Wrist Prosthesis

New Two Degrees-Of-Freedom Hydraulic Wrist Mechanism for Hand Prostheses

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Challenge the future

Wrist Prosthesis

New Two Degrees-Of-Freedom Hydraulic Wrist Mechanism for Hand Prostheses

by

M. N. Verleg

in partial fulfillment of the requirements for the degree of

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in

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Innovative Upper Extremity Prostheses and Orthoses

PREFACE

Although student life is great, for instance borrowing happiness from tomorrow during parties, let train delay influence the effort/reward graph of going into lecture, or experimenting with your biological clock, there comes a time where you look different at things or maybe look back, thinking: "Are you stupid?". This apparently is all part of the process. Needless to say it is still fun to do research for, but once the finish flag is in sight, you could say you grow up and want to finish and plant that flag. This opens a new world yet to be explored, so you can get paid for doing the same work, and do other fun stuff that you couldn't do before. Is this called growing up? For I remain a child at heart, and get excited throwing biodegradable stuff of the balcony so I can look at it falling to the ground. Even though I think I've grown up in the sense that I have acquired skills and obtained knowledge and wisdom so I can fool others thinking I am a grown up. Staying forever young is great, since it doesn't take much to be entertained, and you are in an overall happier mood, but having the prospect of new mind boggling adventures for the price of reaching the summit of this mountain, sign me up. I will probably realize shortly after it is the shortest mountain in the chain. Granting this chance of adventure to other people, especially with disabilities, is the noble thing to say. Which is part of what drove me to dive in the field of hand prosthesis and graduate on that subject. Finding mechanisms interesting enough to always wanting to know how it works, is probably what drives most engineers. I mean, I think I can say that every engineering student has disassembled and reassembled a click-pen more times during boring lectures than trying to lick their own elbow during restroom visits. Speaking of which, I'm going to wrap it up here.

But before I do, I have to thank a couple of people that have made this graduation and life experience a possibility. First off goes a thanks to my mom and dad. Thanks for having me ... figure out stuff on my own, play with this occasional ball of energy, and still muster the time to answer my infinite questions of "Why?". I have to thank my supervisor Dick Plettenburg for this wondrous expedition. A man of whom I have talked the ears off during our sessions of inspiration and guidance. A thanks to Jan van Frankenhuyzen, Hans, and Reinier for the help in and around the workshop. If it weren't for Henny van der Ster and Léon Roessen at DEMO, I would have had an imaginary mechanism with imaginary results. The next group of people have helped me by listening, taking my mind of my studies or other things in life, and being there as friends: Graham Nixon, Hidde Coehoorn, Marthijn Bontekoning, Eelco van Vliet, Jelle ten Kate, Linda Birken, Daniel Robertson, Michelle Dillewaard, Wouter Gregoor, Thijs Muskens, Jolanda Jacobs, Sander van den Broek, Lucas van Gent, Henk-Jan Bosman, and Frank Strooker (together with BJJ Gouda).

Thanks for making this all happen.

Malte N. Verleg
Delft, December 8, 2015

CONTENTS

INTRODUCTION

This chapter is intended as a brief introduction to the subject and a short readers guide for the rest of the thesis.

BACKGROUND

Throughout history mankind has tried to provide eligible hand replacements for people with an arm defect. One of the oldest known examples dates back to about 300 B.C. Since then many different designs were developed to aid people with a limb defect. Other recorded examples date back from medieval ages. But the most progress was made through aftermaths of war.

There are two main causes for limb loss, congenital limb deficiency and amputation. The latter can either result from traumatic injuries or diseases. The loss or absence of a limb is going to affect the efficiency in completing activities of daily living. A patient with a prosthetic hand regains some functionality. This is one demand of the patient/user for a prosthetic hand. Besides the functionality or control of a prosthesis, there are two other aspects in which the demands of the users can be categorized in, cosmesis and comfort. These are the aspects that always seem to return as points of improvement or important issues for attention.

A summary of the categories can be given as: **Cosmesis** is the appearance of the prosthesis, e.g. anthropomorphic natural look versus functional. **Comfort** is the user interpretation of comfort, i.e. is the prosthesis comfortable to wear, easy donning and doffing, not too heavy, comfortable operation. **Control** is desired to be intuitive, low mental workload, and natural looking movements while operating.

Figure 1: Visualization of body powered and externally powered control. Body powered prostheses utilize movements of other bodyparts, e.g. by means of a harness and a cable to harness the movements of the shoulder (in red), to control and power the prosthesis. Externally powered prosthesis use the muscle activity of unused muscles in the stump as signal inputs to control the prosthesis. These signals are picked up by myoelectric sensors (in purple). These prostheses obtain their actuation from an external energy source, e.g. battery or pressurized gas in a cylinder.

