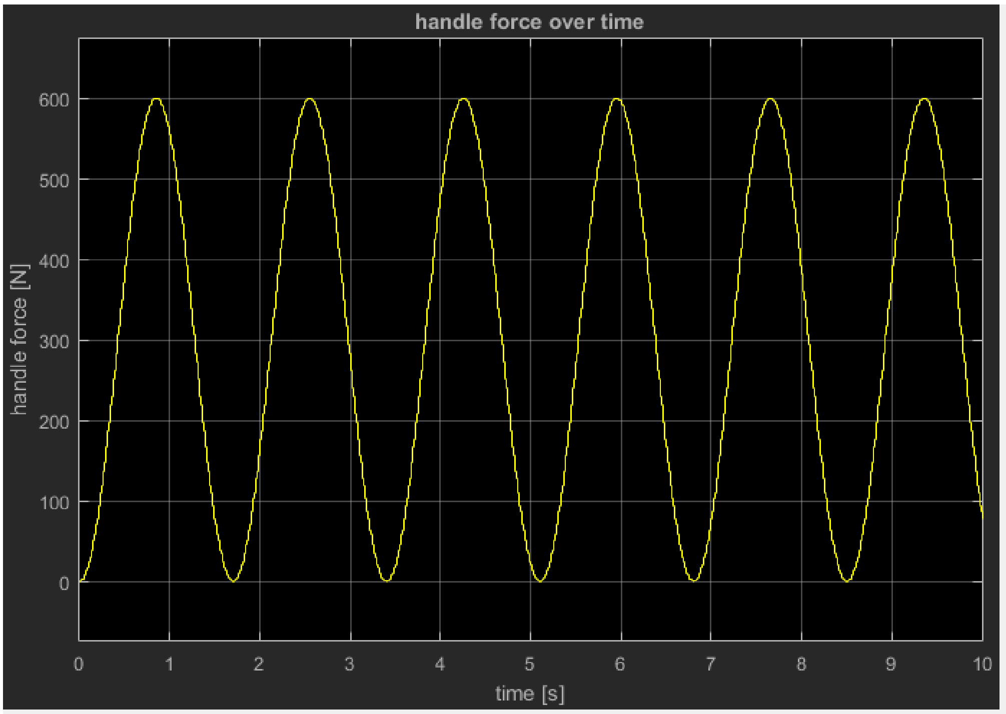
Concept 3a is considered negative because the one side of the rotating chain will be bothering the oar. [PR003]

Concept 5 uses a magnetic field, but this is unlikely to succeed. Very strong magnets should be used to be able to move the oar or bench, with could interfere with other metal parts. This technique will be too expensive as well. [PR003][CR001]

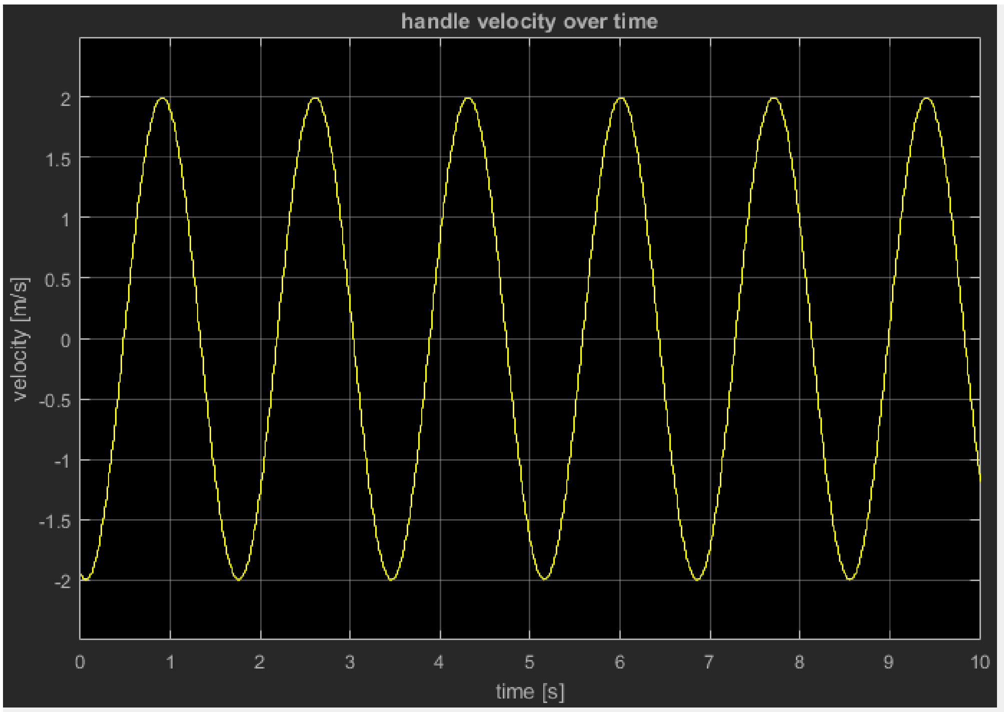
Using a rail will reduce the movability of the oar, the oar can't move up- and downward, in and out the water. Therefore, concept 2b is considered negative. [PR003]

