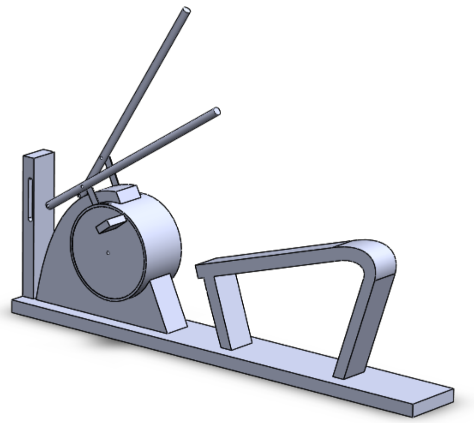
Umaco B.V. & Lode B.V.

# CumbentCruiser

Master Internship Report – A Design Project

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# 2 Introduction

This report is about a new design for the Corival Recumbent from Lode following the design method taught at the masters of Biomedical Engineering. It is at Lode where my internship took place. The Corival Recumbent is a cycling ergometer for older people as well as for people with severe overweight. The internship took about 10,5 weeks but was extended in free time for several more weeks. The Corival Recumbent was to be redesigned and if possible the Recumbent had to be combined with the Cruiser, an ergometer used by people with a lower limb amputation. The primary focus was on this second part. We managed to make a prototype sketch which would allow people with a lower limb amputation to perform on the current Corival Recumbent. In the free time a prototype was made.

The report became quite extensive. We start with an introduction to the Corival Recumbent and the Cruiser in order to make the reader familiar with both products. We then continue with the design methodic, analysis of the problem and the determination of the goals and requirements.
Then, in order to make concepts based on reliable sources, a literature research was performed. We looked for ergometers currently found in literature. These ergometers were then rated based on criteria.
The ergometers that came out as the best were used for making concepts of the new Recumbent. These concepts were again rated via criteria. The best concept were chosen and discussed at Lode.

Then a little research took place of which we could conclude what the prototype had to look like. At this point the 10,5 weeks had passed.
After this my internship at Lode could continue in an attempt to learn more about the production process and in order to make a prototype. Since the making of the prototype was more of an extra it is discussed in less detail but certainly used for future recommendations.

# 3 Analysis Phase

## 3.1 Introduction

A design process is complicated due to the many choices one has to make during the project. It is very important to make the correct decisions at the start of a design project because if they are chosen wrong, drastic changes would have to take place later on. The project you are reading about was a combination of two initiatives which could both influence the direction of the project a lot. The two ideas, the first coming from Lode and the second from Umaco are:

- Designing a new version of the Corival Recumbent ergometer. The Corival Recumbent is currently in production by Lode;
- An attempt to produce an arm-leg ergometer based on the Cruiser, of which only a few were produced. Its potential is now rising due to an increase in the amount of lower limb amputated people.

Both need to be explained further in order to give an explanation of both products and how they affect the project. The first initiative stood on its own but the plan came up to combine it with the second idea, the Cruiser, which could change the design of the new Recumbent a lot.
The Recumbent is a leg ergometer, the Cruiser a combined arm and leg ergometer. Both devices require a very different motion from the user. A combination of both would require a design with either both motions integrated or an entirely different motion which fulfills the goals of both motions. The Recumbent is already being produced by Lode and thus its purpose is already known. The Cruiser though was produced years ago by another producer, so its purpose is not as well known. Research is being performed on it at the Beatrixoord, which is a rehabilitation center.

Before starting with the real analysis phase the Recumbent and Cruiser are explained a little further in detail. The research performed on the Cruiser by the Beatrixoord will also be mentioned.

## 3.2 Corival Recumbent

Lode produces many types of ergometers and in the field of cardio pulmonary rehabilitation it produces the Corival, from which the Corival Recumbent originated. The specifications of both products are therefore very much alike. The Corival is an ergometer which mimics cycling and the position is very much the same as in cycling, see Figure 1 for an image.

Figure 1: The Corival from Lode.

The Corival Recumbent targets a different group of people, namely those who cannot use the Corival itself. This due to having a very high weight or just being old, making these people too big or too weak to perform on the regular Corival. Older people will not have the strength or flexibility to sit in the cycling position for long periods of time.
Therefore, the Corival Recumbent allows the user to cycle in a more comfortable and safe position, as shown in **Fout! Verwijzingsbron niet gevonden.**. The user can sit in a chair which is in a wide leaning back position. Besides the chair the frame is also much stronger than that of the regular Corival. Whereas the maximum user weight for the regular Corival is 160 kg, the Corival Recumbent allows users up to 250 kg.

The basis of both devices is of course the ergometer, which is also the basis of many other devices from Lode. It also revered to as the Angio, a device which only contains the ergometric unit. The Angio can be integrated in many other setups, thereby changing the position of the user but still performing a cycling motion with either hands or feet.

Figure 2: The Corival Recumbent from Lode.

### 3.2.1 Corival Recumbent Complaints

Complaints of users are mainly determining the design requirements for the Recumbent. Currently, most complains of the users and producers are related to the chair:

- The height of the chair can be adjusted by a handle on both sides below the chair. Users sometimes confuse them with the handgrips (white) above these handles, causing them to hold on to the handles during exercise, causing the chair to fall downwards.

- Users of the Recumbent are mainly having overweight. They adjust the height of the chair using leg power, pushing themselves upwards or letting themselves slowly slide downwards. Users pushing themselves up is a heavy task due to their height weight or low strength (elderly). It is also heavy for an assistant to help with this task.

- The mechanism allowing to change the chairs position sometimes gets stuck or does not go smooth enough. The mechanism is explained in Figure 3. The user pulls up the handles, as shown by the blue arrow. Consequently, the parts indicated by the red arrows move in the direction of the arrows. Two plates are attached to the pipe in the middle, in the position as shown no movement along the pipe is possible, they are being held in this position by a spring. When the handle is pulled, the lower plate moves straight, allowing movement along the pipe. When released, the spring puts the plate back in the stuck position. This allows the chair to be placed in every position along the pipe, not at fixed positions.

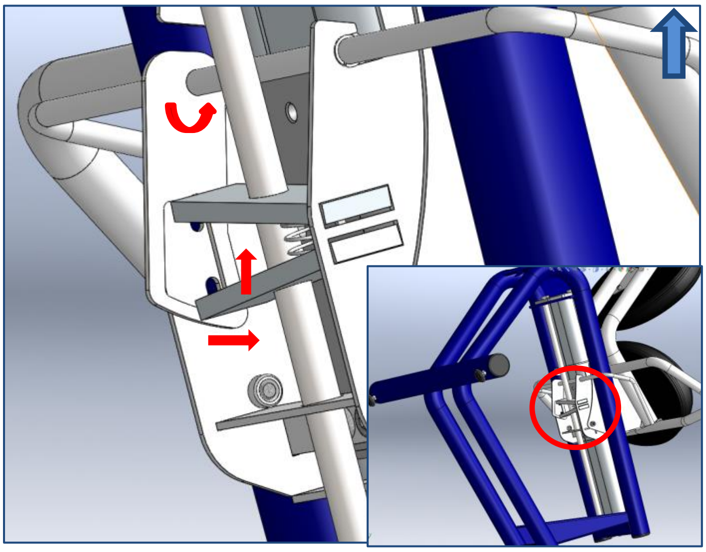


Figure 3: This is the mechanism below the chair that allows the chair to be moved along the pipe. The blue arrow indicates the handle being pulled up by the user, the red arrows indicate the movement of the consequent parts. Picture is from a SolidWorks model.

- Sometimes the patients sizes are still too great to perform well on the Recumbent. Their belly is still in their way. Allowing the chair to recline would solve this problem.

- The height of the handgrips are fixed. Some patients are still too big to reach them well, or their arms are too small.

## 3.3 Cruiser

The Cruiser was produced around 2008 by Enraf-Nonius. Enraf-Nonius produces more products in the field of rehabilitation and medical fitness. The Cruiser did not have enough potential at that time and therefore the production was canceled. Usage of the Cruiser cannot easily be tracked back. Where we still find use of this device though is at the revalidation center Beatrixoord in Haren. They are very content with it.

The Cruiser allows the user to make a continuous rowing like movement. The bars on the side can be pushed back and forth, moving the chair forth and back respectively. This is done using the arms. With the legs the user can also push himself backwards. Thus, it is possible to (partially) take over the work of the legs with the arms. The Cruiser is also called a combined arm-leg ergometer and it allows people with a lower limb amputation to exercise on it.
The mechanism is coupled and once in motion it cannot stop immediately, it has to slow down. Also, the chair moves horizontally as well as vertically. The movement could be described as wobbling, which could induce some motion sickness when the Cruiser is used at higher speeds.

**Figure 4: The Cruiser from Enraf-Nonius. Arrows indicate motion of the handlebars and the corresponding chair movement.**

### 3.3.1 Research

Research on the Cruiser was published first in 2005 by Vestering (Vestering M.M.). They found a higher maximal oxygen uptake with the Cruiser than with an arm only ergometer in 5 LLA patients. With the Cruiser more muscles mass is used than with an arm only ergometer, eliciting a higher maximum oxygen uptake (VO2-peak).
In 2009 the Cruiser was compared with a bicycle ergometer on thirty health volunteers by Simmelink (W. B. Simmelink E.K.). The Cruiser appeared to provide valid and repeatable measurements of physical fitness. The bicycle ergometer appeared more energy efficient, but LLA patients cannot perform on a bicycle ergometer.
Lastly, in 2014 Simmelink published another article on the Cruiser where they calculated the gross mechanical efficiency and cardiorespiratory strain, which appeared to be comparable with cycling. Also no learning effects were observed on the Cruiser, which could be expected for a device with such a specific movement.
The gross mechanical efficiency was calculated from the VO2 and the measured mechanical output. A critical note: in cycling the mechanical output (in power) is more 1:1 related to the physical output delivered by the user than with a Cruiser, where the whole body is decelerated and accelerated every time. Therefore the gross mechanical efficiency is most likely underestimated on the Cruiser.

### 3.3.2 Crucial Specification of the Cruiser

For this project a meeting was arranged with Liesbeth Simmelink. The big question at the start of this project was: Why did they choose the Cruiser? What is the specific motion the user of the Cruiser performs and does it have to be that exact motion or will other motions achieve the same goal? If other motions are allowed there is more design freedom for the new Recumbent.
It appeared the Cruiser was more or less stumbled onto. It is indeed very useful for LLA patients because arm and leg motion are connected and the arms can compensate for the loss of work caused by the loss of the limb. Besides, a significant muscle mass is used when performing on the Cruiser, which causes a significant use of the cardiorespiratory circuit. The overall goal is that the LLA patients will regain or improve their physical fitness, just as is the case for the overweight people and the Corival Recumbent. The exact muscle mass required thought is not defined.

A device with a different movement, as long as they meet the two specifications mentioned above, is allowed and could have more potential.

### 3.3.3 Cruiser Complaints

Some complaints already mentioned about the Cruiser are that the chair is coupled to the moving mechanism and that the user cannot stop immediately, a wobbling motion of the chair which can cause motion sickness and that the power delivered by the user can not be calculated accurately from the power measured by the device.
Beside these we found a bad resistance adjustment of the Cruiser when performing on it, resistance was not increased smoothly. The accuracy of the measurements can therefore be doubted. Lastly, the Cruiser is not compatible with ECG measurements because of the heavy arm and torso movements. But since it is required that the arms are used it is difficult to accomplish an ECG compatible device.

## 3.4 Problem Definition

The general w-questions will be answered separately for both the people using the Recumbent and the Cruiser.

### 3.4.1 Who has a problem and what is the initial cause?

#### 3.4.1.1 *Obese people and Elderly*

For the Corival Recumbent the target population consists of heavily overweight people and elderly. Why are they having overweight? In general overweight is caused by a too high food intake combined with not enough exercise. For the elderly, aging is a general fact of life.

#### 3.4.1.2 *Lower limb amputated*

For the Cruiser the target population consists of people with a lower limb amputation (LLA). The loss of a lower limb may be caused by accidents (trauma), cancer or vascular diseases.

### 3.4.2 What are further problems ?

#### 3.4.2.1 *Obese people and Elderly*

The problems of the people with people consist of a general bad health, a low mobility and requiring a lot of space. Where and when? Having a bad health is a problem in general. Having a low mobility and requiring a lot of space are always a problem but mainly in public. The people with this problem will be slow in transporting (walking, climbing stairs) themselves, upholding other people in public, and they will require more space when in a row of seats in vehicles or buildings. People with overweight will draw attention in general, but especially during the situations mentioned.

For older people the problem of transporting themselves is the same, without the attention drawing because people will understand. Requiring more space around them is not a problem.

#### 3.4.2.2 *Lower limb amputated*

The problems of people with a lower limb amputation is having a low mobility as well. This problem is solved by the use of a prosthesis but this will not make them as mobile as normal people. They will draw attention if the prosthesis is visible or if their walking pattern is very different from normal walking. They will, just like people with overweight and the elderly, be slow in transporting themselves and draw even more attention at such moments.

#### 3.4.2.3 *Lacking Strength*

We mainly see a low mobility as the problem caused by overweight, being old or having a LLA. In general the flexibility and movement possibilities these people have with their legs are low. The biggest problem though is the force required to move, this force required is increased for people with overweight and LLA. People with overweight need to move more mass and people with a prosthesis have an inefficient walking gait.
In the case of elderly they are not able to deliver sufficient force to move. Their overall strength is reduced. This may also be the cause for people with LLA. Before and after amputation a long period of resting is required, reducing their strength during this period.
Thus, walking is a heavy task for people with overweight, LLA or a high age. As a result they become exhausted and cannot walk for long periods of time. The exhaustion occurs in the muscles and or cardiorespiratory circuit (condition).

#### 3.4.2.4 *Lacking Cardiorespiratory fitness*
As explained the target population lacks strength which limits them to be mobile for longer periods of time. Increasing strength will allow them to be more mobile but not necessarily for longer periods of time. For that they need to improve their condition, or cardiorespiratory fitness.

### 3.4.3 How come the problem remains?
What exists is a vicious circle for our target population. As mentioned, the target population lacks strength and cardiorespiratory fitness. This reduces their mobility, reducing these two factors even more.
What normal people can or would do is performing exercises to improve their strength of cardiorespiratory fitness. But our target population cannot easily break through this vicious circle. This is because our target population cannot perform exercise on regular fitness devices. People with overweight do not fit on regular devices, older people require a more comfortable or saver position to exercise and people with LLA lack a limb to do exercise. Some of these patients even have such bad health issues that exercise would be too risky and need to perform exercise in a medical situation with supervision. This last fact causes some of our target population to require a device with medical standards.

In section 3.4.5.1 the problems are put in a cause-effect diagram for an overview.

### 3.4.4 Stakeholders

There are many other parties involved with the problem described having related problems. Below a stakeholders diagram is shown showing these parties and their related problems as well as their expectations of a product solving this problem.

| *Stakeholder* | Characteristics | Expectations | Potentials and deficiencies | Implications and conclusions for the project |
|---|---|---|---|---|
| **Patient** | Very high weight; lower limb amputated; elderly. People lacking strength and/or cardiorespiratory fitness. | Improvement of cardiorespiratory fitness, and thereby a better mobility. Performable exercise apparatus (position). | Patients determine the usability of the product: can complain about usability of product. Complains determine demands. | Wide range of patient conditions leads to very diverse product and its function(s). |
| **Surgeon** | Wants to help as many type of patients as possible, wants to do this as good as possible. | Easy explanation of the device. Easy adjustable device for all type of patients. Accurate device. | Can register the improvements. Can provide information such as complaints or goals. | Product must be innovative but in line with standard devices currently used. |
| **Society** | Increasing population becomes obese, old and amputations occur more often. Other people notice the bad mobility in general or in public. | Better mobility of patient in public, noticing them less. | Via the patient the society is a way to make name in public for the product. Society might also recommend other products to patient. | Name making important here. |
| **Insurance** | Wants product to provide optimal care at low costs. | Lower costs of treatment or device, only more expensive if proven necessary. | Only interested when cost-effective, low complications and reliable. | Essential for sale amounts. |
| **Industry** | Interested in innovative products at low development costs. Needs to keep up with the market, delivering a new product. Needs to update products to solve complaints. | Unique product in the field. Money. In line with other products of the company. | Commercialising the product, but only when simple. | Knowledge of the feasibility of the product. Must approve design. Determines direction of the design. |
| **Work** | An employee that has regular health related issues. Cannot perform all regular tasks. Lower work rate/less working hours. | Reduced frequency of issues. Higher work rate/ more working hours. | | Profits a lot if patients physical fitness improves. |

**Table 1: Stakeholders diagram of other parties having problems related to the problems of obese, old or lower limb amputated people.**

### 3.4.5 Cause-effect diagrams

#### 3.4.5.1 *The problem cause-effect diagram:*

Below a diagram of all problems related to obese, old or lower limb amputated people is shown. These problems were already described in section 3.4.1 to 3.4.3. The problems of the stakeholders are not included since the diagram is already quite extensive. The problems led to the production of the Cruiser and Corival Recumbent, so these are included to show where they come in place. The colors indicate their target population for the corresponding device.

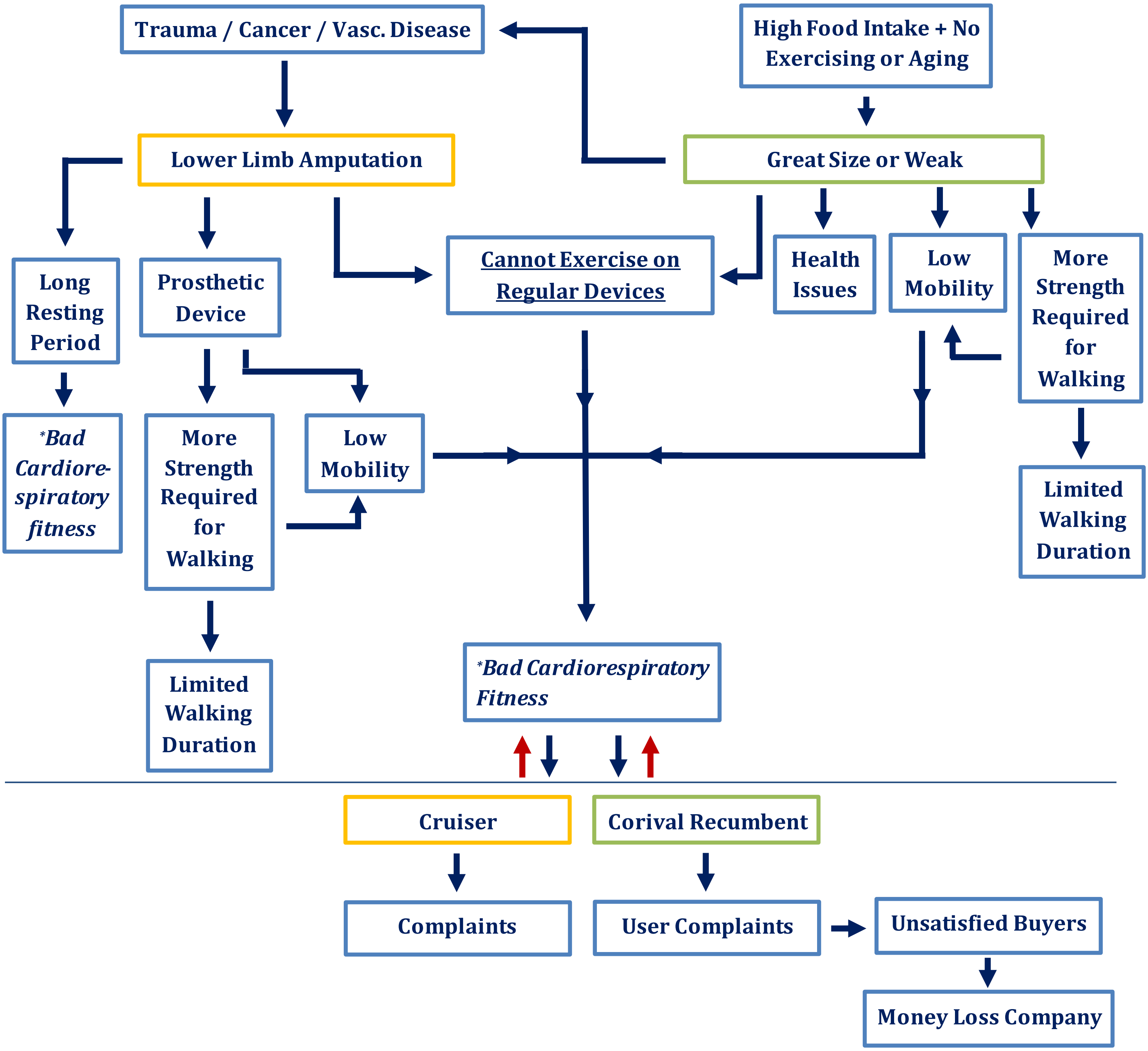



Figure 5: Cause-effect diagram of the problems related to obese, old or lower limb amputated people.