TYPES OF PROSTHESES

To continue the types and different control methods of prostheses are explained. There are two types of prostheses: passive and active prostheses. Passive prostheses are mostly used for cosmeses purposes, but in general lack the functionality of an active prostheses, since most don't have moving parts. Some passive prostheses have the ability to manipulate the hand (fingers or gripper). This is done with the other hand or an object.

Active prostheses are prostheses where there is a mechanism that can be manipulated while the sound hand is occupied. In other words active prostheses are capable of generating net power, where passive prosthesis are not.

CONTROL METHODS

There are two main prosthesis control methods for active hand prostheses, which are the body powered and the externally powered prostheses. Both are explained next. Note that there is a difference between the control and the way the prosthesis is powered. During this thesis the focus lies on the control of a prosthesis. The word powered is merely used since this is how most differentiate between the two types of prostheses.
Body powered control harnesses the movements of other body parts to control the terminal device. This method of control can be seen in Figure 1. In this picture the red strap around the shoulder is used to control the terminal device. By moving the shoulder forward or the prosthesis away from the body, the control cable will pull on the mechanism of the terminal device. This will then open or close the terminal device, whether it is a voluntary open or voluntary close mechanism.
Externally powered control, mostly referred to as myo-electric control (seen schematically in purple in Figure 1), uses EMG signals from muscles to control the terminal device. Two (or more) EMG electrodes pick up muscle activity as input signals for an externally powered prosthesis (mostly electric). The mechanism is then powered externally, the most common is with batteries.

Both control methods have their advantages and disadvantages. But in general, both control methods lack an active controllable wrist mechanism.

THE WRIST

While designing a prostheses, the three categories given earlier need to be kept in mind. From the preliminary literature study conducted it became clear that the motions and functionality of the wrist are desired by the users of hand prostheses, but are currently not provided sufficiently to satisfy the demands of the users.

With a functional wrist the terminal device can be positioned for various tasks, which appeals for more natural movements and improved overall functionality, but with more degrees of freedom to be controlled, the mental workload and difficulty increases to control the prostheses. This makes it less intuitive to control. Therefore, to research a sound control method for the control of multiple degrees of freedom, a prosthesis is needed that can offer the requirements needed of a prostheses to research this. So a wrist mechanism has to be designed. Therefore the goal becomes as follows.

RESEARCH GOAL

Design a mechanism that realizes the motions of the wrist for a hand prosthesis.

OUTLINE

The layout of this thesis is as follows:

PART I SCIENTIFIC PAPER describes the main part of the work done for this thesis in paper form. This paper can be read without having read the introduction or literature study. Appendices are included in this part.

PART II LITERATURE STUDY shows the preliminary literature research done for this thesis.

I

SCIENTIFIC PAPER

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New Two Degrees-Of-Freedom Hydraulic Wrist Mechanism for Hand Prostheses

Malte N. Verleg

Abstract—Since there is a lack of functional active two degree of freedom wrist mechanisms for hand prostheses, one is designed in accordance to the needs of the user, such that it can be provided with hand prostheses and used by patients. A list of requirements is used to design a wrist mechanism, after which the prototype is tested to validate the design compared to the requirements. This is done with a test setup where, among others, torque and position of the mechanism are measured. A hydraulic vane cylinder is chosen as the rotation mechanism for both degrees of freedom, but only one degree of freedom is fabricated and tested as a proof of concept. The vane cylinder leaked and could not muster any significant torque. This leaking is probably caused by scratches in the surface of the cylinder wall. Other requirements could be validated despite this setback. The range of motion for instance could be achieved, only the stroke of the master cylinder had to be increased due to the compression of air. The weight, $21.2\,\mathrm{g}$ for the fabricated working mechanism, and dimensions, $20.7\,\mathrm{mm}$ height and $30\,\mathrm{mm}$ diameter, of the mechanism have also been met. It can be concluded that this hydraulic vane cylinder is a promising wrist mechanism to use in hand prostheses, because it is a small and compact design, but with the recommendation to have a precise fabrication with a smooth surface finish so that the vane cylinder is not leaking.

Index Terms—Wrist Mechanism, Hand Prosthesis, Hydraulics.

1 Introduction

LITERATURE shows [1], [2] that within the prosthetic world, comfort, cosmesis and control are returning aspects and need to be kept in mind for the development of hand prostheses. Although comfort and cosmesis are important aspects and will result in requirements, the focus of this study lies on the control of the prosthesis. Control of multiple Degrees Of Freedom (DOFs) hand prosthesis with an active wrist is a neglected aspect, although users still indicate that they desire more overall function, control, mobility and increased Range Of Motion (ROM) of the wrist [2]–[7]. This is partially due to the difficulty to measure mental workload [8], [9], which arises from the control of multiple DOFs. This also holds for hand prostheses with more than one DOF. After the terminal device (e.g. hand or hook) the motions of the wrist are desirable DOFs to be controlled actively. With a functional wrist the terminal device can be positioned for various tasks, which appeals for more natural movements and improves overall functionality. Most wrist units however, are passive controlled and some are incompatible with other types of prostheses. So to make it possible for users to have an adequate wrist unit on their prostheses, one has to be designed.