Concept 6 is considered negative because of this will affect the comfortable feel, all rower should move identically. [OR001]

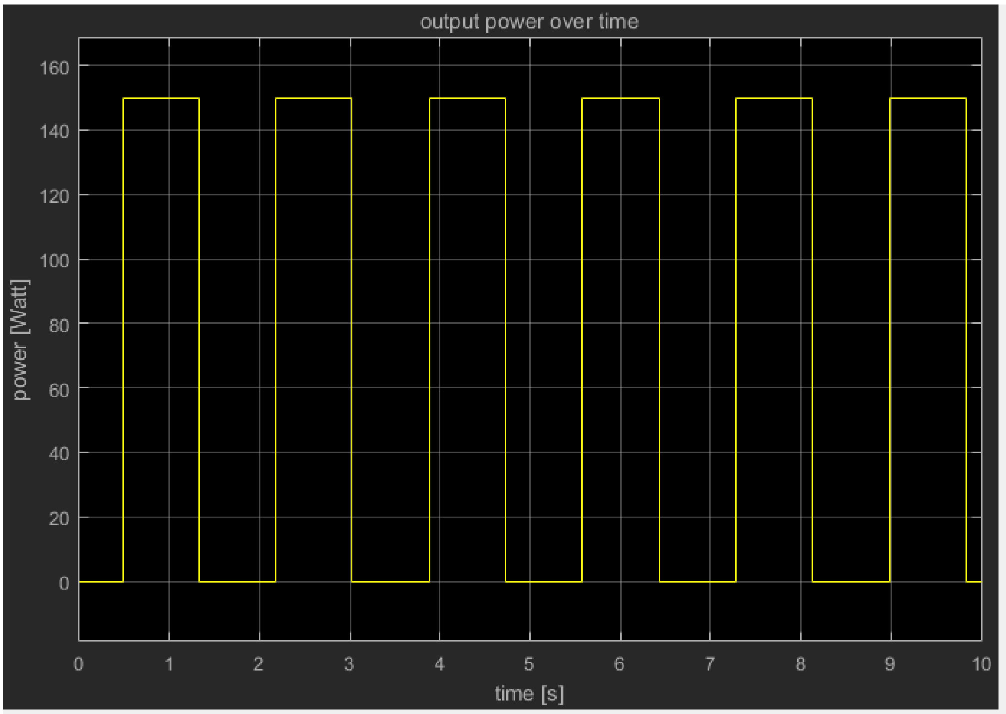
Concepts 8a and 8c are both not usable. This way, no additional power will be delivered. Using this concept, the rower needs to deliver more power during the recovery phase of the stroke, which will be inconvenient. Furthermore, if the rower loses grip on the handle, the oar will jump towards the body, causing dangerous situations. [FR007]



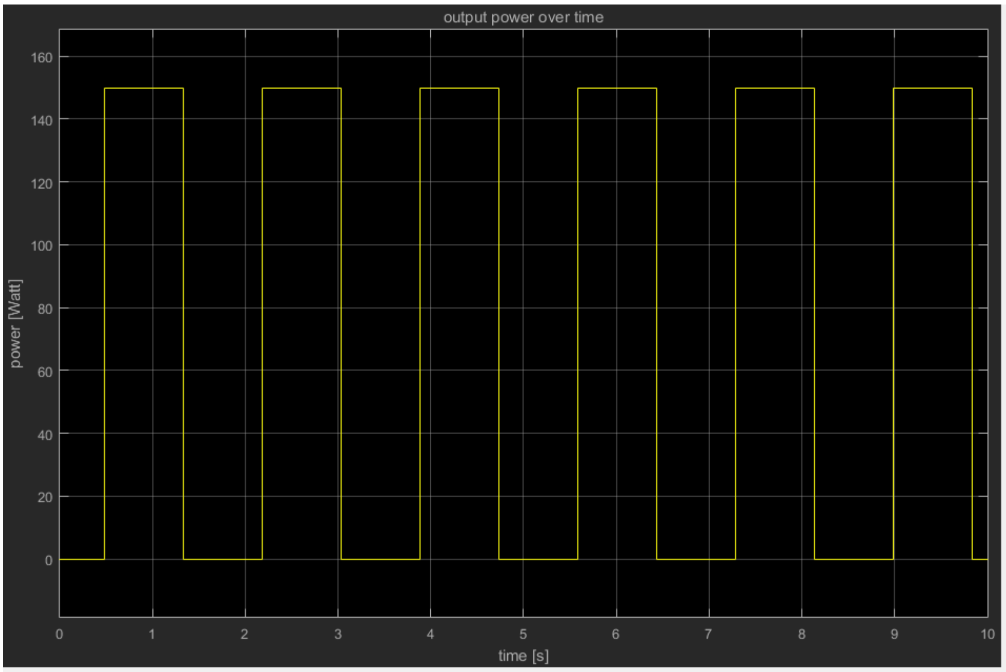
Appendix figure 2. Modeled applied handle force over time.