### 3.4.5.2 *The goal cause-effect diagram*

Below the problem cause-effect diagram is shown again but with red arrows indicating the changes the to be designed product needs to realize. The red arrows mean that the box they apply to will change meaning to the opposite, meaning:
- Low Mobility → Good Mobility
- Limited Walking Duration → Sufficient Walking Duration
- Health Issues → Less Health Issues
- Great Size → Decreased Size

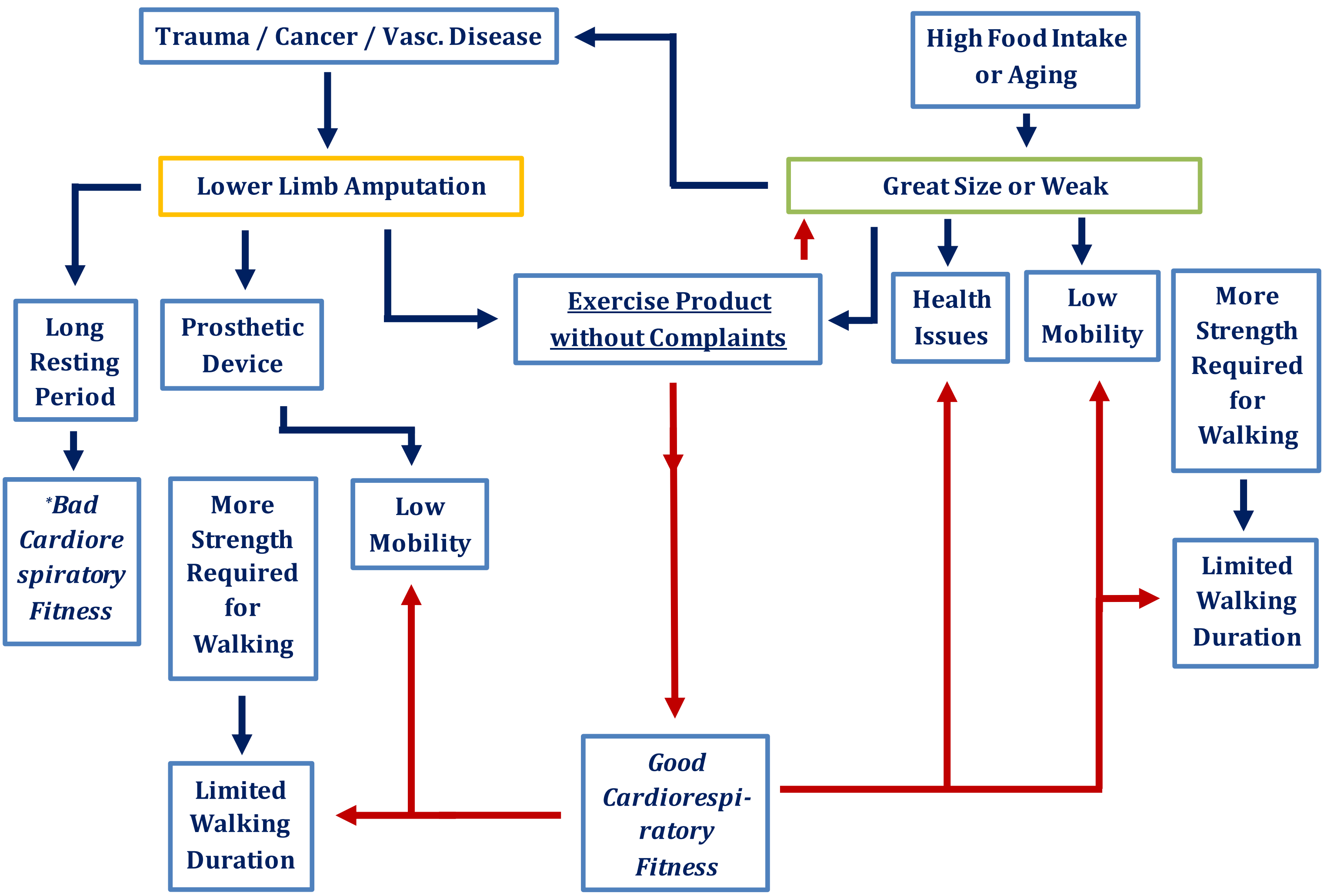



Figure 6: Cause-effect diagram of the goals related to obese, old or lower limb amputated people.

## 3.5 Goal

The goal of the product is to improve the cardiorespiratory fitness of people with overweight, with a high age and with a lower limb amputation.
This will in the long term help them to achieve more fundamental goals, for the people with overweight and elderly:

- Increase the duration they can be mobile
- Lose weight
- Reduce health issues

For the people with a lower limb amputation:

- Increase duration of being mobile

And for the company:

- More sales

Increased strength of the patients is not a main goal but may be accomplished.

## 3.6 Design Assignment

The strategy is to design a device that people with overweight, a high age or a lower limb amputation can use which activates and improves their cardiorespiratory system.

Currently there is the Recumbent for people with overweight and elderly and the Cruiser for LLA-patients. Both devices will be combined into one device that will achieve both goals of both target groups.
When dividing the apparatus into sub goals or parts we remain with the chair, a motion for the legs and a motion for the arms.

**Chair**
For the chair the complaints about the current chair of the Recumbent will be used as guidelines. These guidelines will determine the shape, specifications and adjustment mechanism of the chair. Complaints are already known but confirmation of them and additional complaints can be gathered by questioning users of the Recumbent or questioning specialists supervising these users.

**Arm and leg motion**
For the movements of the arms and legs literature will be used to distinguish the best motions which will achieve the goal ‘improving the users physical fitness’. Also the opinion of specialists will be taken into account.
The feasibility of the mechanical constructions accomplishing these motions will be determined using the company’s experience as well as the requirements. The most feasible motion and corresponding mechanism will be chosen.

## 3.7 List of Requirements

### 3.7.1 User Requirements

- The product can be used by people with heavy overweight, up to a weight of 250 kg
- The product can be used by elderly
- The product can be used by people with a lower limb amputation
- The product must require the user to use a significant muscle mass, such that his cardiorespiratory system will improve
- The user must be able to use his legs, arms or both
- The product must sit comfortably

### 3.7.2 Ergonomic Requirements

- Shape of Lode product
- Movement of hands and legs must be coupled
- Adjustment to correct position of parts must be performed by user self

#### 3.7.2.1 *Chair*

- User must be able to remain on the chair while adjusting the height
- Must require the user less force to change the chairs height than with the current version
- The adjustments of the chair must always go smooth
- **The back of the chair must be able to recline (lean-back) or the whole chair so that there is space for the belly**
- Must be easily reachable
- **Must be wide enough for users up to 250 kg**
- Must be comfortable for users up to 250 kg
- **Must be practical for normal used and users up to 250 kg (be universal)**
- User should feel stable on the chair while performing exercise
- *Detachable for transportation*
- Stump holder

#### 3.7.2.2 *Handlebars*

- May not be confused with handgrips
- Must be easily reachable

#### 3.7.2.3 *Handgrips*

- May not be confused with handlebars
- May not stick out
- Must be easily reachable

#### 3.7.2.4 *Frame*

- Must hold 250 kg within safety limits
- Must have a robust, descent and safe look
- *Front bars must be detachable for transportation*

### 3.7.3 Space Requirements

- Small enough for easy transportation (detachable parts)

### 3.7.4 Wishes

- The mechanism may not force the user to keep moving when he wants to stop. He must be able to stop immediately.
- Fluent chair adjustment

### 3.7.5 Remarks

- Different chair allowed?
- Handlebars below chair but in front, serious modesty problem?

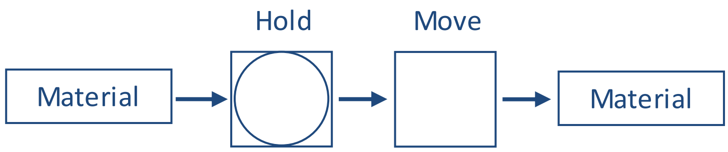
## 3.8 Function Analyses

### 3.8.1 Main Goal

*Improved Cardiorespiratory Fitness.*

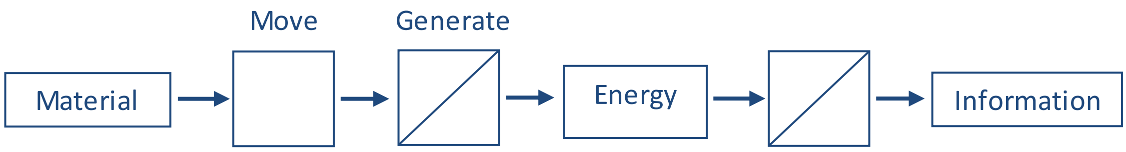
### 3.8.2 Chair

(Hold body and move it to desired position)




### 3.8.3 Angio

(Move arms or legs to generate energy and convert energy to information on display)



# 4 Synthesis Phase I

## 4.1 Introduction

What started as a normal synthesis phase starting with the morphological map extended into an in depth analysis of different ergometer motions. The freedom of motions that the user can perform on the to be designed product was limited to ergometers already used in literature, the mechanical designs accomplishing these motions could still vary.
It was chosen to design the mechanism of the arm and leg motion apart from the chair. Thus the chair design may not be affected (too much) by this design of the arm and leg mechanism. Since the focus was placed on this combined arm and leg motion this was worked out into pre-concepts whereas the chair was only analyzed on complaints and not worked out into pre-concepts. Still the information gathered about the chair can be used in a follow up project.

First in chapter 5.2 the chair will be briefly discussed. An interview was taken about the Corival Recumbent and its implications for the chair design will be discussed in this chapter.
Then different types of arm, leg and arm/leg ergometers found in literature will be discussed and how some of these could be applied to the Corival Recumbent in section 5.3. In this chapter the best ergometer motions will be selected.
In chapter 5.4 several pre-concepts will be shown which are based on the best ergometer motions selected in chapter 5.3. The concepts will be briefly explained.
In chapter 5.5 the best pre-concepts will be selected.

## 4.2 Chair

The chair of our product can have many shapes

### 4.2.1 Cushion (Base, Backrest, Size & Position)

**Base**

The minimum a person can sit on is a chair without a backrest. It could have different shapes such as a square, circle, rectangle (see Figure 7) , triangle, a combination such as a rectangle with a triangular front part or many other shapes and combinations. Also certain shapes could be cut out the legs can fall through as shown in Figure 7b. These gaps could also be cut smoothly as shown in Figure 7c.

Figure 7a – 7c: Different sketches of the sitting part of a chair.

**Backrest**

A chair with a backrest makes more sense and gives support to the back of a person, which is of importance for our group of users. The chair in the middle of Figure 8 looks similar to the chair currently used for the recumbent, with a separate cushion for the lower back and the shoulders. When analyzing chairs for people with overweight, this separate back and shoulder support is not found. Only one solid part seems sufficient, the shape is usually rectangular. Fitness chairs also tend to use the rectangular/triangular shape as shown in Figure 8c.

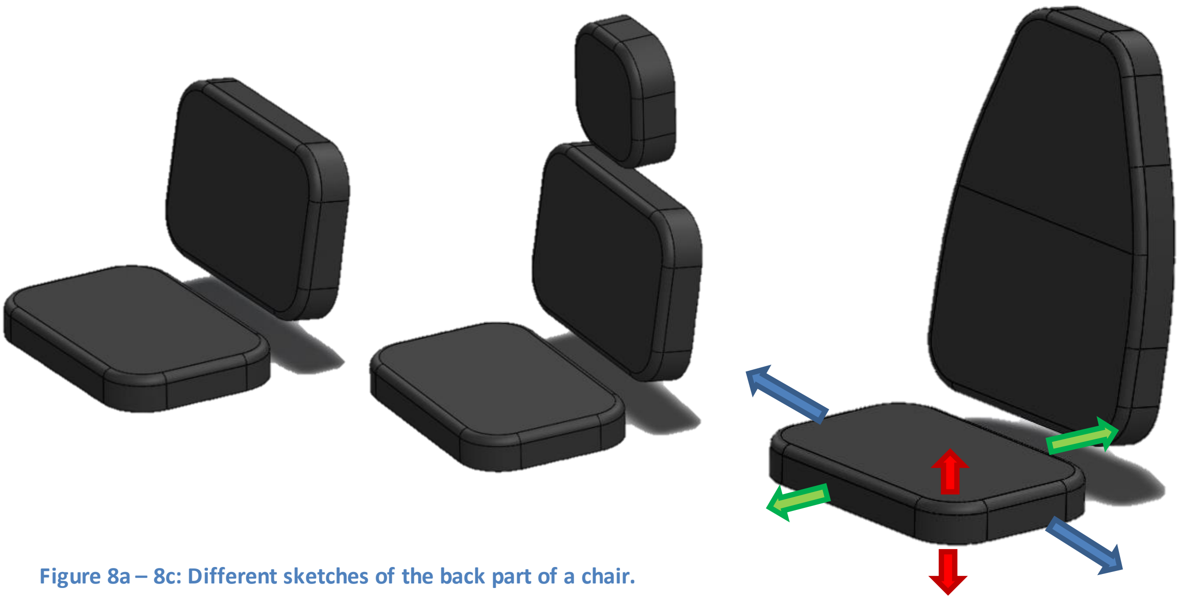


Figure 8a – 8c: Different sketches of the back part of a chair.

**Size**

The size of the base and backrest of the chair may be of varies sizes. The size should be appropriate for all the type of users. Size can vary in length, width and height as shown for the base in Figure 8c by the green, blue and red arrow respectively. Too wide mainly causes problems for the hands to reach handles besides the chair, too long would block the legs from moving down and reach apparatus there and too high would also prevent the user from reach parts below the chair.

**Position**

Cushion parts could be fixed or variable, in the last case allowing to adjustment to a person's size and making the chair more universal but making production more complicated.

**Reclinable**

In order to make the chair universal for normal people as well as for people with heavy overweight, the backrest should be able to recline. This is most likely possible with any of the cushion shapes. One could also chose for the whole chair to be able to recline, with the cushions in a fixed position.

**Handgrip**

Handgrips allow for grip during exercise, in many cases users like to hold themselves tight while performing exercise. Also handgrips allow for assistance during moving in or out the chair. Currently there are complaints of users not being able to reach these handgrips.
When in a fixed position the height of the handgrips is of most importance. When too low some patients cannot reach it, when too high some patients will have the arms in an uncomfortable position. In these two cases persons not being able to reach the grips at all is the worst.
Allowing grips to be variable in height would solve both problems. Handgrips variable in the other directions is of less importance.

Lastly, also already mentioned in the previous section, the whole chair could be reclinable. When reclined backwards the user gets into a more hanging position where gravity holds him in place. This makes the use of handgrips less important.
The position of the handgrips could be anywhere, especially when primarily used for moving in or out of the chair. Placement should not be in the way of other bars such as the handlebars currently.

### 4.2.2 Customer interview

Around two third of the project a meeting took place with Mieke Grijzenhout at the hearth revalidation center at the Sint Franciscus hospital in Rotterdam. She did a small opinion poll with seven patients and with three assistants who help and analyze the patients that come by.

The seven patients varied in age from 56 to 76 years, in weight from 44 to 92 kilo and in length from 1.53 to 1.89 meters. Health issues were hearth or pulmonary related. Also one patient had a stent replacement and one had pain in his lower back.

Overall the patients that come by are elderly and have hearth related problems. They perform around three small interval trainings per week for a period of seven weeks and their cardiorespiratory fitness as well as strength does significantly improve. They can chose themselves whether they keep training on the Corival Recumbent or the normal Corival after some sessions.

A downside is that they use the older Corival Recumbent causing some complaints to be irrelevant. For the interview the significant differences are the handgrips at the front and at the side. Still useful data was obtained and will now be briefly discussed.

Figure 9: The older version of the Corival Recumbent from Lode.

#### 4.2.2.1 *Complaints and suggestions*

**Instep (height)**

Only small patients had trouble getting in the chair, with a length of around 1.45 to 1.55 meters. This is a minority of the patients, others experience no problems with the instep.

Shortening the distance from chair to pedals would solve the problem but also decrease the instep space.

**Stability**

Stability is not a severe problem, only for people with short legs. Some complaints about this point are more related to the handgrips which will be discussed later.

A way to increase stability is to make the seat tilt backwards so that the user falls tightly in the chair. Instep into the chair would be slightly harder unless tilting is optional and can be done after positioning onto the chair. Still the stability problem appears minor.

**Cushion**

Only for people with severely low weight find the cushions too hard.

This problem also appears minor but making the cushions softer would not have severe downsides for other users.

**Chair height adjustment**

The patients appear to experience the adjustment of the chairs position a lot different than the assistants do, the patients hardly complain about it. One might think it is most important what the patients thinks but the assistants assist many patients every day whereas the patient only uses the device once. If the patient is strong and clever enough he can adjust the chair by himself. The other patients need help and in many cases the patient has to get off the chair after which the chair is moved into the right position. Assisting while the patient remains on the chair is a heavy task for the assistants and causes lower back pain over time. Besides being heavy the mechanism also tends to stutter if the patients remains on the chair while adjusting the height.

It should be noted here that the first and older Corival Recumbent design used in Rotterdam has no handgrip on the back of the chair, making it even harder for the assistants to aid in pulling up the chair. Feedback on the second version of the Corival Recumbent is needed to see whether this problem still occurs.

Also a simple but maybe drastic shortcoming was the absence of a length scale which shows the position of the chair. This forced the assistants at Rotterdam to adjust the height of the chair every time. With a length scale it would only be required the first time a patients comes by. The length can be noted and the chair can be put at the same length the next visit straight away and without the patients sitting on the chair.

**Handlebar position *(height adjustment)***

In the older Corival Recumbent version the handlebars are not very close to the handgrips and therefore these two are not often confused with each other. Only one patient had trouble finding the handlebar, his length is average.

The assistants suggested that the handlebar could be placed in front of the chair instead of at the side, but still below the chair. That way it would be similar to car chairs making it also easier to explain to the patients.

**Bottle cage**

A simple feature. In Rotterdam they made their own bottle cage showing the need for it. The second Corival Recumbent still has no bottle cage and this feature must be implemented in the new Corival Recumbent.

**Backrest**

Once more confirmed in this interview is the need for a backrest that can recline. This allows the users to reach a more suitable or comfortable position. More importantly it gives space to users with a bigger belly size. Currently their belly can be squeezed making them short at breath. In America users tend to be even heavier thus the problem will be even greater there. A backrest that can recline appears a must.

**Handgrips**

One patient preferred the handgrips to be around 10 cm higher, his length is 1.84 meters. The handgrips is the older Corival Recumbent version are placed higher than in the current version.

One assistant suggested that the handgrips could be variable in position. In the current version of the Corival Recumbent that handgrips are even lower causing even more users not to be able to reach the handgrips.

<u>Front grips</u>

The older version has handgrips in front next to the interface screen. Users tend to hold this, though putting them in an uncomfortable position. They wish these front grips could be variable in position or just to be position more closely to the user. This would though limit the instep space.

These front grips were removed in the current version because they were only intended to be used during in- and outstep. Still it appeared that users do like to hold themselves tight or at least do something with their arms. Bringing back the front grips could therefore be an option. The optional arm function coming for patients with LLA would allow all users to do something with their arms.

<u>Arm motion</u>

As just mentioned all users could benefit from an arm function implementation allowing them to do use their arms. Also the assistant mentioned that this function would allow the users to reach a higher activity, always being useful.

**Remaining questions**

In the current Corival Recumbent version the handgrips and handlebar are closer to each other than in the older version so that the question whether people confuse these could not be answered.

Another remaining question is how much easier the assistance with the height adjustment is in the current version compared to the older Corival Recumbent. If it appears good enough in the current version the need for a different mechanism would be smaller.

The effect of a length scale should be determined. If other instances do make wise use of the length scale they might only have problems with the height adjustment the first time a patients visits.

#### 4.2.2.2 *Conclusion*

The users on the Corival Recumbent in Rotterdam do achieve their intended goal, their cardiorespiratory fitness and even strength does improve. They do not complain about the Recumbent but their experience on it would improve if:

1- The backrest can recline

2- The handgrips on the side can vary in position
3- They can hold their arms comfortably on front grips or on an arm function

Less important is that skinny people would prefer softer cushions and small people would prefer a closer distance to the pedals.

The experience of the assistance would improve if:

- They can easier assist with the height adjustment, or if all users could do it all by themselves by a mechanical or electrical solution

Remaining demands or suggestions:

1- A bottle cage
2- Handle bar in front below the chair

Questions remaining is whether the handlebars and grips are frequently confused. This would though already be solved by changing the handlebar its position to the front. Also the experience of assistants with aiding in the height adjustment of the chair with the current Corival Recumbent should be checked.