Looking at the desires of the user, the frequency of joint angles during activities of daily-living of a healthy wrist [10], and the mental workload regarding control of multiple DOFs, the conclusion is drawn that the mechanism be of two DOFs. Namely rotation and flexion, where flexion be distal to rotation in accordance to Carlson [10]. Another conclusion is that the mechanism is to be actively controlled by the user, this will give the best option for a functional prosthesis. These conclusions were drawn in the literature study conducted prior to this study. So the goal for this thesis is to **Design a two degree of freedom mechanism that realizes the motions of the wrist in a hand prosthesis.** This mechanism should meet requirements that, directly or indirectly, follow from the desires of the users.

It is found that there is not enough knowledge on the control of multiple DOFs for hand prostheses and mental workload as a result of the control of multiple DOFs, so an additional benefit of this mechanism is that a succeeding research of different control methods for a multi DOF hand prosthesis can be performed. The two most common ways to control a prosthesis nowadays are body powered control and myo-electric control. With the mentioned research another control method can be investigated and evaluated, a so called hybrid control method. This type of control, over multiple DOFs, is a combination of the two control methods mentioned before, and has not been developed or even looked into at all, and might give positive results for the control of multiple DOFs in hand prostheses. But this is something that is of concern in a later stage, after this mechanism is developed and tested properly.

1.1 Requirements

The requirements to get to a functional design are discussed next. The first two requirements are already described above just before the goal is mentioned. Namely that the mechanism consists of two DOFs **[R1]**, rotation and flexion, where flexion is distal to rotation. And the second requirement is the mechanism be actively controlled by the user **[R2]**.

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From a comfort point of view, it is desired that the prosthesis is as lightweight as possible. The prosthesis is not an integrated part of the body, therefore all the weight is suspended at the end of the residual limb, and has to be carried around as dead weight. So compared to the current commercial wrist products, the new design should not exceed their weight. It would be desired to be as low as $51\,\mathrm{g}$ (Table 7) **[R3]**. For a two DOFs active wrist that would be $180\,\mathrm{g}$.

TABLE 1: Existing wrist prostheses and their masses.

Company or Researcher	Mass [g]	Control and #DOFs
Hosmer [11]	105	Passive, 0.5DOF*
Kyberd [12]	200	Active, 2DOFs
Motion Control [13]	143	Active, 1DOF
Ottobock [14]	180	Passive, 3DOFs
	96-51	Active, 1DOF
Texas Assistive Devices [15]	168	Passive, 2DOFs
	180	Active, 2DOFs
Touch Bionics [16]	161	Passive, 1DOF

* *Quick release wrist*

For a natural look (cosmesis), the dimensions need to be specified. So the length and the circumference of the mechanism need to be determined. The mechanism is designed for a child of 4 years old. If a design is made for the smaller individual it is easier to be enlarged, rather than scaled down. It could even be so that down scaling is not possible at all.

Now let a 4 years child be half the height of an adult [17]. The average length of the forearm of adults is 300 mm [18] (length from elbow to palm). Assuming that the limbs are scaling equally, the maximum residual forearm length would be 150 mm. If the wrist mechanism is smaller, more amputees with a lower amputation level can use it as well. Half of the forearm length would be a good starting point. Thus a maximum length/height of 75 mm **[R4]** of the wrist mechanism would be desired.

The size of the mechanism is designed for a prosthesis for children. Thus the design should fit within a 30 mm diameter circle **[R5]**. This dimension results from the size of a child prosthesis' wrist and falls in the cosmesis category.

For both of these requirements, current available wrists are looked at, and can be seen in Table 2. The lowest values for the diameter and the height are both for a one DOF wrist prosthesis. Therefore the estimated requirement values can be used, since they are well below the other values (only the diameter).

TABLE 2: Existing wrist prostheses and their diameters and heights.

Company or Researcher	Diameter [mm]	Height [mm]	Control and #DOFs
Hosmer [11]	50.8		Passive, 0.5DOF
Liberating Technologies [19]	35-43		Passive, 3DOFs
	28.6		Passive, 1DOF
Motion Control [13]	47	70	Active, 1DOF

To further specify this design problem, other requirements need to be quantified and tested. Some of these requirements came from the preliminary literature study, the desired torque and the range of motion. The maximum achievable torque for adults on average is 15 Nm for both DOFs [20]–[23]. This means a mass of 15 kg is held at 0.1 m distance from the axis of rotation, which is quite a hard task for an adult, and let it be an incredible and unimaginable achievement for a child. So let us resort to scaling laws, where force (and torque) relates equally to surface area. Therefore relating it to the length it becomes $S_F = {S_l}^2$. Again the length of a 4 year old is half the length of an adult. Therefore the torque a 4 year old can exert is four times as low as an adult. Thus 15 Nm becomes 3.75 Nm **[R6]**.