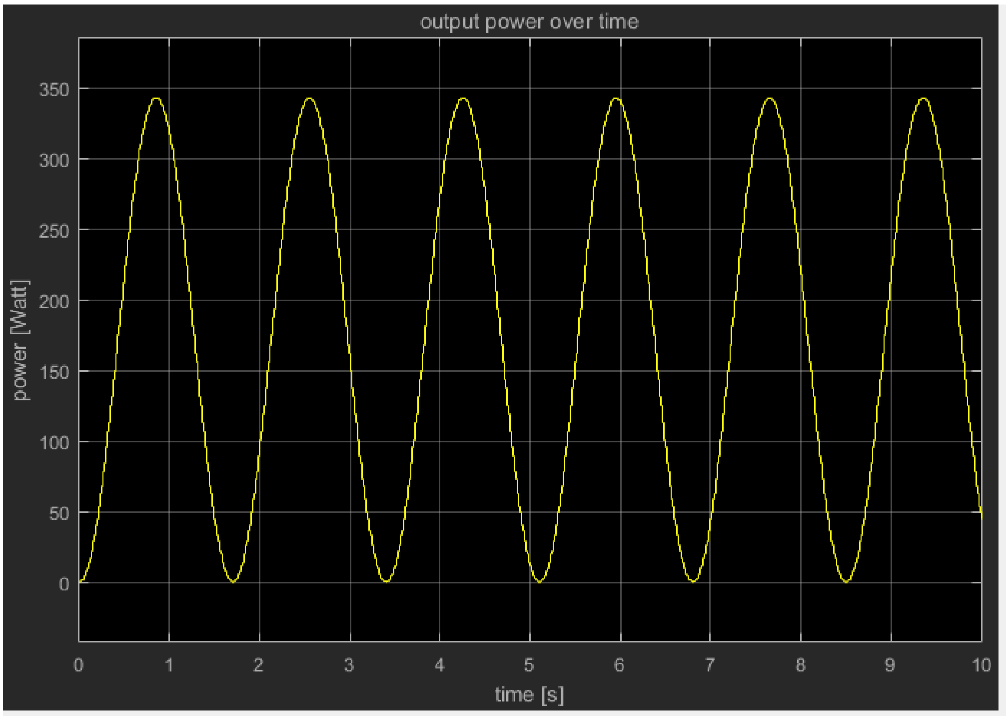
Appendix figure 3. Modeled angular oar velocity over time.



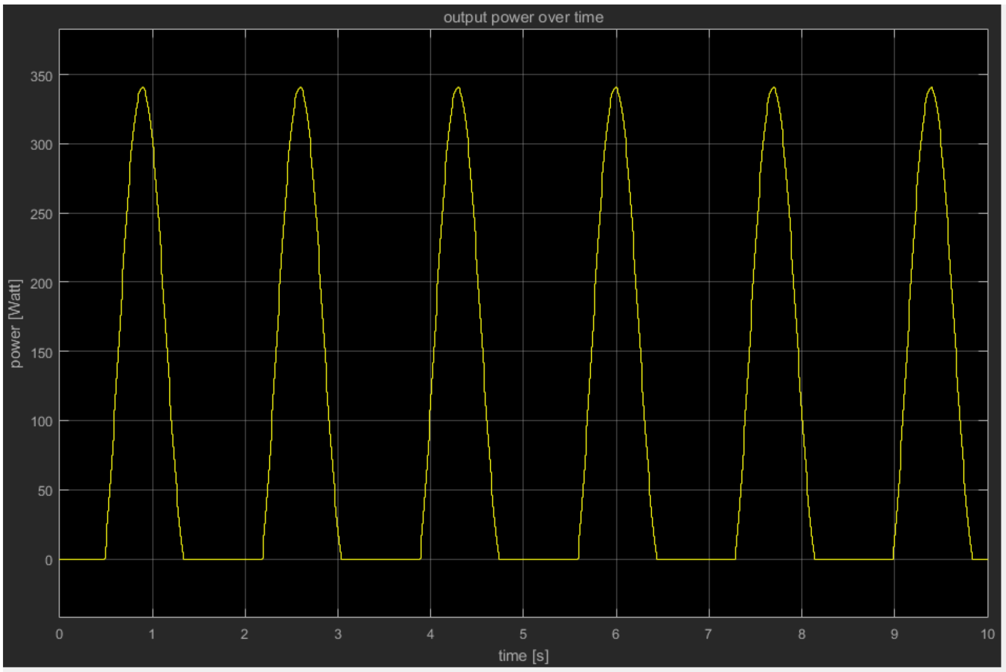
Appendix figure 4. Output signal from the IA system over time.