Changing to an electrical height adjustment is quit a task with some costs included. If adjusting the height with the current version seems sufficient due to the handgrip at the chairs back and the length scale a total turnover would not be needed. Still an electrical adjustment would be a really advanced feature that could be welcomed with enthusiasm.

**Complaints America**

The Corival Recumbent is sold a lot to America. Lode says there are not too many complaints. There is a wish for a backrest that can recline. Also a wider seat is questioned a lot. In Holland though users find the seat too wide. Thus it would be wise to deliver the Corival Recumbent with different seats/cushions depending on the country.

An electric chair adjustment seems a nice idea but raises the costs. A raise of maximally 400 could be acceptable.

## 4.3 Ergometer Types & Selection

In this chapter we will discuss different types of ergometers studied in literature. This is spread over the sections 5.3.1, 5.3.2 and 5.3.3. In the last section 5.3.4. the best ergometer types are selected. Chapter 5.4 continues based on this selection.

### 4.3.1 Exercising the legs (leg-ergometers)

Even though it is important to always think outside of the box, determining the required motion for the legs, and later the arms, should to be scientifically founded. When inventing an entirely new kind of motion you take the risk of it not achieving the desired cardiorespiratory effects. We will now discuss various types of exercises performed by the legs, arms and both arms and legs that are found in literature. For every ergometer there will be a schematic representation shown on the right.
The goal of the motion or exercise is to improve the physical or cardiorespiratory fitness of the user. In literature several parameters are measured describing this fitness, but the golden standard appears to be the maximum oxygen uptake, known as $VO_2$-max (Wilkins). This parameter was used for searching and comparing the various types of exercises.

#### 4.3.1.1 *Cycling*

Running and cycling are generally the easiest exercises to perform. Since running is not possible for our target population we have to limit ourselves to the cycling exercises. The cycling also has to be performed in a recumbent like position.
Cycling appears to increase a person's $VO_2$ significantly in normal people (Faulkner J.A.; Pechar G.S.) and elderly (Blackie S.P.). People with overweight can reach a $VO_2$ peak similarly as normal people (Loftin M.) with cycling exercise.
It appears not to affect the $VO_2$ peak whether being straight up or in the recumbent position during maximal exercise (Quinn T.J.) (Egaña M.), power translation to the pedals is the same in both positions (Capellia C.).

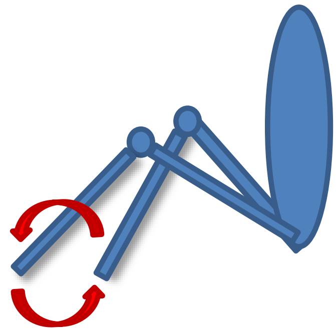


**Figure 10: Schematic representation of the motion performed on a recumbent bicycle ergometer.**

#### 4.3.1.2 *Knee extension (leg pushing)*

Another motion is knee extension, a motion also used in rowing. This movement of the legs is hardly examined and little data is available. It is found to induce the cardiorespiratory system to a lesser extent than cycling does, resulting in a lower $VO_2$ peak (Lazzer S.). Thus, it is preferred to do this type of exercise together with an arm exercise.

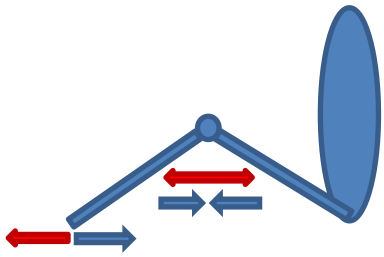


**Figure 11: Schematic representation of the motion performed on a knee extension leg ergometer.**

### 4.3.2 Exercising the arms (arm ergometers)

#### 4.3.2.1 *Arm crank ergometer (arm cycling)*

The simplest arm motion is the same as the simplest leg motion: cycling. Arm cycling and leg cycling have often been compared to each other in research. The $VO_2$ peak reached with arm-cycling is about 60-80% of the $VO_2$ peak found with leg-cycling (Orr J.L.; Louhevaara V.; Franklin). Synchronous or symmetric cycling is not easy to perform with leg cycling, but it is with arm cycling. It appears that synchronous arm cycling is the most efficient (Dallmeijer A.J.), which is most likely why arm cyclist use this motion. When the goal is only to reach a high $VO_2$ peak it might be more useful to stick to asynchronous cycling.

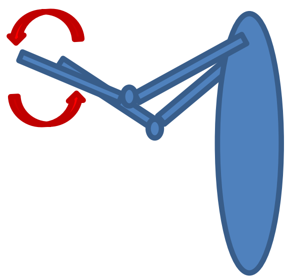


**Figure 12: Schematic representation of the motion performed on an arm crank ergometer.**

#### 4.3.2.2 *Push and pulling (2 hands – 1 grip)*

Although present in combined arm and leg ergometers, arm ergometers which require a push and pulling motion are hardly used or studied in literature. The *Schwinn Airdyne* ergometer on which this motion is performed as well as a cycling motion by the legs has been studied. It was possible to measure the arms and legs seperately (Nagle F.J.) and thus this ergometer could be used to mimic an arm only ergometer. The $VO_2$ peak measured with arms only was 70% of $VO_2$ peak measured with legs only, which is similar to the arm crank ergometers.

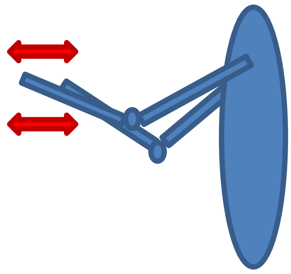


Figure 13: Schematic representation of the motion performed on an arm push & pull ergometer.

### 4.3.3 Exercising arms and legs (combined arm and leg ergometers)

We will now discuss several combined arm and leg ergometers found in literature. In some cases there will already be showed some ideas or sketches that could be implemented into our new Recumbent product.

#### 4.3.3.1 *Arm & Leg Cycling*

A logical combined arm and leg ergometer is where the user makes a cycling movement with the arms and with the legs. Research was performed long ago already on this. The $VO_2$ peak achieved by arm cycling alone and leg cycling alone do not sum up to the $VO_2$ peak reached by exercising on a combined arm-leg ergometer: the combined arm-leg ergometer $VO_2$ peak is about 100% - 110% of that of leg cycling (Bergh U.) (Loudon J.K.) (Gleser M.A.). This approximates values found in running. Remember that arm cycling achieves values 70% of that of leg cycling.

The arm and leg motion can be coupled or uncoupled, for the lower limb amputated target population a coupled device is required. This allows for a variation in work distribution. The highest $VO_2$ peaks are reached when the arms account for 10 – 20% of the total power output.

Figure 14: Schematic representation of the motion performed on an arm-leg ergometer: both cycling motions.

Figure 15 shows an example ergometer of SciFit which already performs this arm and leg cycling motion. For its resistance system it uses a 3 phase combination generator and an eddy current brake, of which the last is also used in Lode ergometers. The arm and leg motion are coupled. Specifications do not indicate a separate adjustable resistance to adjust the arm and leg work distribution. The display show the power delivered and the rounds per minute. In this position the phase difference between arm and leg motion is a quarter, causing all four limbs to be separated by a quarter. This most likely causes a comfortable 'follow up' feeling as well as a good mass distribution for the whole body, resulting in a stable position during cycling. A downfall is that the user cannot lean back totally in the chair.


Figure 15: The PRO2 Total Body Exerciser.

**Advantages:**

- Chair can be designed independently
- Wide instep

**Disadvantages:**

- Fixed arm leg distance (pedal positions)
- Little belly space
- Difficult to perform in lean back position (less comfortable)

**Design Ideas:**

The disadvantages of the Scifit model are related to the front unit which contains the brake and the pedals. It is rigid and positioned relatively close to the users belly. Still the arms need to reach far forcing the user to sit straight up and not comfortably resting its back.

It is not an option to make two separate cycling mechanism which could vary in position, a coupled mechanism is needed for the one-legged patients. Thus, the front unit needs to be smaller in order to make room for the belly and preferably the arm pedals should be adjustable in position or length.

An ergometer found with a relatively small front unit is shown in Figure 16. Although falling in the elliptical or stepper category, it has a small front unit with an arm cycling connected to an elliptical leg cycling motion. Our product would preferably look like this when it comes to the size of the front unit.

Figure 16: The PhysioCycle RXT Recumbent Elliptical Stepper. http://www.fitdir.com/physiocycle-rxt-recumbent-elliptical-stepper.html#

A remaining problem is making the arm pedals adjustable in position. If the axis has to move, the whole chain connected to it has to move as well. This is mechanically challenging. Another option would be to make not the chain but the pedals adjustable in position. This idea is schematically shown in Figure 17.

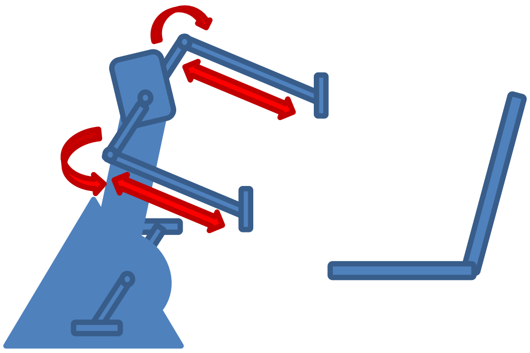


Figure 17: Schematic drawing showing an arm and leg cycling ergometer with the arm pedals adjustable in position.

Note: A downside with this method is that the cycling motion with the arms is becoming more like a push and pull motion.

#### 4.3.3.2 *Stepper Recumbent*

One of the newer products on the field is the stepper in recumbent position. It originated from the cross trainer but was changed into a recumbent stepper allowing people with a low physical fitness to perform similar exercises. For older adults the stepper appears to improve strength and mobility (Johnson T.R.). Compared to cycling the stepper also caused slightly higher $VO_2$ peaks in people who had a stroke (Billinger S.A.).
The left arm and right leg are in phase, just like the right arm and left leg.
The stepper has a complicated mechanism and varies a lot between different ergometers. In normal steppers, where the users stands straight up, air springs are used.

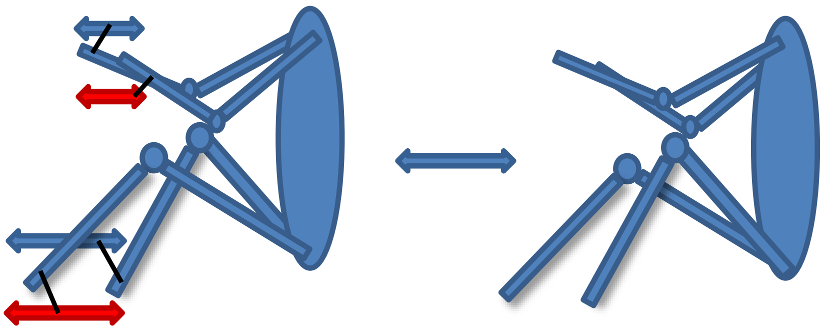


**Figure 18: Schematic representation of the motion performed on a recumbent stepper above. Below the NuStep stepper.**

#### 4.3.3.3 *Schwinn Airdyne Recumbent*

The *Schwinn Airdyne* is an old ergometer but has not developed into a recumbent type yet. It uses air displacement as the resistance mechanism. The motion of the arms and legs are coupled. Similar to arm/leg cycling the $VO_2$ peak reached with the *Airdyne* is about 110% of that obtained with only leg cycling (Nagle F.J.).
Once again, these highest values are only obtained when arms contribute for about 10-20% of the total work. At 30% arm contribution the $VO_2$ obtained is already slightly lower than obtained with leg only exercises. Just like the Scifit arm/leg cycling model, all limbs are separated by a quarter of a phase.

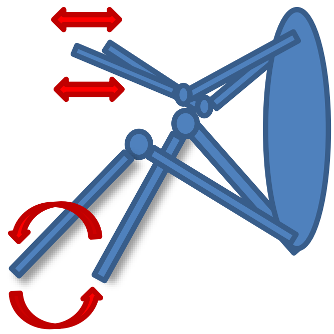
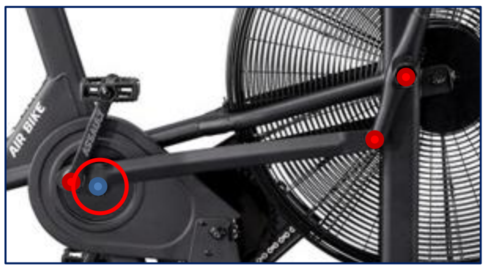


**Figure 19: Schematic representation of the motion performed on a *Schwinn Airdyne*.**

The Schwinn Airdyne uses a clever and simple mechanism to combine the arm and leg movement but changes the axis around which the legs pedal. Figure 20 shows a side view of the Assault Air Bike which is nearly the same as the Schwinn Airdyne. The close up shows all joints present in this ergometer. The blue dot points out the true axis of the chain. The red dot closest to this blue dot is the axis of both the leg and arm pedals. This axis circles around the chain axis as shown by the red circle.


**Figure 20: The Assault Air Bike. Total overview above and a close up below showing all joints.**




**Advantages:**

- Not yet present in Recumbent mode (new product)
- Achievable via simple mechanical adjustment to Corival Recumbent

**Disadvantages:**

- Instep may be blocked by arm pedals
- Resistance mechanism is different from Angio

**Design Ideas:**
The air resistance mechanism has to be converted to Lode's Angio system, it should not be a difficult task.
Figure 21 shows two options of how the arm levers could be placed. The option going below the Angio seems more comfortable for the user but blocks the instep significantly. The upper options narrows the instep as well but making the levers variable in length could solve this problem, as shown by the red arrow. If the whole arm system could be made detachable the normal Recumbent would remain the same. At first sight this idea seems mechanically easy to perform but later it appears more challenging.

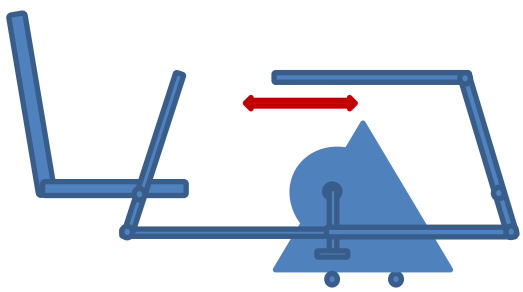


**Figure 21: Idea showing how the Schwinn Airdyne could be implemented to the Recumbent.**

### 4.3.3.4 *Rowing*

Rowing is strictly speaking also an arm and leg ergometer. The trunk though takes a large role in the exercise and is used a lot. Also there is a movement back and forth but only one direction is resisted by the ergometer, when the arms pull and the legs push.
In literature we find similar responses in maximal and submaximal exercises between rowing and cycling ergometers (Thomas R.; Barfield J.P.; Pitett K.H.).

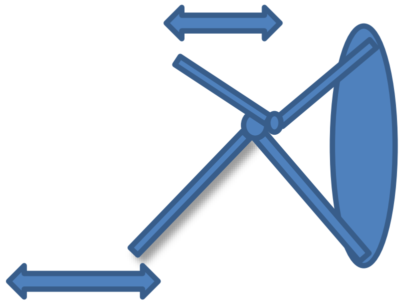


Figure 22: Schematic representation of the motion performed on a rowing ergometer/device.

Of all the possible type of ergometers the rowing ergometer differs the most from the Corival Recumbent. The cycling motion disappears and the chair design will drastically be influenced. Not only the design of the product but the user will have a completely different experience.

There are two types of rowing ergometers, of which one is a relatively new invention.
In the standard rowing ergometer the seat moves, thus the user is also moving, see Figure 23. The seat without backrest provides no support to the users back at all. Even with a good chair in our design, rowing still requires movement of the torso: the user repeatedly reaches forward and falls backwards with his torso. This is the reason why a chair without backrest is used, it gives space to the moving torso.
Another recently developed rowing ergometer is the RowPerfect, where the user does not move but pushes away the device, see Figure 23. This affects our chair design to a lesser extend but the problem with the moving torso remains since the rowing motion remains the same.

Figure 23: Concept 2 rowing ergometer above. Below the RowPerfect.

**Disadvantages:**

- Difficult motion for the user to learn/perform
- No adequate back support possible

#### 4.3.3.5 *Elliptical Recumbent*

Together with the stepper the elliptical recumbent is a relatively new ergometer and therefore less defined and studied. One research does conclude it is a valid and reliable way for testing aerobic fitness and found similar results as found with a study on a Schwinn Airdyne bicycle (Mendelsohn M.E.). With the arms a push and pull motion is performed slightly upwards and with the legs an elliptical cycling motion is performed.

As shown in Figure 24, the elliptical recumbent uses the same mechanism as the Schwinn Airdyne but the brake system is placed beneath the chair. The feet are placed on an extension of the brake system and therefore perform an elliptical instead of a circular motion.

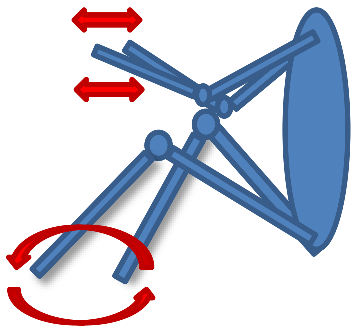


**Figure 24: Schematic representation of the motion performed on an elliptical recumbent. Below the SciFit Rex Elliptical Recumbent.**

**Advantage:**

- Lesser use of knee joint

**Disadvantages:**

- Design of the chair interfered
- Instep space reduced/blocked
- Input/output correlation?

**Design Ideas:**

The arm levers should be made adjustable in position as is done with the double cycling ergometer idea from Figure 17.

### 4.3.4 Ergometer Selection

In this section the selection table will be shown and discussed in order to find out which ergometer motion is the most suitable for the users. For each criterion the weight factor will be discussed and how well it is met by the different types of motion.

**$VO_2$**

Based on the literature study no differences between the VO2 effect of different ergometers could be found. There appear to be too many variables involved that make it too complicated to compare the ergometers. In order to rank the different ergometers they would need to be compared to each other in recumbent position, with the same type of users, with the same exercise intention and the long term effect of the $VO_2$ maximum would need to be observed. The literature found indicates only that the ergometers are sufficient or promising to be used for $VO_2$ improvement. Sometimes comparisons were done but circumstances were too specific to make overall conclusions. Therefore it is assumed that all ergometer types have a sufficient $VO_2$ effect.

#### 4.3.4.1 *Comfort of motion*

It is complicated to give an indication which motion is the most comfortable to perform without experiencing the motion itself. It is though the most important criterion for the user and thus for the product, therefore this criterion is given the maximum weight factor of 5.
Since the stepper resembles walking most closely it is given 5 points. Followed by 4 points for the cycling ergometers: the arm/leg cycling, the Schwinn Airdyne and the elliptical. The Cruiser is an unfamiliar motion and might even cause motion sickness at high speeds, giving it a 3. Lastly, the rower is given two points because it requires experience and because the back is poorly supported during rowing.

#### 4.3.4.2 *Uniqueness of product*

This criterion is a nice addition to a product but is not a qualitative criterion, therefore it has the lowest weight factor. Only the Schwinn Airdyne and the rower are not yet present in recumbent position. They are given a 5. The Cruiser will be a remake and deserves a 4, whereas the other products are not new and deserve a 1.

#### 4.3.4.3 *Freedom of Chair Design*

Some ergometer motions require space beneath the chair and therefore limit the design freedom of the chair. The more freedom the better because this allows the most options. Since at forehand we do not know how the chair design we only give this a weight factor of 1.
The arm/leg cycling, the stepper and the Schwinn Airdyne all allow maximum freedom. The rower gets the least points since the back is hardly supported. The elliptical and cruiser are given a 3 because the space below the chair is occupied.

#### 4.3.4.4 *Body Balance*

Due to the loss of a limb the body of people with LLA is less in balance. This extends to exercising: in most exercises the user performs the same motion with both legs, performing this with only one leg causes imbalance. This imbalance may not be too great but decreases comfort.
The motion where this imbalance occurs the least is where to user pushes himself back, with one leg the user can still push himself back without causing a serious momentum sideways. Therefore the Rower and Cruiser are given 4 points on this criterion. The remaining exercises will cause equal disbalance and deserve only 2 points.
This criterion is much related to comfort and will therefore be also given a weight factor of 5.

#### 4.3.4.5 *Input-Output Correlation*

The input-output correlation mentions how well the physical input of the user is related to the power output of the device. This is affected by the type of motion and the quality or accuracy of the device. The Angio, Lodes specialty, can calculate the power very accurately. All ergometers will be transferred to a system with an Angio. Thus, all devices can be treated as equally accurate.
The type of motion remains. The relationship between in- and output with cycling is closest to 1 on 1. This makes the arm/leg cycling ergometers the best on this criterion.
Next we have the Schwinn Airdyne and the Elliptical, where the legs perform a cycling motion but the arms perform a push and pull motion. Acceleration and deceleration is not measured by the Angio and worsens in- and output correlation. Also energy might be lost in the joints connecting the arm and leg motion.
The stepper has only push and pull motion, for the arms and for the legs, making the relationship is worse.
Lastly we have the Rower and the Cruiser. Two complicated movements on which it is very hard to say what the correlation will be, the whole body is accelerated and decelerated. A lot of energy will not be measured by the Angio.
Even though not as important as comfort, this criterion is very important for the scientific and medical use of the device. The device will give an indication of the users fitness and therefore requires accurate measurements. Therefore the criterion weight is given a 4.