The range of motion is something that does not need to be scaled down or up. Even though children are, in general, more flexible compared to adults, they are still humans and have the same limbs and movements. Therefore the value of 90° **[R7]** [10], [24]–[27], for rotation as well as flexion, is sufficient to use as a requirement for this mechanism.

During manipulation of the terminal device it can be imagined that it would be convenient if the wrist mechanism is locked in place. By doing so the focus can shift from the wrist to other tasks. This would result in a lower mental workload, since there are less DOFs to be actively controlled at that instant. Thus the mechanism should have an easy to lock function/mechanism **[R8]**. This would also mean, if implemented, that research, where control is shared between two DOFs, can be conducted. Because at any given time, one of the two DOFs has to be locked in position. So the other DOF can be manipulated. The last indirect requirement is a mechanism that can be used with different control methods **[R9]**. Thus switching between control methods has to be incorporated in the design, and should not be hindered by the mechanism itself. This last requirement is especially important for future research. With easy switching, research can be conducted on different control methods for a multi-degree-of-freedom active controlled prostheses.

To summarize the following list of the requirements is made:

- **[R1]** Two degrees of freedom: Rotation & Flexion
- **[R2]** Active controlled
- **[R3]** Maximum weight of $51\,\mathrm{g}$ ($180\,\mathrm{g}$: active, 2DOFs)
- **[R4]** Length of maximum 75 mm
- **[R5]** Fit within 30 mm diameter circle
- **[R6]** Maximum torque of 3.75 Nm
- **[R7]** Range of motion of 90° for both DOFs
- **[R8]** Lockable mechanism
- **[R9]** Possible to switch between control methods

These requirements are used to design a wrist mechanism for a hand prosthesis. From a cosmesis and comfort point of view it is desired that the design is to be as small/compact and light as possible.

2 METHODS

The design started out with a broad view of the problem and requirements. During the design process calculations were made and are shown within the appendices. These are preliminary theoretical results and are used to compare to the measured results (Results 3) to validate the design (Discussion 4).

In the next part the design process and the preliminary results are described, where the formulas and calculations can be found in the Appendices.

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2.1 Hydraulic Transfer Medium

Several principal mechanisms were considered for the design of the prototype. For instance mechanical, hydraulic, pneumatic and electric. Table 3 shows a first impression summery of the advantages and disadvantages of the different transfer media.

TABLE 3: First global impression for transfer medium considerations. The advantages and disadvantages of different transfer media are listed here.

	Advantage	Disadvantage
Mechanical	Simple	Challenging geometry
		Challenging locking
Hydraulic	Simple locking	Sealing (Leakage)
	Simple switching control methods	
Pneumatic	Simple locking	Compressible
	Simple switching control methods	
Electric	Functionality (programmable)	Switching control methods needs conversion
		Heavy actuators
		Batteries needed (heavy)

A mechanical design has the advantage that it has a relative large amount of design options. But it is pretty difficult to lock in place. Not that there are locking mechanisms of difficult designs, but it will increase the size of the mechanism considerably. A hydraulic mechanism has the advantage of an easy locking mechanism [28](stopping the hydraulic fluid from moving, locks the system), and it is fairly easy to switch between control methods, since there is no conversion needed for the actuating cylinders driving and controlling the mechanism (mechanical and electrical cylinders are available). A disadvantage is that leakage always occurs, be it very little, but it might cause trouble in the long run for body powered prostheses (closed system). A pneumatic system has the same advantages as a hydraulic system, but it has a big flaw. Air or another gas is compressible, and this is something that cannot be used in body powered prostheses, because it is a closed system. Therefore a pneumatic transfer medium drops out. The last is an electric transfer medium. The disadvantage of this kind of transfer medium is that it uses heavy actuators and batteries to power the mechanism. But the biggest disadvantage is that conversion is needed to give feedback to the operator.

So the conclusion is drawn that a hydraulic mechanism would already satisfy some requirements, and would therefore be the primary choice of transfer medium. Mechanical designs are the secondary choice since it gives different options while designing, and they probably cannot be denied, since eventually a mechanical movement is desired. Therefore it will be used as an addition to the hydraulic system.

Three promising hydraulic concepts are chosen. All have a cylinder or something similar that is sealed with o-rings. Choosing an o-ring seal keeps the concepts relatively simple, since no difficult sealing principles need to be utilized.

The first concept is a curved cylinder (Figure 1a). This concepts uses the flexibility of the hydraulic fluid to establish the desired rotational motion. This way no mechanical conversion is needed to convert linear to rotary motion. A mechanical arm is needed to transfer the force from the cylinder to the rotation axle. The work plane of this arm has to be kept empty so the mechanism can rotate.