Appendix figure 5. Output signal from the IAF system over time.

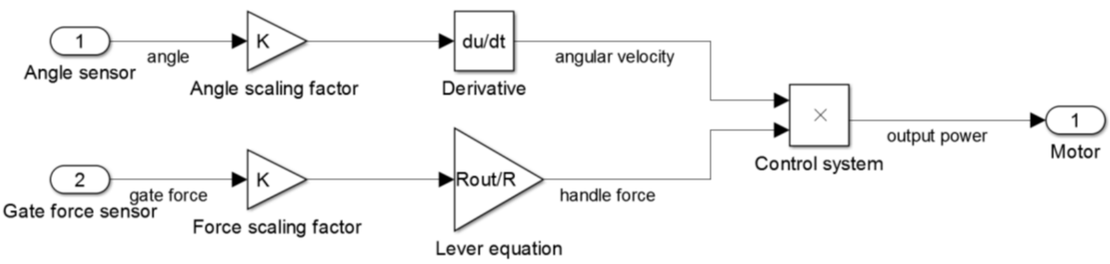


Appendix figure 6. Output signal from the DF system over time.

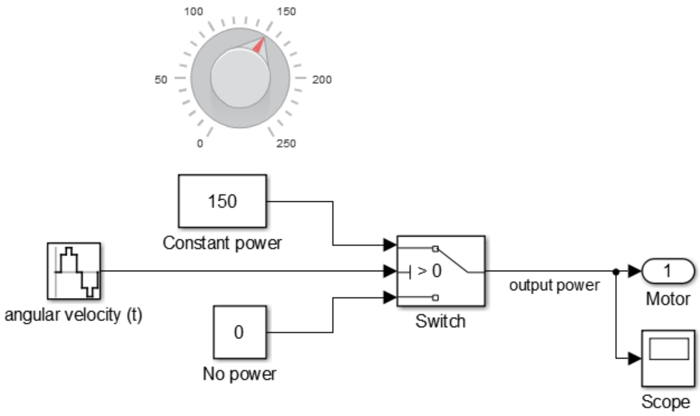


Appendix figure 7. Output signal from the DAF system over time.