#### 4.3.4.6 *Applicable to the Corival Recumbent*

Another low weighted criterion which is still of importance for the realization of the product is whether the type of motion can easily be implemented into the current Corival Recumbent. This speeds up the design process and allows us to build forward on knowledge about the Corival Recumbent. The wish for a device for users with LLA is put central in this project but the bulk of the users (elderly/overweight) will still want to use the normal Corival Recumbent. Therefore this criterion is given a weight factor of 2.
Only two ergometers are easily implementable into the Corival Recumbent, namely those already using a cycling motion and those not affecting the chair design: the arm/leg cycling and the Schwinn Airdyne. They are given a 5.
The stepper allows free chair design but a complicated use of the Angio, giving it a 4. The Elliptical can use the Angio but complicates chair design freedom, giving it a 3.
The Rower and the Cruiser are hardly related to the Corival Recumbent and are given a 1.

#### 4.3.4.7 *Performable by all users*

The type of users have been discussed and the ergometer type should be useable by all of them. Since all designs should work for people with LLA we only have to discuss the elderly and the people with overweight. This point is very important but if it would be optional to order the Recumbent with or without an arm motion implementation the product would remain universal. Therefore the weight factor is given a 3.
Arm/leg cycling, Schwinn, Stepper and elliptical should be usable by all users since the user can just lean back and do the exercise.
The Cruiser has a high instep and its space around the chair is a bit limited, being a problem for people with overweight. It might not be too much of a problem and it is therefore given a 4.
The rower of course is hard to perform for elderly and people with overweight. It is given a 2.

**Skipped Criteria**

Cost and safety were not yet discussed because it depends heavily on the mechanical design. These criteria will be used for the pre-concepts in the next chapter. In their current state all ergometers are being used in practiced and therefore assumed sufficiently save.

**Selection Table:**

| | Weight Factor | Arm/Leg Cycling | Stepper | Schwinn Airdyne | Rower | Elliptical | Cruiser |
|---|---|---|---|---|---|---|---|
| Comfort of Motion | 5 | 4 | 5 | 4 | 2 | 4 | 3 |
| Uniqueness of Product | 1 | 1 | 1 | 5 | 5 | 1 | 4 |
| Freedom of Chair Design | 1 | 5 | 5 | 5 | 2 | 3 | 3 |
| Body Balance | 5 | 2 | 2 | 2 | 4 | 2 | 4 |
| Input Output Correlation | 4 | 5 | 3 | 4 | 2 | 5 | 2 |
| Applicable to Corival Rec. | 2 | 5 | 3 | 5 | 1 | 3 | 1 |
| Performable by all User Types | 3 | 5 | 5 | 5 | 2 | 5 | 4 |
| Total | | 81 | 74 | 81 | 53 | 75 | 64 |

Thus, the pre-concepts are primarily based on the Schwinn Airdyne, Arm/Leg Cycling, the Elliptical and the Stepper, if mechanically possible.

## 4.4 Pre-concepts

What now follows are sketches of several pre-concepts based on the ergometer types discussed. We can rank these concepts again to obtain one to three ideas to work out in more detail.

### 4.4.1 Horizontal Push-Pull Concept

The first ideas are very much related to the Schwinn Airdyne and the elliptical. In the Schwinn Airdyne the arm levers turn around one fixed joint and thus the users hands follow an arc. If the arm levers are not too long this arc is close to a comfortable horizontal motion. In the recumbent the arm levers have to be much longer causing a much greater arc, this is uncomfortable. One cannot maintain an almost horizontal arm lever motion with just one joint and such a long lever. Below we see how we can obtain an almost horizontal arm lever motion via the addition of an lever and extra joint. Currently the arm levers are floating in the air, they should be supported by a sliding joint at the position indicated by the red arrow in Figure 256.

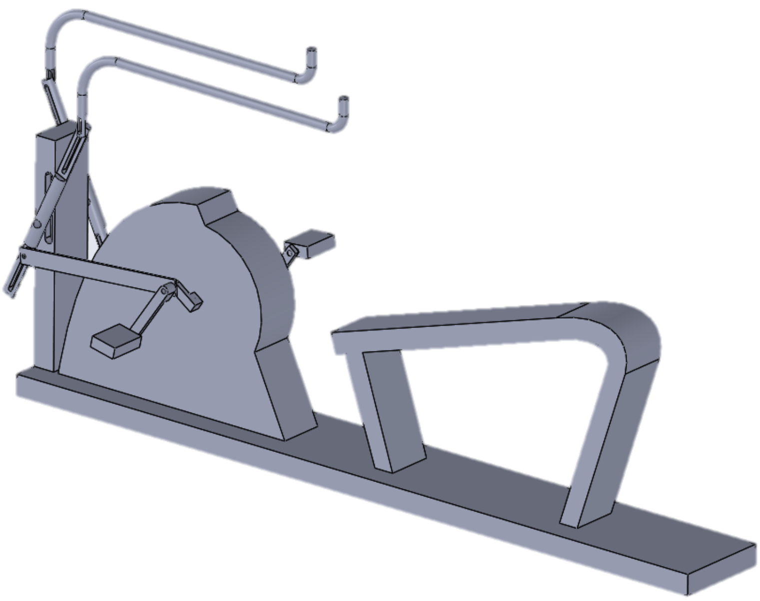


Figure 265: The Schwinn Airdyne concept in a recumbent form. A rough shape of the recumbent is shown to indicate the distance to the chair. The frame around the Angio is still free to design.

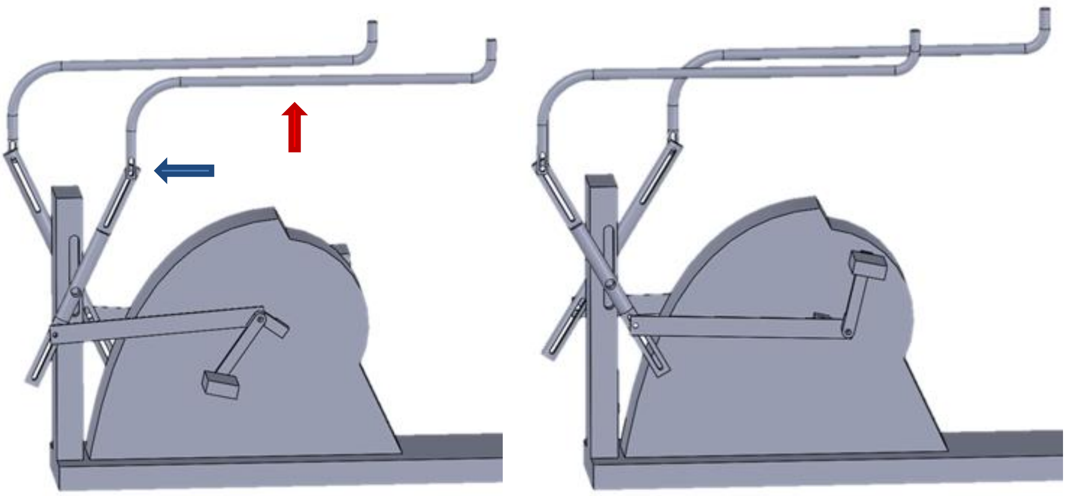


Figure 256: The motion of the Schwinn Airdyne concept is shown for two different positions. The blue arrow indicates a 'floating' joint, the red arrow a fixed joint. The fixed joint is fixed in position but may still turn.

**Notes:** In this as well as in the following concepts the exact height of the arm levers is not precise. The length of the levers should be adjustable as well as the position of the hand grips making it as universal as possible.
In this concepts as well as in the coming concepts some parts are still floating in the air. This is because the frame of the recumbent is not yet defined, it could be different for every different concept.

**General Problems:** A problem with this concept as well as with the following three concepts is that the pedals are widened, the so called q-factor is increased. Luckily the Angio is relatively small from itself so that a wider q-factor is allowed to a certain extend. There are bicycle ergometer from for example Ergoline where the q-factor is about 4 cm greater, meaning 2 cm at each side. Special pedals should be created for this concept and the q-factor should be kept as small as possible while maintaining enough strength. A strength analysis would be required on the pedals as well.

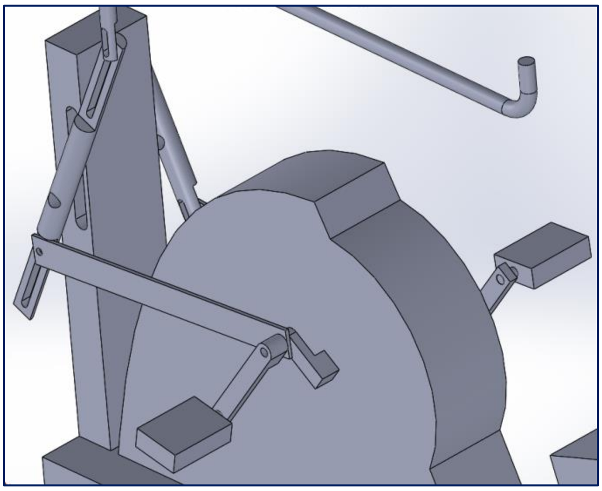


Figure 27: Close up of the crank used in the concept 1, which has to be wider than a normal crank.

**Disadvantages:**

- Wider q-factor
- Mechanically complicated (extra lever, extra sliding joint)

### 4.4.2 Angled Push-Pull Concept 1

Compared to the previous concept this concept is more similar to the original Schwinn Airdyne with only one fixed joint. As already explained, due to the long arm levers the users arm perform a long arced motion. With precise placement of the fixed joint and flexible joint, red and blue arrow respectively in Figure 28, the path of the end of the arm levers can be defined. The arc is angled compared to the previous concept, where it was horizontal.

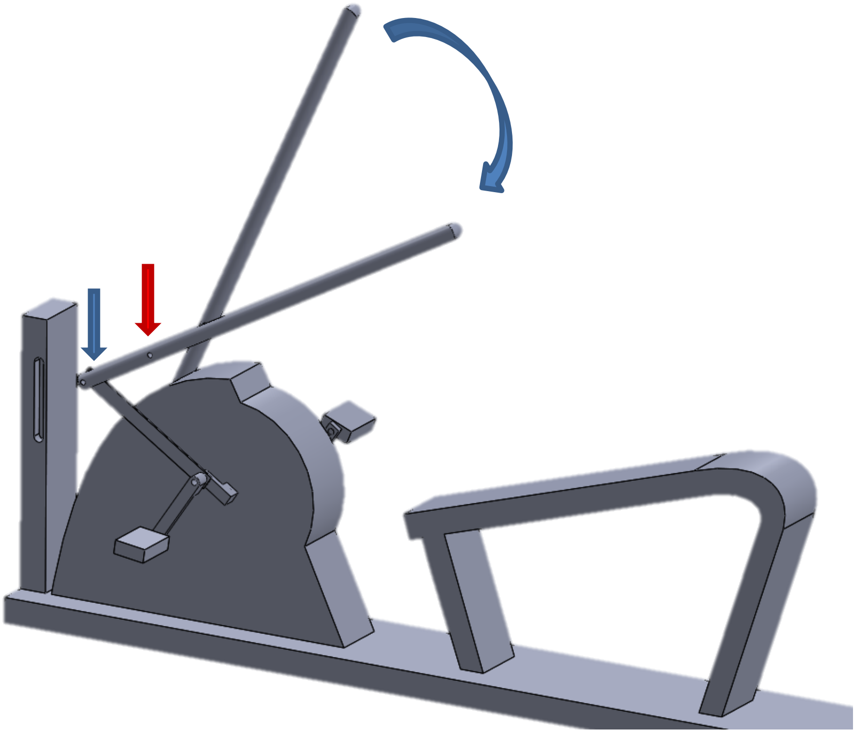


Figure 28: Sketch of the Elliptical Schwinn Concept. There is only one fixed joint in this concept, indicated by the red arrow. The left blue arrow indicates a flexible joint.

**Notes:** Compared to the previous concept it should be judged which motion is most comfortable for the user to perform: horizontal or circular.
The position adjustability of the arm levers is not as easy as with the previous concept. Just making the levers longer is not an option for longer users, it will allow them to reach further but the levers will also come closer to their body. A lever shape similar to the arm levers used in the Elliptical is most likely suitable.

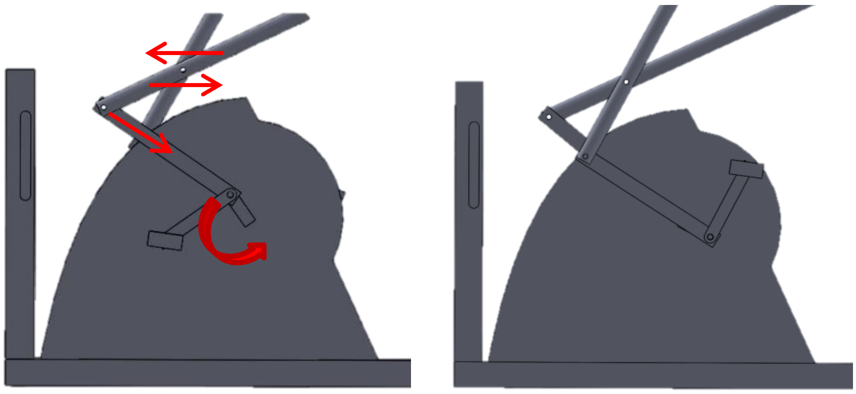


Figure 29: Closer view on the mechanism connecting the arm and leg motion.

**Disadvantages:**

- Wider q-factor
- Complicated arm lever shape

### 4.4.3 Angled Push-Pull Concept 2

The Angled Push-Pull Concept 2 is of course very similar to the previous Concept 1 version. It only has the fixed and flexible joints switched.

The fixed joint is positioned more closely to the surrounding frame making a connection between the two easier, if the frame in the new design will not differ drastically. Next, the lever effect is more effective in this concept: the ratio between the smaller and bigger lever is larger. This results in a smaller and more compact lever overall. It has advantages over Concept 1 version and no disadvantages at this current state, these might be found later. The disadvantages in general are the same as those for the Elliptical Concept 1.

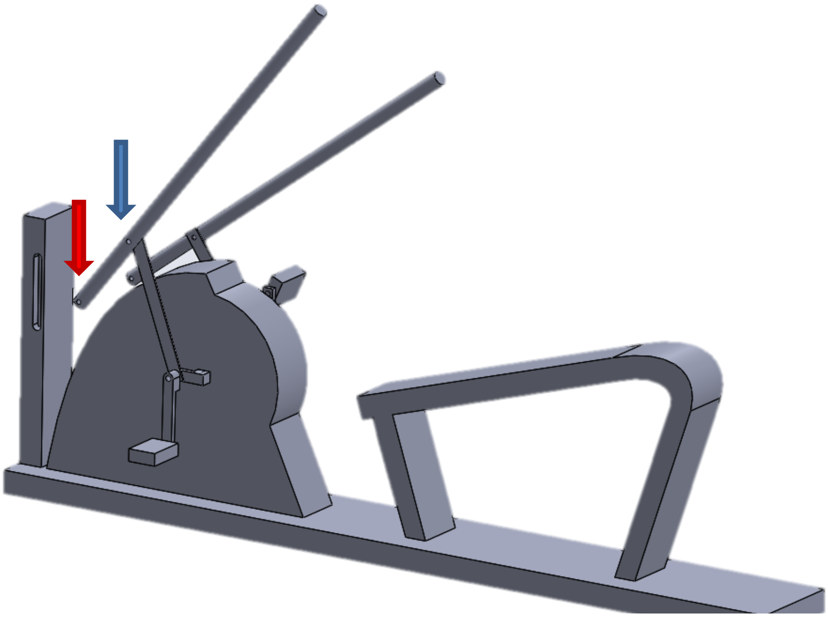


Figure 30: A second version of the Elliptical Schwinn Concept with a more efficient lever connection compared to the first version of this concept.

**Disadvantages:**

- Wider q-factor
- Complicated arm-lever shape

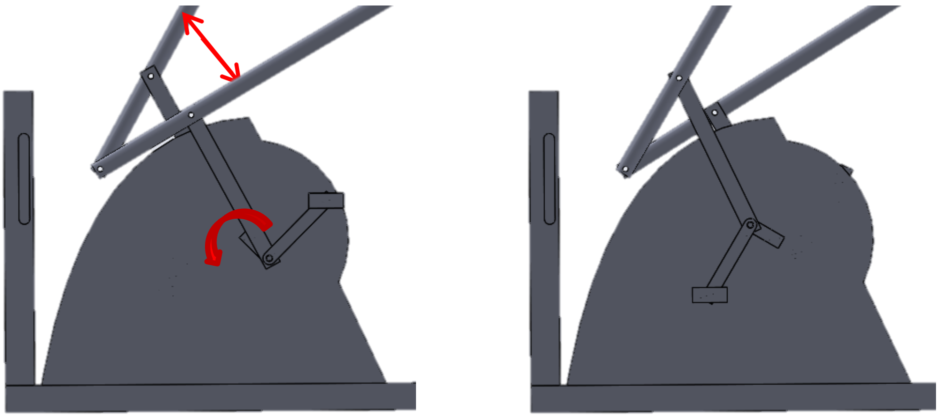


Figure 31: Close up of two position showing the motion of the Elliptical Schwinn Concept 2.

### 4.4.4 Push-Pull Slider

In the last Schwinn-like concept we use a slider in the lever through which the cycling cranks can move.

The position of the fixed joint in this concept is placed below the cranks. The arm levers are therefore positioned more forward, closer to the users body. The design of the arm levers should be similar to those used in the Elliptical.
The advantage of this concept is that the fixed joint is positioned closely to the bottom of the frame. A connection may be implemented easily. Also the force transformation from the cranks to the arm levers is the most direct in this concept. Lastly this concept is the most compact. The disadvantages found in the previous two concepts though remain.
A downside of this concept is that the arm and leg motion are slightly out of phase: the arm motion is not entirely symmetric. The arm levers turn over when the smaller crank stands perpendicular on the arm lever, both these stages are shown in Figure 33. This may affect the *Comfort of motion* drastically.

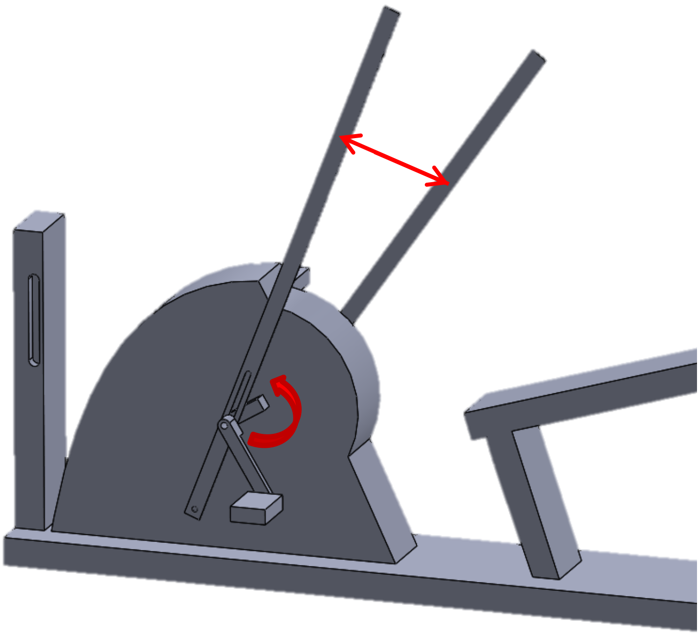


Figure 32: The Schwinn Slider. It still uses the Schwinn cranks but these are directly connected to the arm levers via a slide system.

**Disadvantages:**

- Wider q-factor
- Complicated arm-lever shape
- Slight asynchronous movement

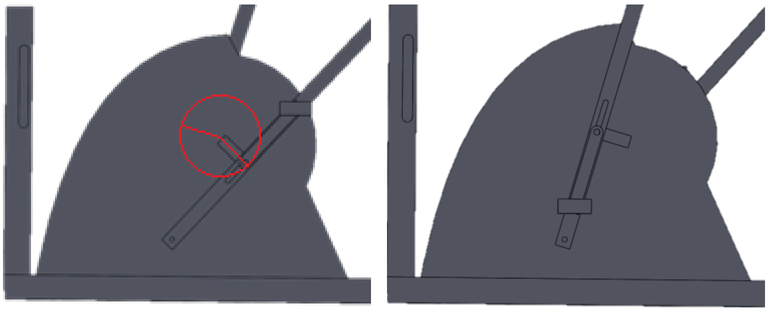


Figure 33: The Schwinn Slider concept at two stages, in between both phases.