The second is a cylinder attached to a rack and pinion (Figure 1b). Here a mechanical transmission is used to obtain the desired rotary motion. It is a good example of a hydraulic transfer medium with mechanical parts.

The last concept is a vane cylinder (Figure 1c), where the piston is non cylindrical and positioned above the rotary axis. The same applies for the vane cylinder as for the curved cylinder, no mechanical conversion is needed, since the transition from linear to rotary motion is achieved by the fluid.

All these concepts are so called slave cylinders, and are controlled by the user with a master cylinder. The exact control method is a choice the user has to decide on, or the research on control method mentioned earlier can give an answer in the future.

Calculations were made for these three concepts (Appendix A). The results of these calculations can be seen in Table 4. Generic formulas were used for these calculations, for the pressure, internal forces, volumes and torques (Appendix A).

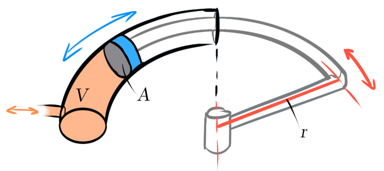
The force and stroke applied by the master cylinder is set to $50\,\mathrm{N}$ and $50\,\mathrm{mm}$ for the first calculations, which are reasonable values for a body powered prosthesis. Then the surface area (and diameter) and the moment arm are determined, such that the results of torque and range of motion of all the concepts are similar to one another. As can be seen in Table 4 all three concepts have similar results for torque and range of motion from the Matlab calculations (seen in Appendix A). The next step is to compare the dimensions of the three concepts. From Table 4 it can be seen that only the vane cylinder could fit within $30\,\mathrm{mm}$ diameter **[R5]**. The curved cylinder will come outside the boundaries of $30\,\mathrm{mm}$ since the diameter and moment arm together are greater than half the requirement **[R5]**. The rack and pinion cannot be seen right away, but what it comes down to is that the cylinder either lies outside 30 mm diameter or there is not enough space for the rack to be inside the $30\,\mathrm{mm}$.

For the vane cylinder and the rack and pinion the axle could lay off-center. This would make the rack and pinion fit within the $30\,\mathrm{mm}$. But comparing the two still would give the vane cylinder an advantage, since it would still be smaller having a height of $5\,\mathrm{mm}$ compared to $7\,\mathrm{mm}$.

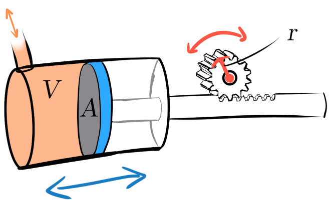
The biggest advantages of the vane cylinder are that it is operating at only half the pressure and its utilization of the available space. Both the curved cylinder and the rack & pinion have more empty space within their dimension boundaries than the vane cylinder.

TABLE 4: Results from Matlab for the three different concepts. The variables can be seen in an illustration in Figure 3. The dimensions are that of the cylinder itself, the overall dimensions of the mechanism are different.

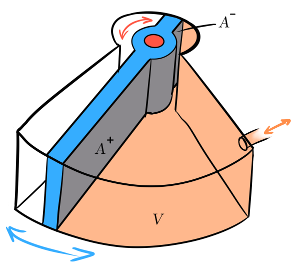
	Curved Cylinder	Rack & Pinion	Vane Actuator	
Activation Force; F_c	50	50	50	[N]
Stroke; x	50	50	50	[mm]
Diameter Master	3	3	7	[mm]
Dimensions Slave	$d = 5$	$d = 7$ [x2]	$h = 5$ $l_1 = 16$ $l_2 = 7$	[mm]
Moment arm; r	12.5	3		[mm]
Results				
Max. Torque; T_v	1.74	1.63	1.63	[Nm]
Max. Range of Motion; φ	82.5	87.6	88.0	[°]
Max. Pressure; p	70.7	70.7	31.4	[Bar]



(a) Curved Cylinder.



(b) Rack and Pinion.



(c) Vane Cylinder. The plus and minus indicate positive and negative relation of the areas to the torque. The leverage arms can be seen in Figure A.2

Fig. 1: Three different hydraulic concepts. V is the volume with hydraulic fluid, A is the surface area on which the pressure of the hydraulic fluid acts, r is the leverage arm of the torque.

2.2 The Vane Cylinder

The vane cylinder is chosen, because it is the most compact concept in comparison to the others. Revised calculations (seen in Appendix E, Listing 1) with more accurate variables (Tables C.1 and C.2), show that the results from Table 4 are less accurate. But with varying parameters of geometry, all three concepts get in the same range of torque and range of motion. Thus this decrease in performance would also hold for the other concepts. Therefore the vane cylinder is chosen, since it is the smallest design with similar inputs and outputs. The results from these revised calculations can be seen in Table C.3.