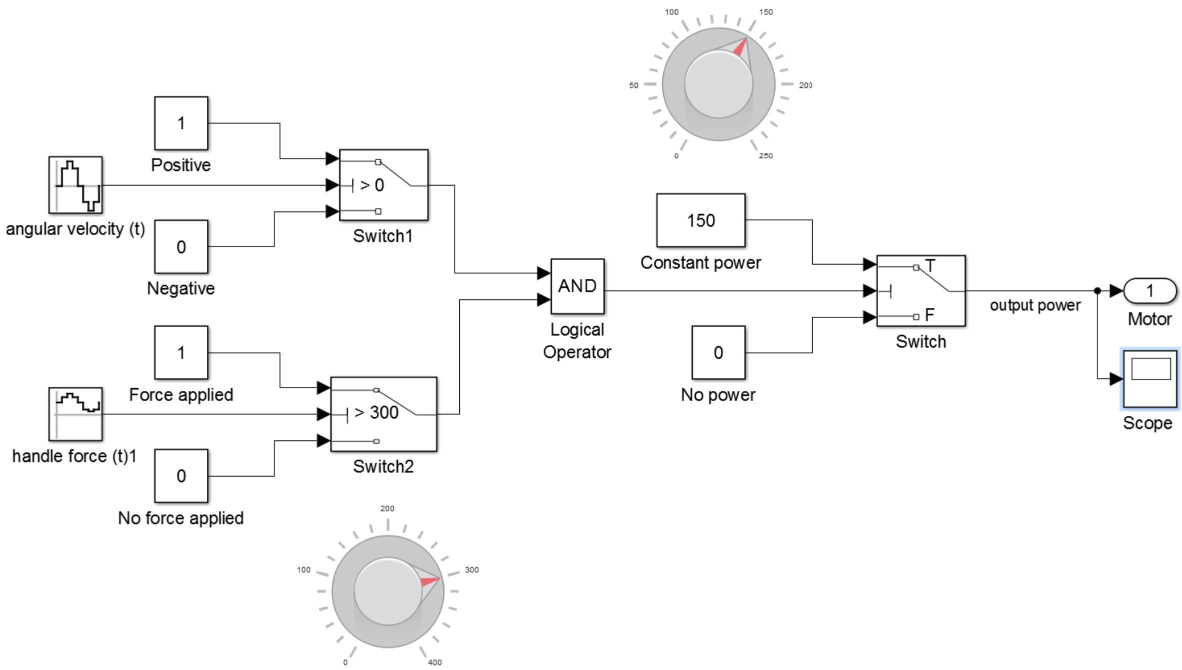
APPENDIX VIII CONTROL SYSTEMS IN SIMULINK



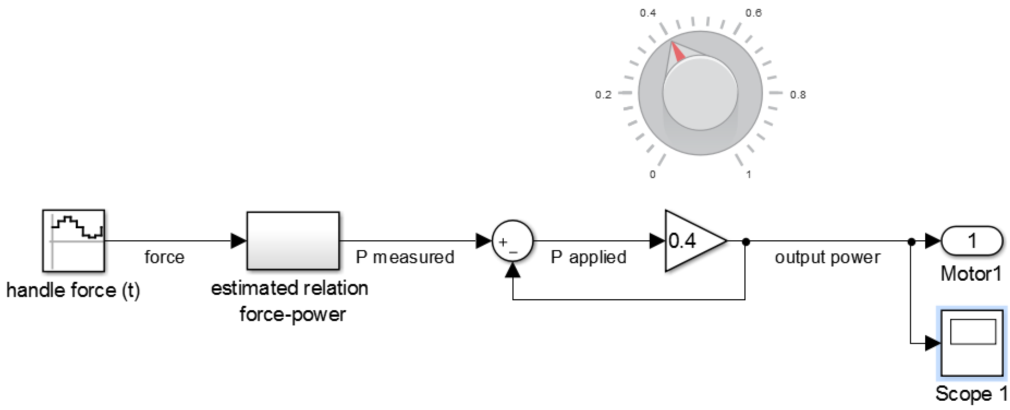
Appendix figure 8. System that converts input signals from the sensors into other usable signals for the further control system.



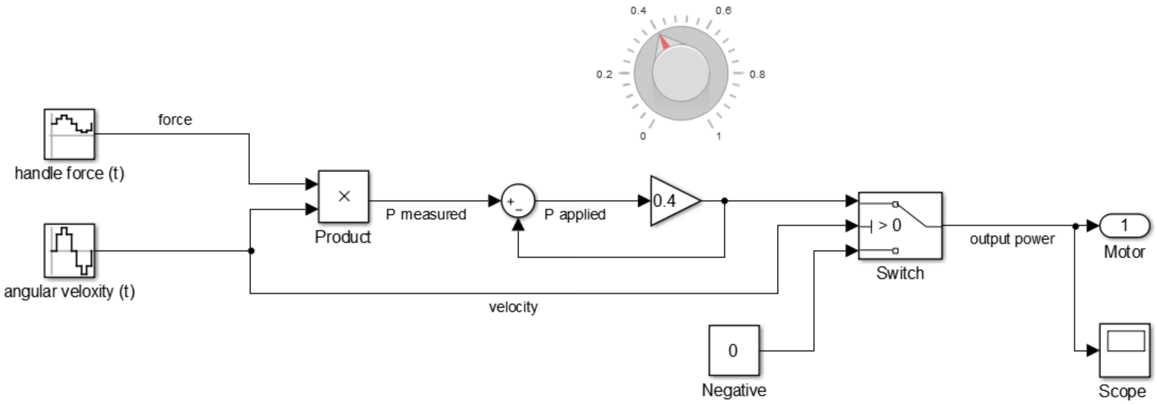
Appendix figure 9. The IA system, comparable to the IF system.



Appendix figure 10. The IAF system.



Appendix figure 11. The DF system, comparable to the DA system.



Appendix figure 12. The DAF system.