### 4.4.5 Stepper Angio Concept

The next two concepts use a different strategy which convert the cycling motion of the Angio into a stepping motion. This is done via the scotch yoke mechanism, which is explained in Figure 344. The crank is fit in a slider and can move up and down through it. The slider itself can only move left and right.

When implemented into the Recumbent we have to attach the pedals onto the slider, so that the user can push the sliders away. The arms can then pull the sliders back. This all makes use of the Angio system. The system causes more friction which the Angio system cannot calculate though.

In a stepper the arm and legs are crosslinked: left to right and vice versa. The easiest way to connect the system like this is via a direct connection, as shown in Figure 35. Yet this causes spatial and safety problems. The bars in this state are sliding along each other, causing the risk of cutting of something that falls in between. Thus a cap is needed to prevent this from happening as shown in Figure 36.

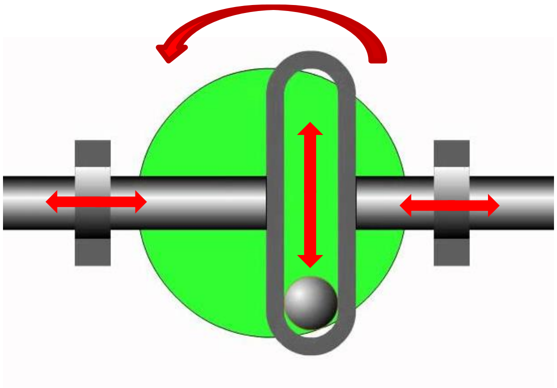


Figure 34: Schematic representation of a scotch yoke mechanism which converts a circular motion to a linear motion or vice versa.

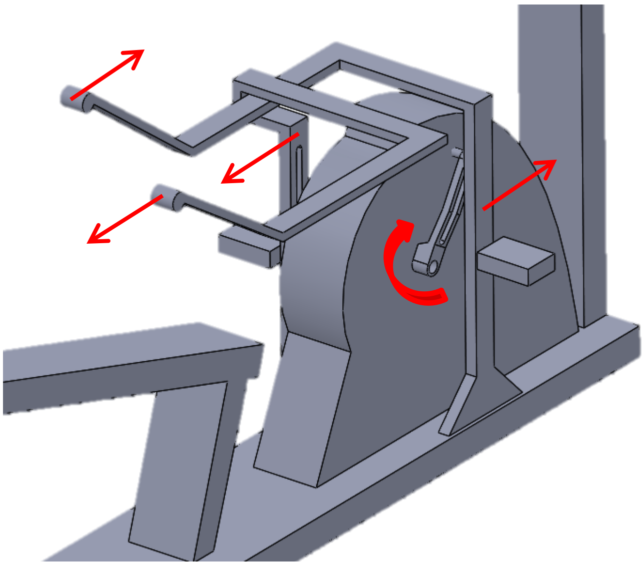


Figure 35: The Angio turned into a stepper via the use of the scotch yoke mechanism. This concepts mimics a stepper.

**Problems:**

- Wide construction
- Complicated construction
- Esthetical problems
- High resistance
- Lack of a free wheel

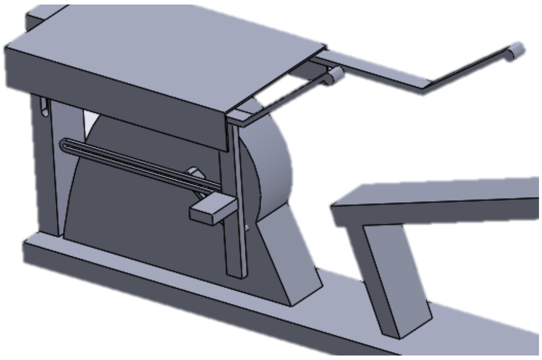


Figure 36: Addition of a cap to the stepper concept preventing the cutting or scissors effect of the moving parts.

We also see in Figure 366 a different attachment of the slider, being at the same height as the crank axis. This way the force is applied without a great momentum, which is present with the concept shown in Figure 355. The downside is another moving part that sticks out.

### 4.4.6 CumbentCruiser Concept

The motion performed in this concept mimics that of the Cruiser. The Angio cranks point the same direction thus both legs move symmetrically. The sliders are pushed away and pulled back by the arm levers. In the Cruiser this motion was similar but the arm levers made a little arc, as well as the chair. In this concept that chair remains stationary.
The movement performed on the Cruiser is an unfamiliar movement, just as is the case in this concept. But it appeared that users on the Cruiser did get used to the motion. The Cruiser seems to have more of a goal whereas the motion in this concept might seem a bit useless. Still the mechanical system is relatively easy and compact.

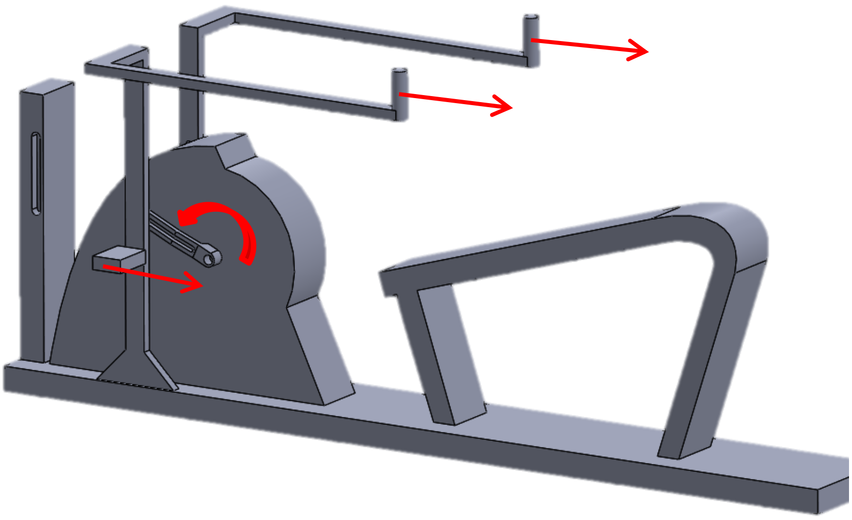


Figure 37: The CumbentCruiser concept which mimics the motion of the original Cruiser.

**Problems:**

- Silly motion
- Resistance

### 4.4.7 Arm/leg Cycling

Finally there is the arm/leg cycling concept, not worked out in too much detail here. As explained in the ergometer section the arm/leg cycling has limited space around the users belly and the users in the Scifit model had to sit more up straight in order to reach the arm pedals. In arm/leg cycling both cranks are connected to the same belt, which is not drawn in the concept.
In this concept it is tried to let the user reach the arm pedals with more ease by converting the circular motion to a push and pull motion. The precise size and position of the arm system could be different from what is drawn in Figure 38, in the current state the *Instep Space* is quite limited.

Another concept was to keep the arms cycling and make a whole system which can turn around some point. It would turn around the base Angio which remains in position and the arm system would move along an arc closer to or away from the user.
Where all other concepts work 'outside' the Angio model this concept has consequences within the Angio brake system. The belt is changed and a different Angio covering cap is required. These come along with other complications of which better knowledge about the Angio system is required.

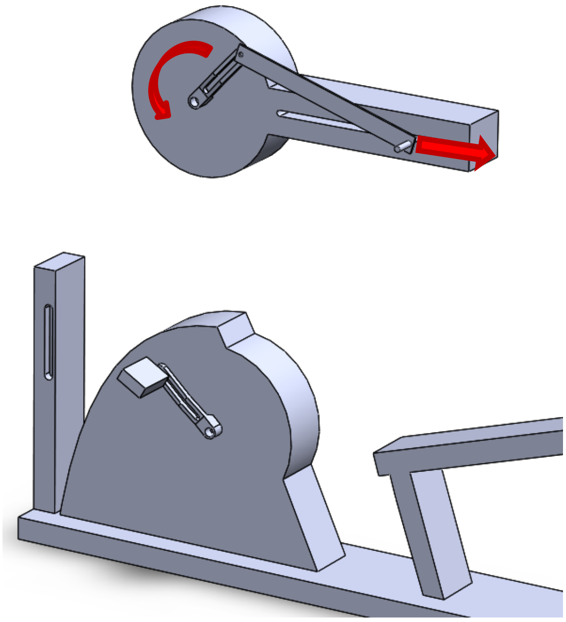


Figure 38: Arm/leg cycling concept. Detail is limited, both arm and leg cranks should be connected via a chain.

## 4.5 Pre-concept Selection

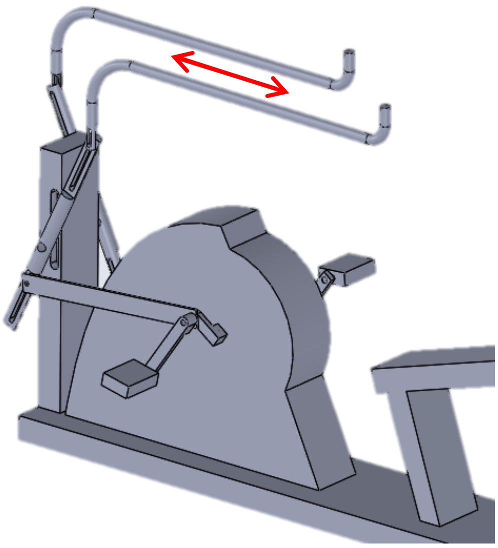
The following changes have been made to the selection table. The *Applicability to the Corival Recumbent* has been replaced by *Mechanical complexity*. All ideas should be applicable to the Corival Recumbent by now and only the complexity matters. *Body balance* and *Performable by all users* types has been removed since all concepts perform equally well at these criteria. *Safety*, *Costs*, presence of a *Free wheel* and the *Instep space* have been added.

**Weight factors**
*Safety*, *Comfort* and the *Reachability of the arm levers* are the most important weight factors. *Reachability of the arm levers*, which has to be universal, is strongly related to the *Comfort* for the user. Next we have the *Resistance,* which affects the power measurement accuracy, at 4 points because the accuracy of Lode products is important.
The remaining criteria are given a 3 since if these criteria are not fulfilled optimally it is not the worst case scenario: Concepts may be too complex but this cannot easily be predicted at forehand (*Mechanical complexity*). The same is the case for the *Costs*. These criteria will though be important at later stages of the project and should therefore already be considered. The presence of a *Free wheel* is a nice addition but was not present in the original Cruiser. Lastly, the *Instep space* is important for people with overweight, but with the possibility to choose a Recumbent with or without an arm function decreases the importance of the instep space criterion.

| | Weight Factor | Hor. PushPull | Angled PushPull 1 | Angled PushPull2 | Schwinn Slider | Angio Stepper | Angio Cruiser | Arm/Leg Cycling |
|---|---|---|---|---|---|---|---|---|
| Comfort of Motion | 5 | 5 | 5 | 5 | 4 | 5 | 3 | 5 |
| Resistance | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 4 |
| Mechanical Complexity | 3 | 4 | 5 | 5 | 5 | 2 | 3 | 3 |
| Safety | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 |
| Costs | 3 | 3 | 4 | 4 | 5 | 2 | 3 | 2 |
| Free Wheel | 2 | 5 | 5 | 5 | 5 | 1 | 1 | 5 |
| Instep Space | 3 | 5 | 5 | 5 | 5 | 4 | 4 | 4 |
| Reachability Arm Levers | 5 | 5 | 4 | 4 | 4 | 5 | 5 | 4 |
| Total | | 133 | 138 | 138 | 136 | 108 | 109 | 123 |

We will now briefly discuss significant criteria for every pre-concept.

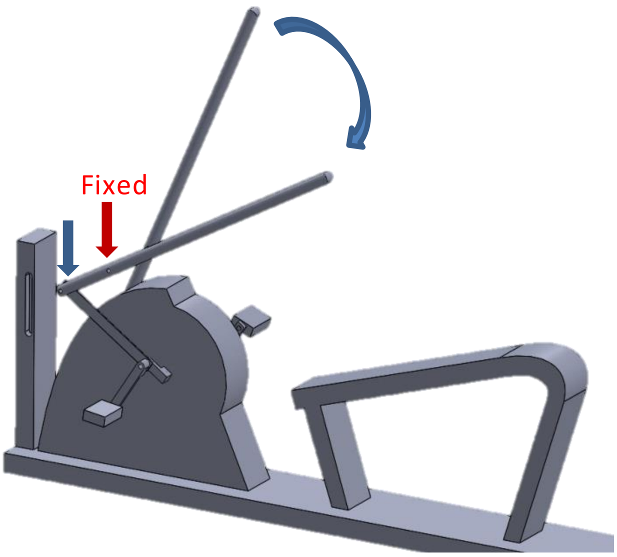
### 4.5.1 Horizontal Push-Pull Concept



| | |
|---|---|
| Comfort of Motion | 5 |
| Resistance | 3 |
| Mechanical Complexity | 4 |
| Safety | 5 |
| Costs | 3 |
| Free Wheel | 5 |
| Instep Space | 5 |
| Reachability Arm Levers | 5 |
| Total | 133 |

If the arm levers are horizontally and vertically adjustable the *Reachability of the Arm Levers* (5) should be optimal as well as the *Instep Space* (5). The horizontal push and pull motion is assumed optimally *Comfortable* (5). The use of several connecting bars and corresponding joints though make the concept a bit more *Mechanically Complex* (4), also increasing the *Resistance* (3) and the *Costs* (3).

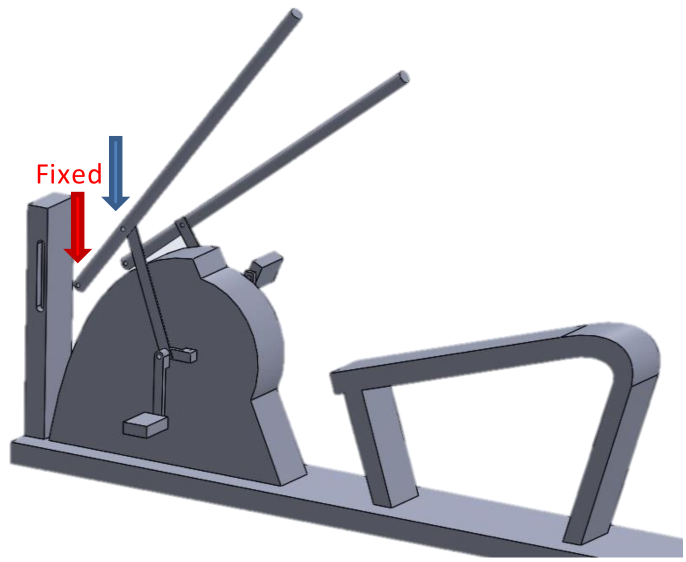
### 4.5.2 Angled Push-Pull Concept 1




| | |
|---|---|
| Comfort of Motion | 5 |
| Resistance | 4 |
| Mechanical Complexity | 5 |
| Safety | 5 |
| Costs | 4 |
| Free Wheel | 5 |
| Instep Space | 5 |
| Reachability Arm Levers | 4 |
| Total | 138 |

Compared to the previous concept this concept is less *Mechanically Complex* (5) and the *Resistance* (4) and *Costs* (4) are also affected positively by this. Only the *Reachability of the Arm Levers* (4) is a bit worse since it is not possible to adjust the position both horizontally and vertically. The adjustment of the arm levers should be as universal as possible by having the right shape, as was used in for example the original Elliptical Recumbent. The *Resistance* (4) is slightly worse than optimal in this concept.

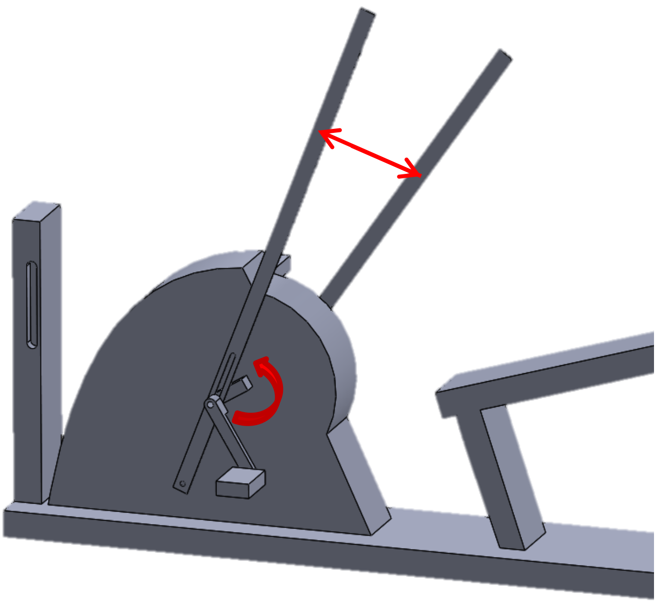
### 4.5.3 Angled Push-Pull Concept 2




| | |
|---|---|
| Comfort of Motion | 5 |
| Resistance | 4 |
| Mechanical Complexity | 5 |
| Safety | 5 |
| Costs | 4 |
| Free Wheel | 5 |
| Instep Space | 5 |
| Reachability Arm Levers | 4 |
| Total | 138 |

Mechanically relatively the same as the Schwinn Elliptical Concept 1 the Concept 2 scores similar to all criteria. As mentioned in the previous chapter Concept 2 had some advantages over Concept 1, namely the arm lever efficiency and mechanical complexity. But these slight differences do not make a significant difference in the table but should be kept in mind, Concept 2 is preferred over Concept 1.

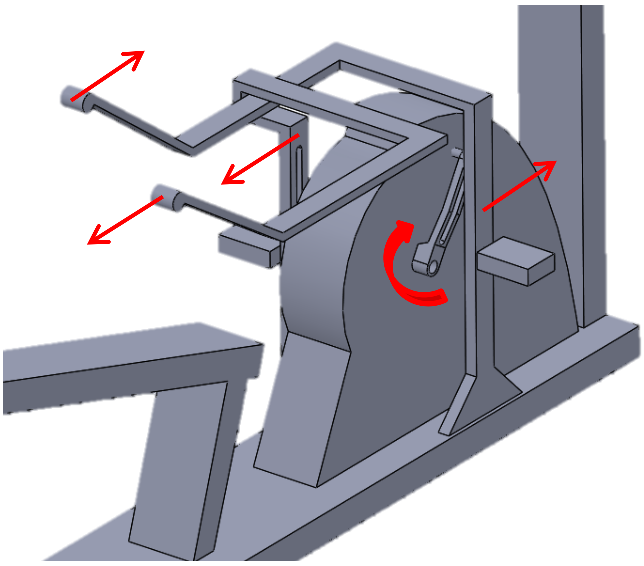
### 4.5.4 Push-Pull Slider



| | |
|---|---|
| Comfort of Motion | 4 |
| Resistance | 4 |
| Mechanical Complexity | 5 |
| Safety | 5 |
| Costs | 5 |
| Free Wheel | 5 |
| Instep Space | 5 |
| Reachability Arm Levers | 4 |
| Total | 136 |

The Schwinn Slider is the most compact and thus *Mechanically* the least *Complex*. This does not make a significant difference at this specific criterion but it does so at the *Costs* (5) criterion, less bars and materials are used.
A downside is the *Comfort of motion* (4). The arm motion is slightly out of phase and this might in the end even be a crucial point to not accept this concept. It can be seen in SolidWorks that the arm levers move forward sooner than backwards, which should occur at the same time.

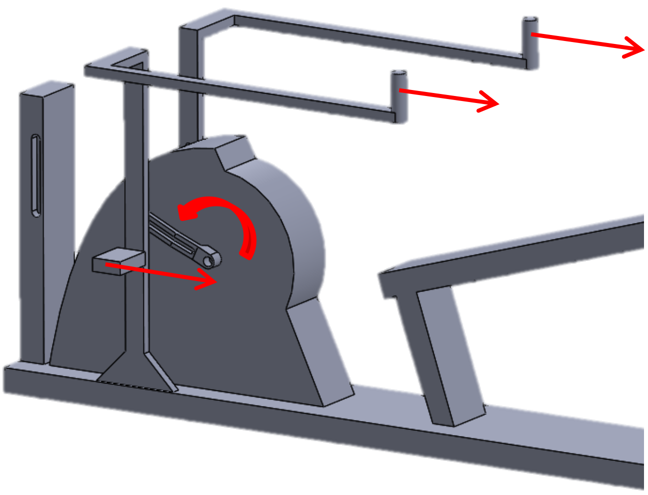
### 4.5.5 Angio Stepper



| | |
|---|---|
| Comfort of Motion | 5 |
| Resistance | 3 |
| Mechanical Complexity | 2 |
| Safety | 4 |
| Costs | 2 |
| Free Wheel | 1 |
| Instep Space | 4 |
| Reachability Arm Levers | 5 |
| Total | 108 |

This concept cannot work without a *Free Wheel* because it can get stuck at the turnover positions. The *Safety* (4) of this concept is slightly less because of this missing *Free Wheel* (1), the arm levers might hit the patients when it keeps moving on. The *Instep Space* (4) is also reduced due to the larger amount of bars. The *Mechanical Complexity* (2) is high, increasing the *Resistance* (3) and *Costs* (2) also significantly.