Although the concept is not meeting the demands of the torques while moving, it could hold if the system is locked. This has to be validated. The crucial factors are the seals, and the accuracy of fabrication. Both could add or subtract to the performance of the mechanism. Existing vane actuators have been found and picked out, Table 5. As can be seen the hydraulic vane actuators do not meet requirement **[R5]**. All the found vane actuators have quite a considerable length. If two were to be stacked together, in any configuration, the total mechanism would lay well outside the boundaries of requirements **[R4]** and/or **[R5]**. Especially taking into account that these are the bare actuators, so a lot more space will be taken for the entire wrist mechanism. Therefore the decision has been made to design a custom vane cylinder specific for the use as a wrist mechanism for hand prostheses, since it is presumed that it is possible to have a smaller functional design that does meet the requirements. The design can be seen Appendix B.

TABLE 5: Available pneumatic and hydraulic vane actuators.

	Pneumatic		Hydraulic	
	Festo [29]	Norgren [30]	Parker [31] (double vane)	Micromatic [32] (double vane)
Model	DSM-6-...-P	M/60280	HRN10D	MPR-1x.4
Diameter [mm]	29.4	29		35.5
Height x width [mm x mm]			55 x 55	
Length [mm]	48	46	95	51.6
Torque [Nm] (at bar)	0.15 (6)	0.15 (6)	3 (17.5)	0.23 (6.9)
Range of Motion (°)	90 & 180	90 & 180	90	100
Mass [kg]	0.045	0.04	1.0	0.10

The examined existing vane actuators require 5 to 6 seals for single vane and 7 to 8 seals for a double vane (the vanes and the stator both need one seal, the axle needs two seals, and depending on where the seam is, 1 or 2 seals are needed at the outer side of the cylinder), Figure 2a. Relatively large vane actuators use a different method of sealing, seen in Figure 2b. This would require fewer sealing locations. For a single vane 3 seals would suffice, so this strategy is implemented for this design.

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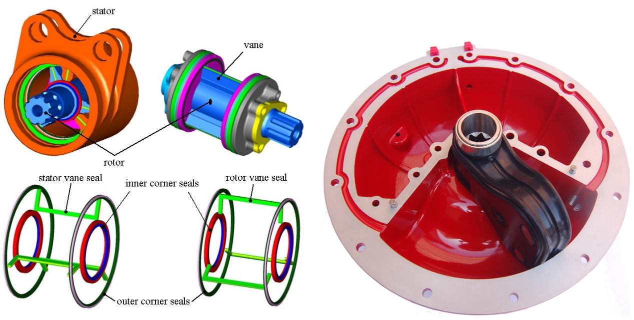

(a) An illustration of a vane actuator with 3 stators and 3 rotors (vanes) [33].

(b) A larger vane actuator with a different sealing method. http://www.easytork.com/products_eva.html

Fig. 2: Two different sealing strategies are shown.

2.3 Experimental Setup

One degree of freedom (rotation) is fabricated and assembled as a proof of concept, to test this vane cylinder as a working principle, on this scale. An experimental setup is designed such that the range of motion and torque can be measured and compared to the theoretical values.

Two modes will be tested: the first is where the vane can be moved (unlocked), and the other is where the vane is held in place, the locked state. This last mode is to see if the required 3.75 Nm torque can be resisted by a locked system. The desired units to be measured are that of the rotational angle (φ) and torque (T_v), of the vane cylinder, and the actuation force (F_c) and position (x) of the master cylinder. An illustration can be seen in Figure 3.

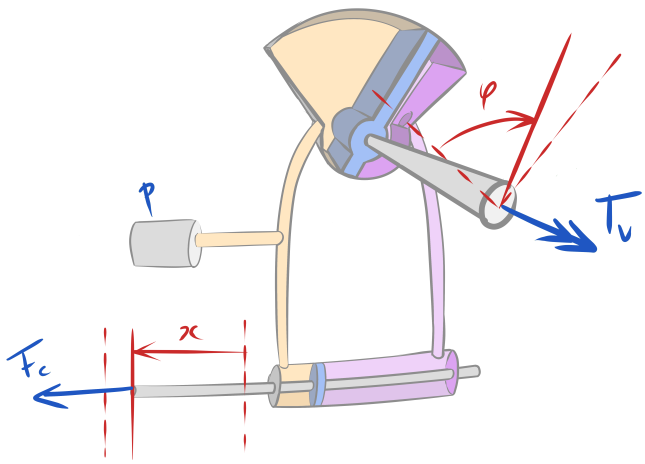

Fig. 3: Test setup of the vane cylinder attached to the master cylinder. Shown are the variable that are going to be measured. T_v is the torque on the axle of the vane cylinder, F_c is the force on the axle of the master cylinder, φ is the rotational angle of the axle of the vane cylinder, x is the linear displacement of the axle of the master cylinder, p is the pressure of the hydraulic fluid within the system

The following apparatus' are used:

Pressure sensor Thermotechnik DRTR-AL-10V-R60B. With a range of 0 to 60 bar which translates to 0 to 10 V.

Load cell Model: B3G-C3-50kg-6B, with a load capacity of 50kg, class C3.

LVDT stands for Linear Variable Differential Transformer; Model: Schaevitz lcit 2000

A load cell and LVDT will be attached to the axle of the master cylinder. The force (F_v) and the translation (x) will be measured this way. A pressure sensor will be put between the master- and vane cylinder to measure the pressure within the system during operation. The torque (T_v) is measured with weights suspended on a fixed arm (a wheel) on the axle of the vane cylinder. This wheel is also used to measure the rotation angle (φ). By marking the wheel and using an indicator on said wheel, a fairly rough measurement of the rotation angle can be made. This would suffice as a measurement, since it is not needed to know the angle on a tenth of a degree accuracy.

3 Results

Figure 4 shows the fabricated parts. Then in Figure 5 the test setup can be seen. While assembling the parts the vane cylinder would fit together but was unable to move. Steps have been taken to solve this problem, A solution was to add a laser cut gasket (Figure 7a) between the two shells to increase the distance between them. The thickness of the gasket is $0.15\,\mathrm{mm}$ and was sufficient to allow the vane to move freely. In section 3.1 the parts have been measured individually.

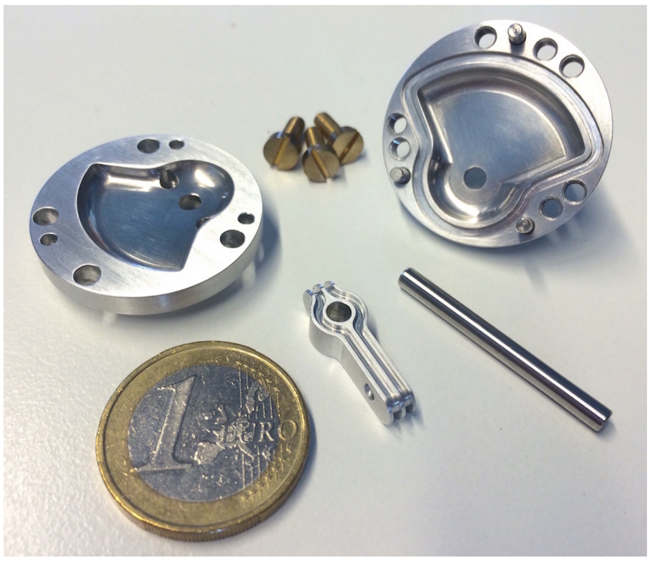

Fig. 4: Shown are the parts for the rotation mechanism. Both shells that encapsule the vane can be seen on the top left and right. The right shell has the groove for the o-ring. The vane lies in the middle with the axle to the right. A one euro coin for scale.

Unfortunately, after assembly including the gasket, the vane cylinder leaked, as can be seen in Figure 6. After investigating the leak, it became clear that water was coming through the bearings. The leaking became more severe moving the master cylinder piston one direction than the other direction. This leaking resulted in not being able to obtain data for the performance (torque) of the vane cylinder. After further investigation, to figure out where possibilities of leaking were, scratches where found in the surface of

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both shells in which the vane lies, Figure 7. Compare these surfaces with the surfaces in Figure 4, it can be seen that they where not there initially.

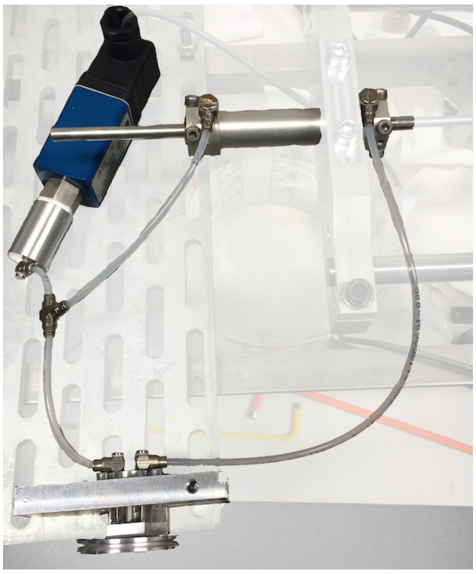
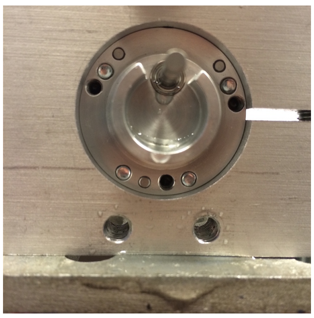


Fig. 5: A top view of the test setup. The vane cylinder is clamped in the test setup, seen at the bottom of the image. A wheel is attachted to the axle to read the angle. Two cable run to the master cylinder (top right). On the left side cable, the pressure sensor is attached (blue).

(a) A white paper underneath got wet after the first test.



(b) From this side it became clear that the vane cylinder was leaking through the bearings, not the hose connectors at the back.