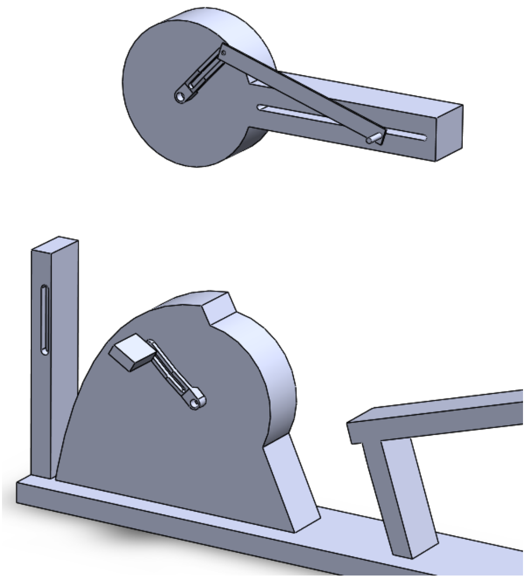
### 4.5.6 Cumbent Cruiser



| | |
|---|---|
| Comfort of Motion | 3 |
| Resistance | 3 |
| Mechanical Complexity | 3 |
| Safety | 4 |
| Costs | 3 |
| Free Wheel | 1 |
| Instep Space | 4 |
| Reachability Arm Levers | 5 |
| Total | 109 |

As discussed the *Comfort of the Motion* (3) in this concept might be low due to a meaninglessness of the motion. The *Mechanical Complexity* is slightly less than the previous concept, affecting the *Costs* (3) in a positive way but not the *Resistance* since the sliding system is unchanged. The *Instep Space* and *Free wheel* are the same as the previous two concepts.

### 4.5.7 Cycler



| | |
|---|---|
| Comfort of Motion | 5 |
| Resistance | 5 |
| Mechanical Complexity | 3 |
| Safety | 5 |
| Costs | 2 |
| Free Wheel | 5 |
| Instep Space | 4 |
| Reachability Arm Levers | 4 |
| Total | 123 |

The motion of the cycler in its current state is very similar to the first concept. Compared to the other concepts this concept has the least *Resistance* (5) since both cranks apply their force directly onto the belt. *Mechanically* (3) this concept is a bit complicated and not worked out into great detail, but most likely the *Costs* (2) are increased significantly. Also the *Instep Space* (4) is limited in the current state. The *Reachability* of the *Arm Levers* (4) is almost optimal but might still be too far away at the furthest position.

### 4.5.8 Conclusion

The highest score is achieved by the Angled Push-Pull Concepts. The resistance, complexity and costs are very low making this concept the most viable. To be certain, the concepts and the selection method were discussed with employees at Lode. They agreed upon the Angled Push-Pull Concepts being the best ideas but suggested a variation of the concept. This will be discussed in the next chapter.

# 5 Synthesis Phase II

## 5.1 Introduction

In this chapter we will discuss two more things. First of all a major problem was detected with the first four concepts in the previous chapter, they contained scissoring effects. This means that some parts that move alongside each other can cut off something that falls in between, meaning serious safety issues for the product. Luckily an idea came up to solve this issue and that will be discussed first.

Then we will show the variation upon the Push-Pull Slider concept suggested by the employees at Lode. This variation was assumed to be more comfortable but a test was needed to verify this. This test and its results will also be shown.

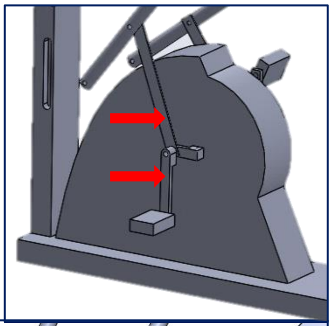
NOTE: In chapter six the prototype will be discussed. It was initially not planned to build a prototype and the project would have ended with what is discussed in this chapter. Though still relevant, the prototype gave much more practical information about a future product than what we find in this chapter.

## 5.2 Scissoring Effect and Solution

For safety reasons there has to be a distance of at least 1.2 cm between parts that move along each other. In the winning concepts this problem exists around the cranks. The top figure of Figure 39 shows with red arrows the two parts that move along each other within the critical distance of 1.2 cm. Initially it was tried to widen the distance, but this increases the Q-factor (the distance between both cranks) severely, reducing the comfort of cycling.

Then an idea was presented that had already been used in previous Lode cycling ergometers: a circular plate crank. The longest outer part of the crank which is connected to the pedal is replaced by a turning circular plate. It is shown in lower figure of Figure 39.

This solution is necessary but comes with advantages as well as disadvantages.



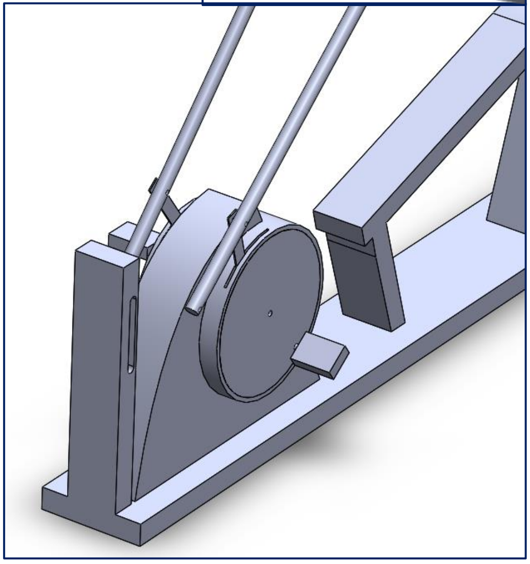


Figure 39: Upper picture showing the two parts that move alongside each other within the critical region of 1.2 cm. Lower picture showing the solution with a circular plate crank.

**Advantages**

- Saver look: not only is the scissoring problem solved, also the complete mechanism is shielded of. This looks compact and save.
- Separate arm and leg motion. In this model both crank parts turn around the central axis. Increasing the length of one of the two cranks does no longer affect the other crank.

**Disadvantages**

- The housing needs to be cut. Cutting does not necessarily increase the costs, but the special circular crank and the widening of the housing does increase costs.
- Space: the widening of the housing increases space. With the concept shown in Figure 39 this will cause no problem. But with the variation on this concept with the arm levers placed between the chair and Angio this might become a problem.

The part connecting the arm and lever motion, the part indicated by the upper red arrow in Figure 39, needs to move through the housing. This gap should be made a small as possible and preferable some rubber should be placed in there, preventing anything to fall or slide in during the motion.

## 5.3 Horizontal Push-Pull Concept 2 (Variations)

As already mentioned a new variation of the winning concept was came up with during the selection procedure: horizontal arm levers instead of angled (slightly vertical). This would increase the motion of comfort since it was assumed to be less stressful for mainly the shoulders. It was concluded that a small research would need to conclude whether this is variation is more comfortable. Because this variation has some downfalls over the original idea:

- The arm levers are put closer to the chair, blocking the instep almost entirely
- Complicated arm lever shape. It most likely has to be similar to this in order for the legs to be able to move around it reaching the pedals, and for the arms to be able to reach it.

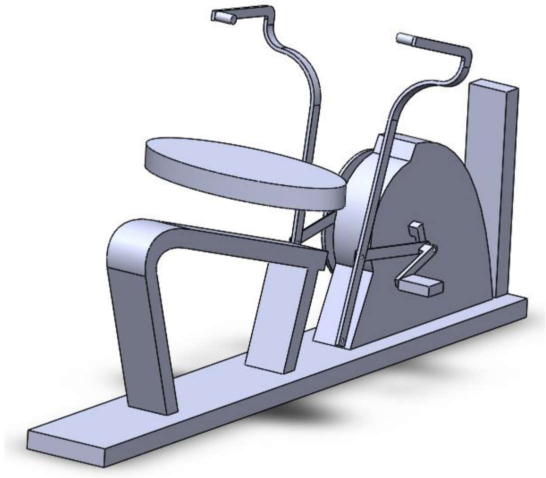


Figure 40: The Horizontal Push-Pull Concept 2, a variation on the winning concept. The arm levers are put between the chair and the Angio system, the arms of the user will now make a more horizontal movement. This is assumed to be more comfortable.

A second variation was also came up with but it may be more practical for a quick prototype, see Figure 41. Because with this variation a standard crank can be used. Making the special crank from Figure 40 is quite difficult on short terms.
The downfall with this variation of Figure 41 is the transfer of the forces delivered from the arms levers onto the cranks. It is not very direct and may be inefficient. Also due to inefficiency it may be heavy for the material. Still this idea might be useful for a quick prototype in order to test the comfort of motion of the whole concept due to the relative ease of production.

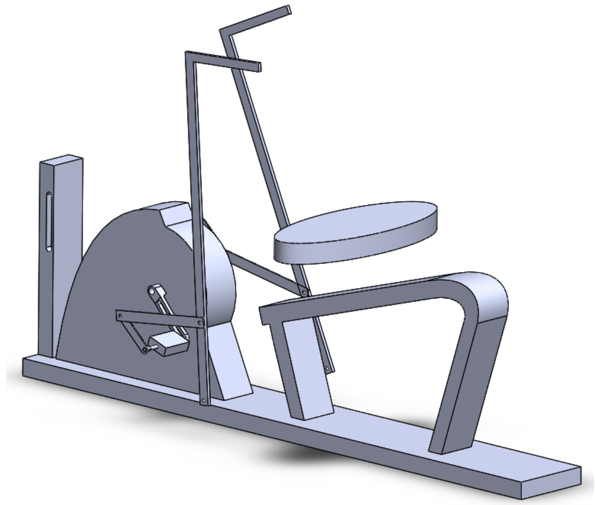


Figure 41: Another variation upon the winning concept, which may be more usefull for a quick prototype since it uses the standard crank.

## 5.4 Comfort Test

Initially, it was planned to build a prototype in order to find out which type of arm motion is the most comfortable: more horizontally or more vertically. A cross trainer was bought to transform into a prototype. There appeared to be not enough time. In order to still find an answer the cross-trainer was just turned around and placed at different angles via the primitive use of pallets, as shown in Figure 42. Our goal is to answer whether people prefer a more horizontal or a more vertical arm motion. We also make an attempt to calculate the arc that is the most universally comfortable. This might also become a region in which several arcs are universally comfortable.

Figure 42: One of the first setups in the arm motion comfort test. In this setup the users has to move his arms almost vertically.

Several colleagues performed the arm motion at different angles and positions. In Figure X for example you can see a different setup compared to the one of Figure X. Subjects were asked to rate every setup, with a grade between one and ten. Around 15 different setups were mainly used, based on the preference of the subject. All subjects were filmed for several motions on each setup in order to calculate relevant angles and lengths afterwards, see Figure 40.


Figure 43: Subject with his arms fully stretched (left) and fully bent (right) for a specific setup. Also showing angles and distances that were calculated.

The horizontal and vertical distance of the hands were calculated when the arms were fully stretched and fully bent, showed in Figure 40 on the left and right respectively. Their positions were calculated relative to the point where the chairs base and backrest intersect, see the red dot in Figure 40.
The length of the lever in the middle was used as a reference, its real length was measured beforehand, being 72 cm. An open source program called Kinovea was used to calculate the angles and distances in the videos recorded. Added in with red lines, for clarity, is how the angle of the upper arm was calculated.
At this points the downfalls of the test should be mentioned. First of all the large amount of setups could confuse the subjects in their judgement. Next, the accuracy of the measurements was not very high due to the use of a low definition camera, the angle of the camera to the setup and the handwork that goes into using Kinovea. Still, relative distances can be more useful than actual distances and these relative distances should not differ too much from reality.

### 5.4.1 Results & Discussion

In an attempt to find a subjects most preferred setup we started with an in general uncomfortable setup and built up to the most comfortable one. In some cases this was clear whereas in other cases many setups in between were also experienced as (most) comfortable.
We obtain four graphs per subject: the horizontal (X) and vertical (Y) position of the hands when the arms are maximally stretched and when maximally bent. These four graphs are shown below for the first subject. Remember that these distances are relative to the chairs base and backrest intersection.

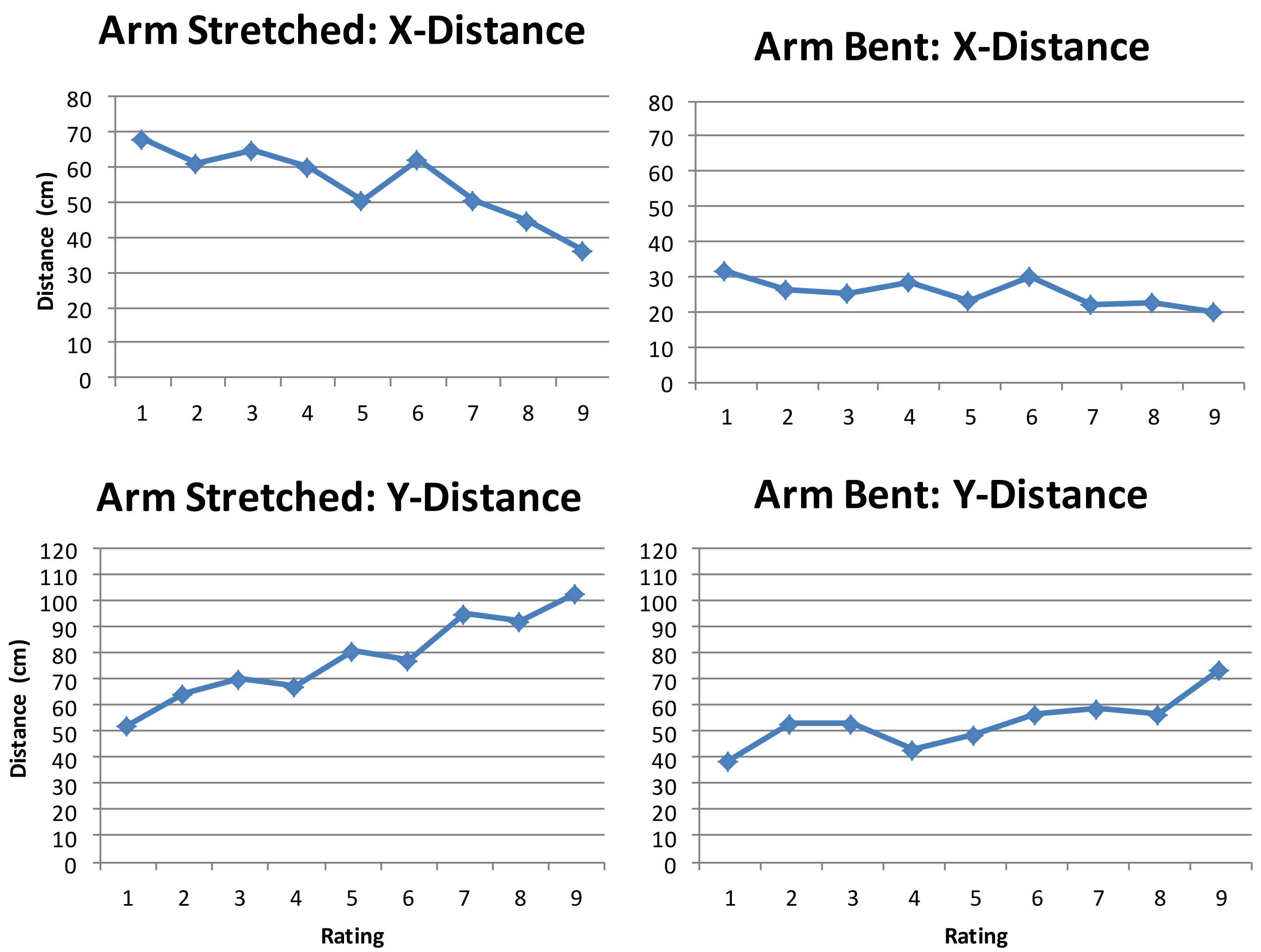



Figure 44: Graphs showing the horizontal (X) and vertical (Y) distance of the hands to the chairs base and backrest intersection point. These values can be used to calculate a person's most preferred arm motion.

These graphs can be used to calculate this subjects most preferred motion or arc. We can also calculate his least preferred motion. We can use just use the subjects best and worst values for this or we can calculate a regression line. We then use the best and worst value of this regression line.
These four graphs show consistent trends, calculating a regression line would make sense. For other subjects the trends could be different or less significant. This is also due to calculating average values when several setups were ranked equally. Calculating the average does not always make sense, especially not when angles and distances varied greatly. Yet, one cannot just choose one out of the equal rated setups and ignore the others setups. Taking the average is the least unfair option.

### 5.4.2 Horizontal versus Vertical

Below in Figure 42 we can see for 5 subjects their most preferred motion. Using the stretched X and Y value and the bent X and Y values we can calculate the ending and starting point of the arc respectively. The exact arc through these points is roughly estimated. The blue arcs are calculated based on the exact best rated values from for example Figure 41 and the orange arcs are calculated based on the best values from the regression lines.

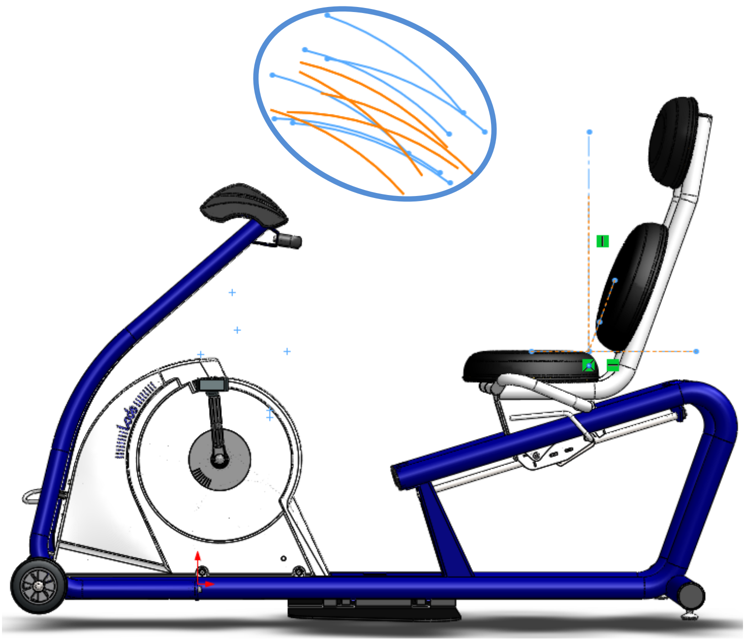


Figure 45: Sideview of the Corival Recumbent showing the most preferred arm motions of 5 subjects. In blue true distances are shown, in orange the distances are based on the regression line.

Next, in Figure 43 the best and least preferred arm motions are shown together. Only true values are used, so no on regression line based values. We can see that preferred arcs are far more horizontal than the least preferred arcs.

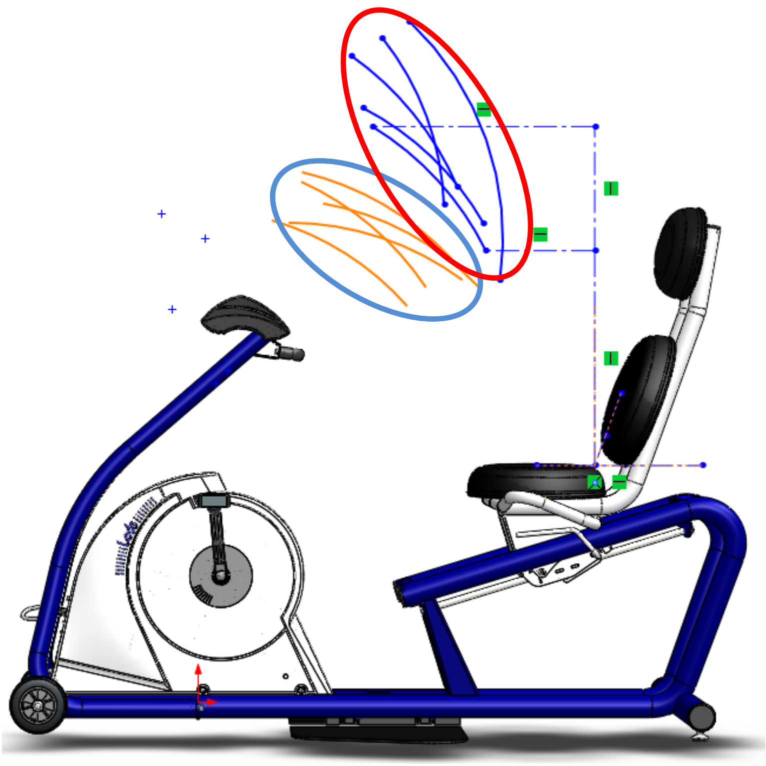


Figure 46: The most preferred arm motions of 5 subjects in the red circle and the least preferred arm motions in the blue circle.

In order to confirm whether subjects prefer a more horizontal movement we calculated for all their rated setups the vertical difference of the motion (ΔY). The more horizontal the setup, the lower ΔY. Figure 44 shows a graph of the 5 subjects showing their ratings and the corresponding ΔY. The lines shown are regression lines, with 4 out of 5 being significant. This means there is strong evidence that the more horizontal motions are preferred. The most horizontal motion still had a ΔY of around 10 cm, a ΔY of 0 could not be achieved. These results suggest that a complete horizontal motion would

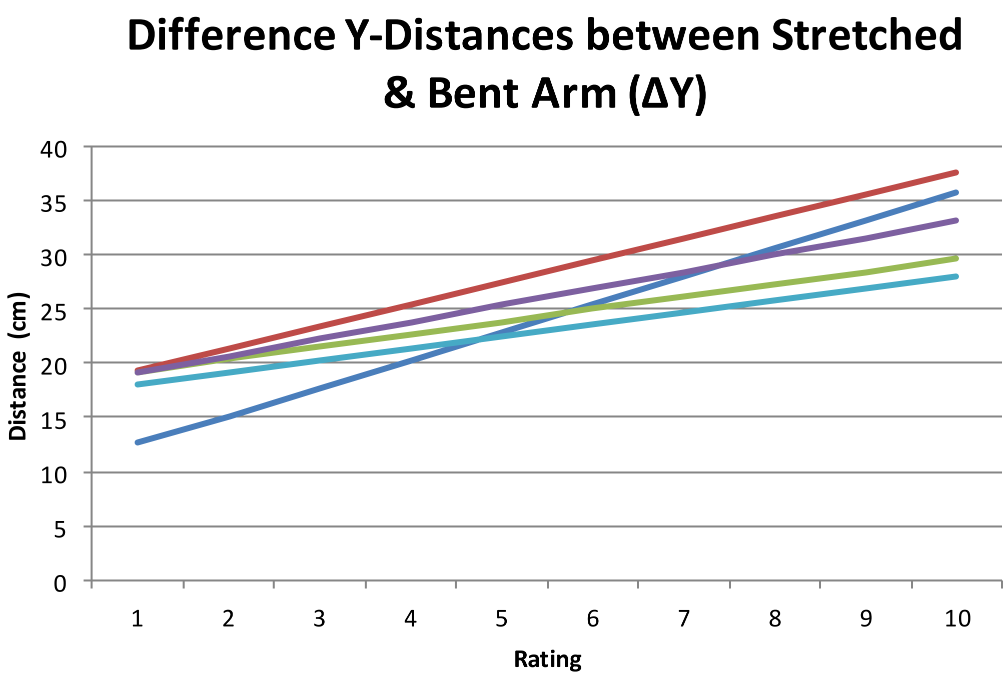



Figure 47: Graph showing the regression lines of 5 subjects showing their judgement relative to the difference in vertical distance (ΔY) of the arm motion.

be most preferred. This does not mean that a slight angle (slightly vertical motion) is always uncomfortable. We noted that the more a person leans back the more comfortable and practical a slight angle is.

### 5.4.3 Height, Depth & Length

Thus we now know that the arm motion needs to be horizontal or close to it. With the remaining information we can estimate the average acceptable height and depth of this motion: the X and Y position. These estimates give us an indication of how a prototype should be build. The exact values cannot be taken too precise because they are just an average and because of the downfalls of this small research already mentioned. A prototype can tell us how universal certain positions are and how many adjustments are needed to the height of the arm grips for different subjects.

The graph below shows us the most preferred height (Y-position) of six subjects and their corresponding body length when their arms were in the bent position. The lighter blue line shows the average, being 46,6 cm, which is what we will take as the height prescription. The results are shown in a graph to show that there is no correlation between the preferred (Y-) height and body length. This is most likely due to the mentioned downfalls and the small amount of subjects.
We only look at the X- and Y-distances in the bent position because this varied the least, compared to the stretched position, and people placed the chair in order to sit comfortably mainly in the bent position.

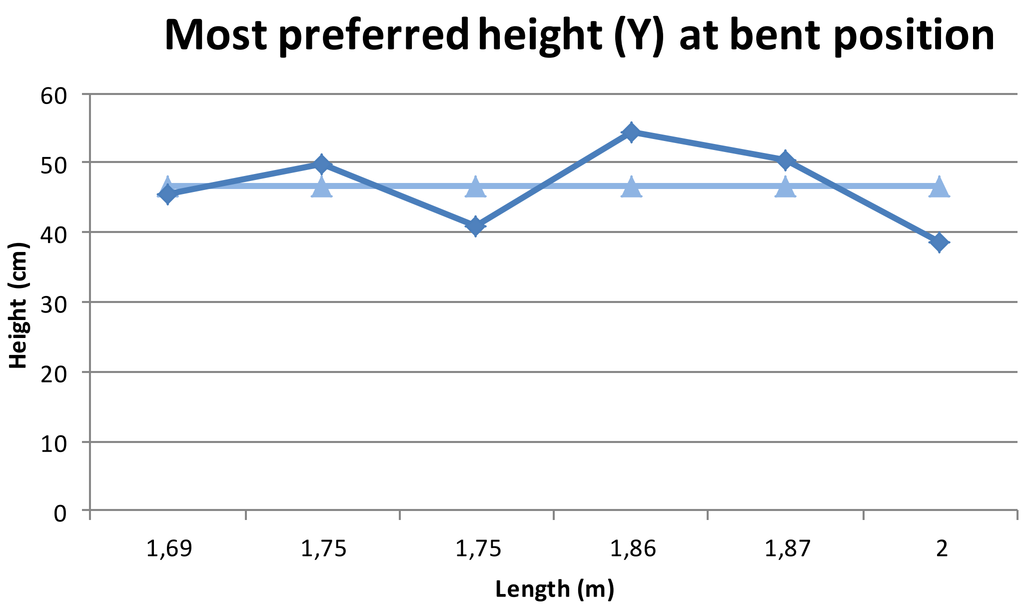



**Figure 48: The highest rated height distances of six subjects when the arms were in bent position. The lighter blue line shows the average, being 46,6 cm. There is no correlation between the height and the body length of the subjects.**

For the same six subjects we have the preferred depth (X-position), with an average of around 31,9 cm. This is shown in Figure 46. There is again no correlation between the body length and the preferred depth. One should actually look at the length of the arms instead of body length, but still there are not enough subjects to find significant data.

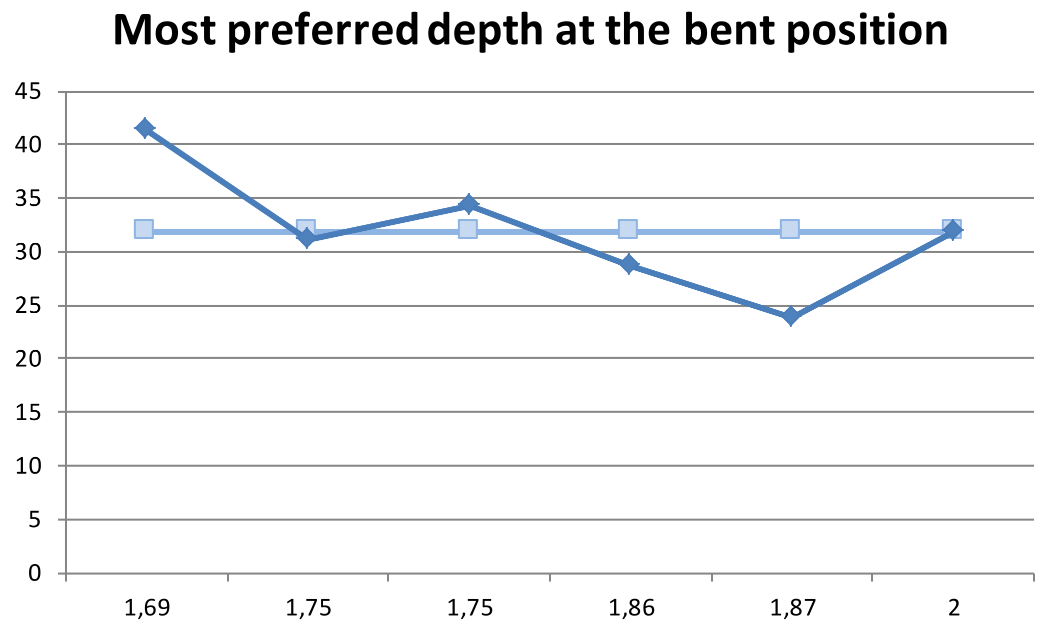



Figure 49: The highest rated depth distances of six subjects when the arms were in bent position. The lighter blue line shows the average, being 31,9 cm. There is no correlation between the depth and the body length of the subjects.

Last but not least we have to determine the strike length. Since subjects never performed an entirely horizontal motion we do not know whether the strike length used is also comfortable when completely horizontal. The strike length of the cross trainer is about 35 cm. On the Corival Recumbent the user sits still, the shoulders do not move. While in a cross trainer the user stands and mimics walking, where shoulders do move. Therefore with the cross trainer a bigger strike length is allowed. Still, a user can hold the grips are different heights, varying the strike length. For a prototype we stick to the measured 35 cm.

# 6 Prototype Building

At this point the internship had reached its end. I continued to stay at Lode to build a prototype. This in order to learn about the production of a product and in order to find out whether the proposed concepts could work. We will not go into too much detail about the production but try to mention the most important or most interesting steps. The use of the prototype gave a lot of information about the possible future product, this will be discussed at the end of this chapter.

## 6.1 Overdrawing the cross-trainer

The cross-trainer used in chapter 5 was originally planned to be turned into a prototype. We started off with vague ideas of how we could convert this cross-trainer into a recumbent-like design. Once a solid idea was there I started with overdrawing the relevant parts of the cross-trainer into SolidWorks. This helped me to understand how the cross-trainer was build and how these kind of components are made in general. For example, roller bearings are used in the cross-trainer and at Lode the general concept of the roller bearing was taught to me. It was after building the prototype and using the rolling bearings in it where I really became to understand its usefulness.

Though I could overdraw most simple parts, the roller bearings for example were a bit too complex to overdraw. Luckily, one can just download SolidWorks drawings from the internet and use these in your own designs.
We see the roller bearing on left in the combined picture below. It shows several other parts drawn in SolidWorks as well and their corresponding position in the cross-trainer.

The general idea was to shorten the parts indicated by the numbers 1 and 2 and to turn the part indicated by a 3 by 180 degrees. The remaining parts without an arrow were not used.

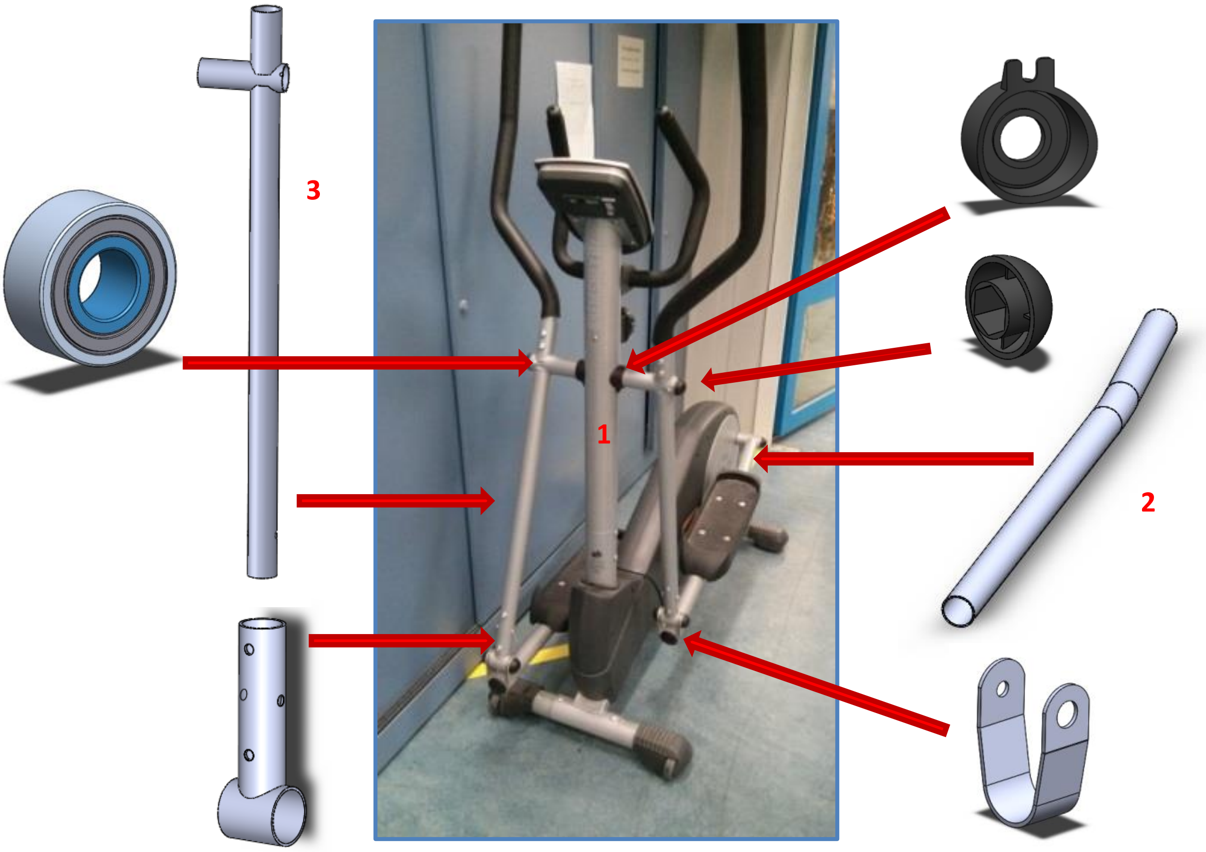



Figure 50: The cross-trainer used for the making of the prototype. Also showing several parts overdrawn in SolidWorks and their corresponding position in the cross-trainer.

## 6.2 Designing and building the prototype

We now show you the end design of the prototype in Figure 51 so that you can relate the parts that we will be discussing to the rest of the design. You can see how the parts indicated by a 1 to 3 have been changed compared to these same parts as shown in Figure 50.

First of all in Figure 51 we see the addition of the Angio system. A Solidworks model was of course already present at Lode and the Angio model was used to design around. Besides modifying the parts 1 to 3, we also created new parts, these are shown in red in Figure 51. We will discuss these parts soon.

Also to add, a base was designed to hold everything together. It appeared to be too weak as it is shown here and it was thickened during production. This was not drawn in Solidworks but will be shown later on in real life pictures. We first shortly discuss the modifications.

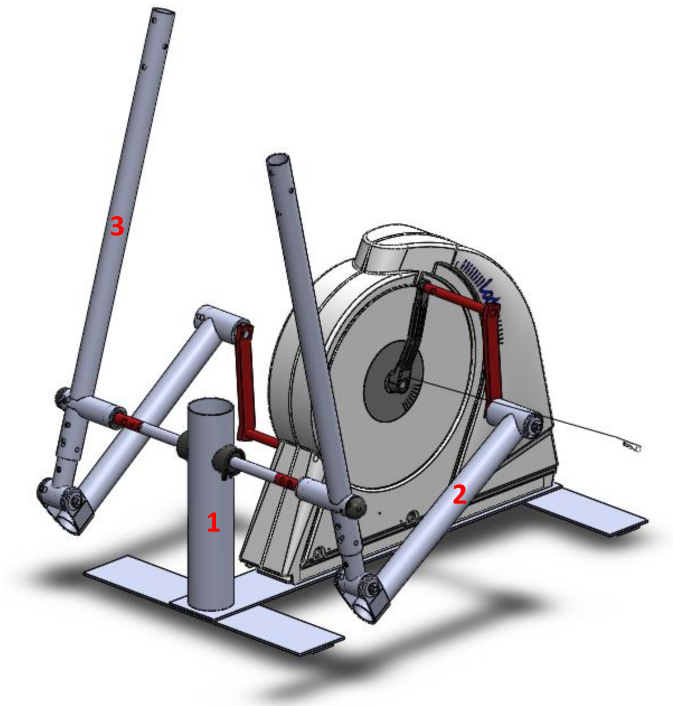



Figure 51: The almost end design of the prototype drawn in SolidWorks. The parts indicated by 1 to 3 have been modified, their old shapes can be seen in Figure 50. The red parts are newly created parts for the prototype.

### 6.2.1 Modifying parts 1,2 and 3, and the base

The arm levers (part 3) from the cross trainer were not modified but only used in the opposite direction, the top and bottom are switched.
Part 2 was only shortened. But in order to do that the small axis on the back had to be cut loose first. Then half a circle was cut out in the middle of the bigger tube and the smaller axis was welded onto it again.
The main frame (part 1) was only disconnected from the rest of the cross trainer and horizontally cut using a flex machine into this shortened shape. It was then welded onto the base.
The base in this state was built by using three beforehand cut plates which were welded onto each other in the orientation as shown. Holes were cut for screws which allowed the Angio to be screwed

onto the base. As already mentioned, the base frame was made stronger later on. This was done via the use of bigger tubes instead of the thin plates.
The modifying of the parts was the most time consuming compared to the creating of the new parts, which were simple spindles. Also the strengthening of the frame took more time as well as the fine tuning. This to give a rough idea of the time management.

### 6.2.2 Spindles (one example)

Six axises, or spindles, were created for the prototype. We discuss one as an example for the rest. The red axis connected to the main frame (part 1 in Figure 51) is shown in Figure 52. There are two of them connected to the main frame, both holding their own arm lever (parts 3 in Figure 51).

This relatively simple part helped me to understand the production of these kind of parts in general. The way these parts are drawn in SolidWorks are related to how they are made in production. Spindles are made in a lathe which spins the spindle. By holding the spindle against a stronger cutting part, several parts of the spindle can be cut out, in 360 degrees. Therefore in SolidWorks most dimensions of a spindle are displayed in diameters or radii.

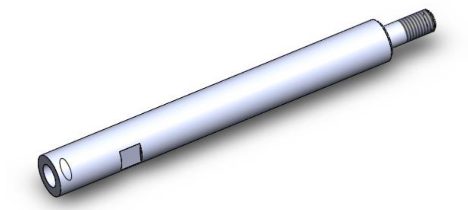


Figure 52: One SolidWorks model of an axis used in the prototype. In Figure 52 it is the red part connected to part 1.

This spindle contains a thread on the left and right side. The left thread is cut inside so that the spindle can be attached onto another thread. The thread on the right allows other parts to be connected onto the spindle. Since the diameters of both threats are equal, more of these spindles can be attached to each other.

If drawn properly in SolidWorks, the program allows you to make a sketch of the part which can be used by those who need to produce the corresponding part. Figure 53 shows the sketch of the spindle, with all the relevant dimensions shown in the upper left part of the figure. On the lower left you can see the whole paper that is printed and given to the producer, the one that uses the lathe. The paper contains the name of the part, name of the creator, the dimensions and scales used, the date and often the material that is used. On the upper left you can the dimensions of the diameters and most often the depth of threads. Since the lathe cuts 360 degrees around the spindle, or inside, the most relevant dimensions are the depths of these cuts.

This spindle was created twice. For the prototype two more doubles of spindles were made. It is not a time consuming process, the making of the six spindles took about two hours.

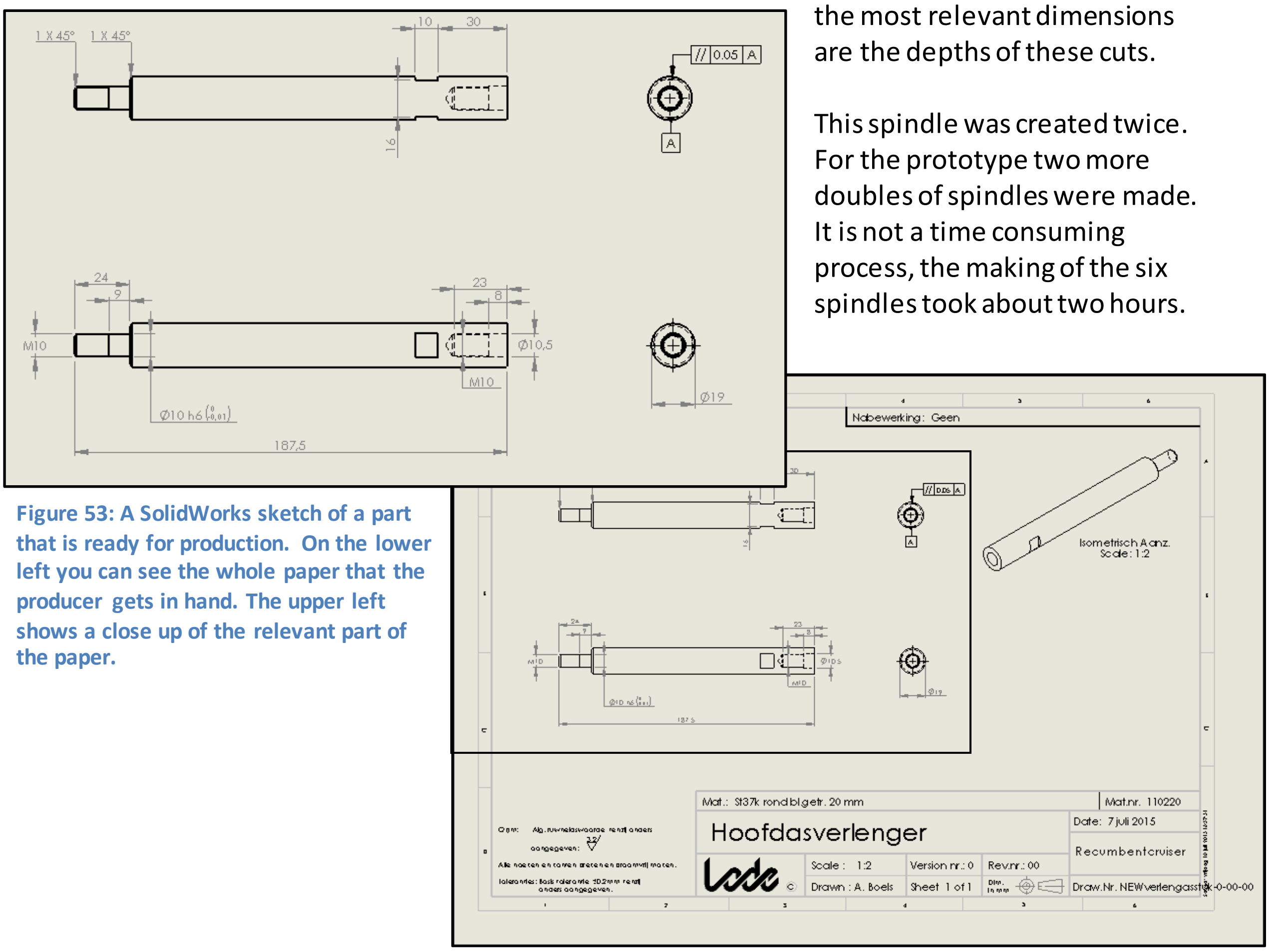



Figure 53: A SolidWorks sketch of a part that is ready for production. On the lower left you can see the whole paper that the producer gets in hand. The upper left shows a close up of the relevant part of the paper.

### 6.2.3 Cranks and phase difference

While the Angio system could remain the same in the prototype the cranks could not, new cranks had to be made. In standard vocabulary the crank was the part connecting the pedals to the driving system. Due to the attachment of extra parts to the crank the word crank now refers to more. Figure 54 shows what the crank consists of now.

In the prototype and possibly in the end product the cranks need to fulfill three extra functions in addition to their current function:

1- Connect the motion of the feet to the motion to the arms. In chapter 5 we discussed an inside and outside approach for this connection, where the inside approach resulted in a scissoring effect. The outside approach is used in the prototype due to the use of th e cross trainer. The cranks now need to direct the force to the outer sides (from part 1 to 3 in Figure 54).
2- Introduce a phase difference between the arm and leg motion. This is needed for comfortability. We will see this in more detail soon.
3- Reduce the circle diameter of the parts connected to the arm levers in order to maintain the right ratios.

#### 6.2.3.1 *Crank production*

The end result of the crank is shown in Figure 54. The black original 'crank' is the one used in the Recumbent. It is used in the new crank as well.
Part 2 is the only part not made at Lody, it was laser cut by another company, which was faster and cheaper. It was originally planned to weld parts 1,2 and 3 to each other and then to screw part 1 into the original crank. Yet this appeared not stable enough and the original crank was also welded onto the rest.

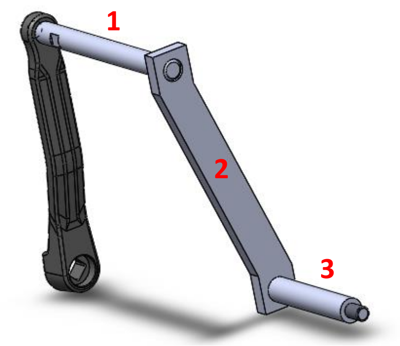



Figure 54: The crank used in the prototype. All four parts are welded onto each other.

Note: The orientation of the parts has to be maintained exact and a screw thread can lead to differentiations. A counter screw is a suitable idea for an end product.
Also the shape of part 2 was often received as weird by those who saw it. It was made this way so that the horizontal parts could be aligned parallel to the original crank, which automatically results in the correct orientation.

#### 6.2.3.2 *The phase difference*

Figure 55 explains function two and three of the crank: the phase difference and the diameter reduction of the circular motion. It is all caused by the placement of axis 1 compared to axis 3 from Figure 54. Part 2 causes this orientation.
In Figure 55 you can see that part 3 from Figure 54 is brought 45 degrees forward relative to part 1 from Figure 54.
Part 3 is also brought closer to the original axis of the Angio, leading to the smaller diameter of circular motion of part 3.
You can see the real prototype in this orientation in Figure 57 on the next page.
It is also very important to note that other phase differences are possible by changing part 2 of Figure 54.

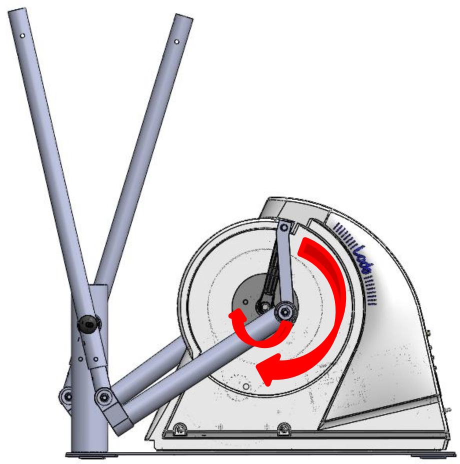


Figure 55: This figure shows the phase difference and the diameter reduction of the circular motion, both introduced by the use of the cranks.

## 6.3 Final prototype and conclusions

Before we draw our conclusions and propose suggestions we first show you the end shape of the real prototype and summarize the small improvements it underwent concerning the dead moment and the appearance.

### 6.3.1 Fine tuning towards the end prototype

The first time all the modified and produced parts were connected made the first prototype state. It was not solid at all and users could not easily use the prototype. There was a lot of open space causing a heavy dead moment during cycling. At this dead moment the user had to put his leg in an uncomfortable position in order to move the crank forward.
Figure 56 shows the orientation of the cranks when the dead moments occurs. The lower the user sits the easier it is for him to move the crank forward, at this specific orientation. Much fine tuning was needed to remove the dead space and in the end the dead moment problem was reduced drastically, still noticeable though but acceptable.
The fine tuning included enforcing the base frame, improving the alignment of parts and adding better roller bearings to the prototype.
The dead moment still occurs but some solutions were made up already which will be discussed soon. It also appeared that practice helped to work around the dead moment. The timing of pushing the arm levers is important, if done properly the dead moment is hardly a problem.

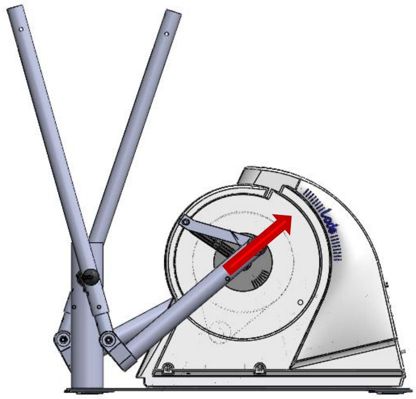


Figure 56: Side view of the prototype showing the moment the problem of the dead moment occurs. At this moment the crank will not easily move forward via the use of the arm levers only.

Below in Figure 57 we see the end result of the prototype in real. Noticeable additions are the stronger base frame, the pedals and elongated arm levers with a rubber grip.
The pedals were 3D printed and added at the last moment. It is useful as well as good looking. It was made such that a feet grip could be added as well. These help the user to lift the pedals up when they need to go upwards.
The elongations of the arm levers was needed and allowed the user to sit back during exercise which is much more comfortable. The levers are now closer to the user.
The base frame is much thicker in the end state, the Angio hardly wobbles. It only looks a bit clucky.

Figure 57: Pictures of the end state of the prototype. It was used in this configuration with the chair in front. Note the addition of the bigger base frame, the elongation of the arm levers and the addition of pedals with feet grip.

The last thing we show here before we go to the conclusion are the two configurations used with the prototype: the rowing like configuration and the cross trainer like configuration. Several people preferred different configurations and it was not conclusive. Summarizing the advantages and disadvantages:

### Rowing configuration

**Pro**

- Most similar to the motion of the cruiser
- Equal force distribution for the arms
- More motion with the whole torso (maybe causing a bigger $VO_2$ effect)

**Con**

- Less intuitive motion
- More motion with the torso (could be less comfortable on the long term)

### Cross trainer configuration

**Pro**

- Intuitive motion
- Stable position during exercise (less torso movement)

**Con**

- Unequal force distribution for the arms
- Turning of the butt during exercise (could be less comfortable on the long term)

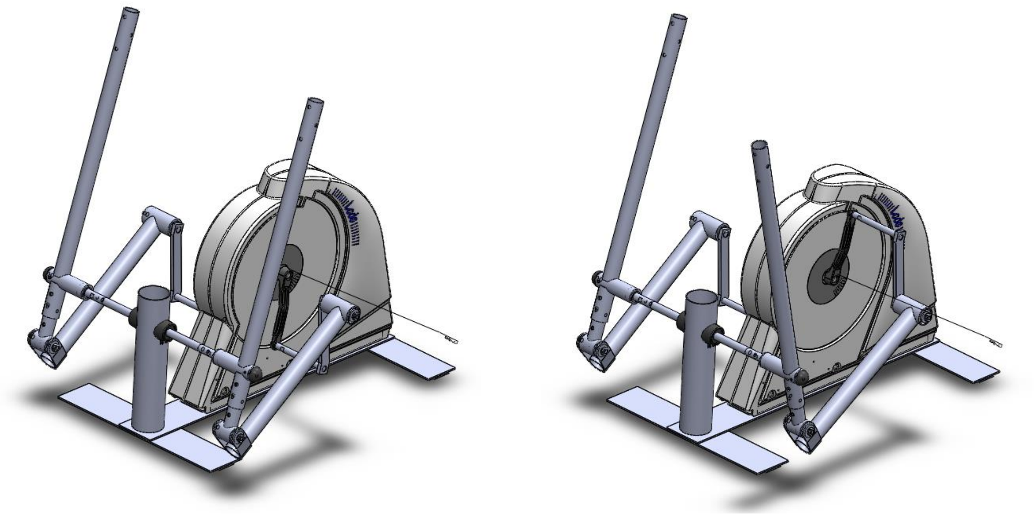


Figure 58: Left: rowing like configuration. Right: cross trainer like configuration.

We see that the same points can be seen as both pros and as cons. It depends on the preferences of the user. This means that the general preference should be investigated.
It should also be mentioned that other configurations are possible as well, especially when other phase differences are used. In the rowing configuration the arms are a quarter of a phase in front of the legs. In the cross trainer configuration both legs are half a phase separated from each other, the arms as well, the arms and legs differ by a quarter of a phase from each other. Other configurations include a 40/60 phase distribution instead of a 50/50 distribution.
**Note:** It is also very likely that it is comfortable if the user constantly pushes himself back into the chair and not pull himself out of it. If possible this should be maintained.

### 6.3.2 Conclusion

#### 6.3.2.1 *Potential of the product for one legged and normal users*

The most important conclusion is that the prototype was usable with one leg. The idea has worked out and has potential for people with an amputated leg. It would be of great value if a patient could come by and use the prototype. If patients would approve the idea it would be a very good reason to proceed with it.

The recumbent cross trainer or ‘rower’ can also have potential for normal users. The recumbent version of these products are not yet present on the market and it could be the first of its kind. The cross trainer is a widely used fitness apparatus for those uncomfortable with outside running. A recumbent version could be a first start for those with severe overweight, severe pains and other issues.

##### 6.3.2.1.1 Arm contribution

The biggest question for normal users is how much the arms should contribute to the total workout. It is a first question already how much they currently contribute because it is difficult to calculate due to the dead space. If possible to calculate, it should be estimated what is comfortable. Luckily, it is already useful when the arms slight contribute simply because of the face that users prefer to do something with their arms instead of doing nothing. This again increases the potential of the product.

#### 6.3.2.2 *Dead moment*

The dead moment is the biggest issue of the product. If removed almost entirely the product would have great potential. It is mainly relevant for the one legged users though. Users with two legs do not experience the dead moment.
It should first be evaluated by patients with one leg how they experience using the prototype. Maybe they learn fast and hardly experience any problems.
Still solving the dead moment problem improves the quality of the product. Reducing the dead space in the product drastically reduced the dead moment during the prototype fine tuning. Further reducing the dead space should reduce the dead moment even more. It is possible via the use of stronger materials and better alignment of some parts to do this. It also affected by the approach: the inside or outside approach mentioned in chapter 5. We will discuss these both approaches next.

It was opted to use a flying wheel which would keep the movement going once set in motion. This should solve the dead moment problem but introduces a potential danger issue, the arm levers will also not stop moving. These could hit the user or others.
**Note:** This danger issue could also already be present in the current prototype. It should be considered at forehand if this might become a serious issue.

#### 6.3.2.3 *Inside or outside approach*

The advantages of the inside approach is the better transfer of the forces, reducing the dead moment problem and the dead space in the system. The downside of this approach is that a scissoring effect is introduced. This most likely requires a special Angi o cap to prevent this from being an issue. It also a slightly more complicated idea to build than the outside approach, which we already know how to build. Lastly the inside approach limits the instep more directly than the outside approach. If not designed properly this instep would become a big problem.

The outside approach can also compromise the instep but most likely to a lesser extent. The outside approach also has potential for being disconnectable, making the arm levers an extra feature instead of a standalone product. If disconnectable, the instep would also be much improved. The downside of the outside approach is of course the worse transfer of the forces and the potential presence of dead space.

#### 6.3.2.4 *Future*

Before building a more definitive product Lode should evaluate the comfort of the prototype in its current state. Invite patients and asks their opinions. The prototype is a good point to move on from. Evaluated should be the comfort, the dead moment, the position of the arm levers (height and depth), the phase difference between the arm levers and pedals, the position of the chair and what else comes on the table.
Then the realization can begin and one should choose between the inside or outside approach. Of course it is not that black and white, one should design both approaches to see their real advantages and disadvantages. At the moment the outside approach seems to have the most potential.
If the outside approach is chosen one should keep focus on designing it with strength and good alignment between the arm and leg connection. Also the crank should be cleverly designed so that it can be easily produced. Making the arm levers detachable is a very nice addition pushing the product just over the edge, but it might also be just too much of the good.

This ends the report. The conclusion is mainly related to chapter six and thus to the prototype. This is the most relevant information for the product and for the company. If no prototype was made the conclusion would have included more about the previous chapters.

# 7 Acknowledgement

At forehand I would like to thank the following people for assisting me during the internship. First of all Jasper den Boer, my direct supervisor and manager of Umaco. He was always available for help and was very nice and easy to work with. He was passionate and could help thinking at the same level in order to give adequate advice. He was also able to not only assist with the project but also with my functioning as a person and pointing out relevant points for improvement.
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# 8 Bibliografie

B.V., Lode. *Corival*. sd. 9th February 2015. <http://www.lode.nl/en/product/corival/4/id_segment/3>.

B.V., ProCare. *Lode Corival Recumbent*. sd. 9th February 2015. <https://www.procarebv.nl/cardiopulmonair/product/lode-corival-recumbent>.

Bergh U., I.L. Kanstrup, B. Ekblom. „Maximal oxygen uptake during exercise with various combinations of arm and leg work.” *Journal of Applied Physiology* (1976): 41:191-196.

Billinger S.A., B.Y. Tseng, P.M. Kluding. „Modified Total-Body Recumbent Stepper Exercise Test for Assessing Peak Oxygen Consumption in People With Chronic Stroke.” *Physical Therapy* (2008): 88:1188-1195.

Blackie S.P., M.S. Fairbarn, G.N. McElvaney, N.J. Morrison, P.G. Wilcox, R.L. Pardy. „Prediction of Maximal Oxygen Uptake and Power during Cycle Ergometry in Subjects Older than 55 Years of Age.” *American Review of Respiratory Disease* (1989): 139:1424-1429.

Capellia C., L.P. Ardigò, F.S. & P. Zamparoa. „Energy cost and mechanical efficiency of riding a human-powered recumbent bicycle.” *Ergonomics* (2008): 51:1565-1575.

Dallmeijer A.J., L. Ottjes, E. de Waardt, L.H. van der Woude. „A physiological comparison of synchronous and asynchronous hand cycling.” *Int. Journ. Sports Med.* (2004): 25:622-626.

Egaña M., O'Riordan D., Warmington S.A. „Exercise performance and VO2 kinetics during upright and recumbent high-intensity cycling exercise.” *Eur. J. Appl. Physiol.* (2010): 110:39-47.

Faulkner J.A., D.E. Roberts, R.L. Elk, J. Conway. „Cardiovascular responses to submaximum and maximum effort cycling and running.” *Journal of Applied Physiology* (1971): 30:457-461.

Franklin, B.A. „Exercise Testing, Training and Arm Ergometry.” *Sports Medicine* (1985): 2:100-119.

Gleser M.A., D.H. Horstman, R.P. Mello. „The effect on VO2 max of adding arm work to maximal leg work.” *Medicine and Science in Sports* (1974): 6:104-107.

Johnson T.R., S.D. McPhee, M.S. Dietrich. „Effects of Recumbent Stepper Exercise on Blood Pressure, Strength and Mobility in Residentsof Assisted Living Communities: A Pilot Study.” *Physical & Occupational Therapy in Geriatrics* (2002): 21:27-40.

Lazzer S., D. Salvadego, S. Porcelli, E. Rejc, F. Agosti, A. Sartorio, B. Grassi. „Skeletal muscle oxygen uptake in obese patients: functional evaluation by knee-extension exercise.” *European Journal of Applied* (2013): 113:2125-2132.

Loftin M., L. Heusel, M. Bonis, L. Carlisle, M. Sothern. „Comparison of Oxygen Uptake Kinetics and Oxygen Deficit in Severely Overweight and Normal Weight Adolescent Females.” *J. Sports Sci. Med.* (2005): 4:430-436.

Loudon J.K., P.E. Cagle, S.F. Figoni, K.L. Nau, R.M. Klein. „A submaximal all-extremity exercise test to predict maximal oxygen consumption." *Medicine & Science in Sports & Exercise* (1998): 30:1299-1303.

Louhevaara V., A. Sovijärvi, J. Ilmarinen, P. Teräslinna. „Differences in cardiorespiratory responses during and after arm crank and cycle exercise." *Acta. Physiol. Scand.* (1990): 138:133-143.

Mayo J.J., L. Kravitz, J. Wongsathikun. „DETECTING THE ONSET OF ADDED CARDIOVASCULAR STRAIN DURING COMBINED ARM AND LEG EXERCISE." *Journal of Exercise Physiology* (2001): 4:53-60.

Nagle F.J., J.P. Richy, M.D. Giese. „VO2 responses in seperate and combined arm and leg air-braked ergometer exercise." *Medicine and Sciene in Sports and Exercise* (1984): 16:563-566.

Orr J.L., P. Williamson, W. Anderson, R. Ross, S. McCafferty, P. Fettes. „Cardiopulmonary exercise testing: arm crank vs cycle ergometry." *Anaesthesia* (2013): 68:497-501.

Pechar G.S., W.D. McArdle , F.I. Katch , J.R. Magel , J. DeLuca. „Specificity of cardiorespiratory adaptation to bicycle and treadmill training." *Journal of Applied Physiology* (1974): 36:753-756.

Quinn T.J., S.W. Smith, N.B. Vroman, R. Kertzer, W.B. Olney. „Physiologic Responses of Cardiac Patients to Supine, Recumbent, and Upright Cycle Ergometry." *Arch. Phys. Med. Rehabil.* (1995): 76:257-261.

Simmelink E.K., Borgesius E.C., Hettinga F.J., Geertzen J.H.B., Dekker R., van der Woude L.H.V. „Gross mechanical efficiency of the combined arm–leg (Cruiser) ergometer: a comparison with the bicycle ergometer and handbike." *International Journal of Rehabilitation Research* (2014): 00:000–000.

Simmelink E.K., Wempe B.J., Geertzen J.H.B., Dekker R. „Repeatability and validity of the combined arm-leg (Cruiser) ergometer." *International Journal of Rehabilitation Research* (2009): 32: 324-330.

Vestering M.M., Schoppen T., Dekker R., Wempe J., Geertzen J.H. „Development of an exercise testing protocol for patients with a lower limb amputation: results of a pilot study." *International Journal of Rehabilitation Research* (2005): 28:237-244.

Wilkins, Lippincott Williams &. *ACSM's Guidelines for Exercise Testing and Prescription*. American College of Sports Medicine, 2010.