Fig. 6: Front and back side of the vane cylinder in the test setup after operation and a leak is detected.

(a) Bottom shell, with the largest scratches. Also the gasket can be seen laying on top of the bottom shell (brown).

(b) Top shell

Fig. 7: Scratches on the survace of the two shells. Encircled in red are the most notable scratches seen on the surface.

3.1 Parts Measurements

The parts have been measured, to make sure the o-ring compression is correct. Table 6 shows the measured values and the theoretical values. The compression (a [%] of d_s) can be calculated as follows:

$$
\begin{aligned}
a &= \left(d_s - \left[\frac{(h_T + h_B + d_g) - (S_2 - 2 \cdot S_1)}{2} \right] \right) \cdot 100 \qquad (1) \\
&= 16.25 - 18.75\%
\end{aligned}
$$

The intended compression was 8%.

TABLE 6: Measurements of individual parts. How the variables are measured can be seen in the corresponding figures.

Part		Desired [mm]	Measured [mm]	Corresponding Figure
Vane Height	(D_v)	4.8	4.789	Fig. 10
Gasket	(d_g)	0.15	0.15	-
Shell Top	(h_T)	2.5	2.41	-
Shell Bottom	(h_B)	2.5	2.35	Fig. 8
O-ring	(d_s)	1.0	1,00 - 1.025	Fig. 9b
Auxiliary measurements	Shaft (S_1)		0.978	Fig. 9a
	Vane height + shaft (S_2)		5.191	Fig. 9c & 9d

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(a) Using the bottom of the chamber as a baseline.

(b) Measuring the flat surface edge of the top shell.

Fig. 8: Measurement setup to measure the dept of the chamber in the top shell. The bottom shell is measured in a similar manner.

(a) Measurement of two shafts. Both had the same measurement.

(b) O-rings are measured under a microscope. With a scaling factor of 40:1.

(c) One groove is measured with the auxiliary shafts in the grooves on both sides.

(d) The other groove is measured in a similar manner.

Fig. 9: Auxiliary measurements which are used to calculate the o-ring groove dept and the o-ring compression.

(a) Measure location on the long side at the end.

(b) Measure location on the long side near the axle.

(c) Measure location on the short side

Fig. 10: The height of the vane is measured to compare to the depth of the chambers of the in the shells.

Although the vane cylinder leaked, other requirements could be measured. Table 8 shows a summary of the results. The results will be walked through step by step:

[R1] The mechanism is designed with two degrees of freedom (rotation and flexion). Although only one degree (rotation) is tested, both are accounted for in the design.

[R2] The wrist has the possibility to be of an active controlled mechanism as well as passive. The rotation mechanism has been tested and is an active 1DOF vane cylinder.

[R3] The maximum mass of the entire wrist mechanism (as in Figure B.1) is 72.8 g according to Solidworks. The rotation mechanism has a mass of 21.2 g (measured). The other values can be seen in Table 7.

TABLE 7: Overview of the masses of the individual components compared to the masses in solidworks. Here a minus indicates N/A.

	Mass [g] Solidworks (incl. o-ring)	Mass [g]	Mass incl. o-ring [g] (incl. o-ring and gasket [g])
Top Shell	8.58 (8.66)	8.71	8.78 (8.82)
Bottom Shell	5.93	6.27	-
Vane and axle + PVC pins	2.55 (2.64)	2.50	2.59
Bolts incl. washers	3.53*	3.53	-
Total	20.67	21.00	21.20
Hose incl. connectors	-	9.465	-

* *The bolts in solidworks weighted in at 0.4 g, which is a big difference with the measured value, therefore the measured mass is taken.*

[R4] The length/height of the total mechanism including the grey platform is 52.5 mm (seen in Figure B.1). The height of the assembled components from Figure 4 is 20.7 mm. This is including the connection point for the rotation bearings, but excluding the end of the axle sticking beyond that point (this is only for the test setup, and not in the original design).

[R5] The mechanisms outer measurements are that of a 30 mm diameter circle.

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[R6] The maximum torque is $0\,\mathrm{N\,m}$ in the unlocked mode, and $0.1\,\mathrm{N\,m}$ in locked mode ($=0.5\,\mathrm{kg}\cdot 9.81\,\mathrm{m/s^2}\cdot 20\,\mathrm{mm}$). This was measured without moving the master cylinder. Figure 11 shows the vane cylinder with a weight attached to the wheel. Also the glue bond between the axle and vane has been tested. The maximum torque the bond could hold was $0.7\,\mathrm{N\,m}$ ($=3.5\,\mathrm{kg}\cdot 9.81\,\mathrm{m/s^2}\cdot 20\,\mathrm{mm}$). This was measured without moving the master cylinder, Figure 11. The current results with this setup and with leaking can be seen in Figure 12. It was observed that, with the weight on the wheel (blue), the vane eventually started moving.

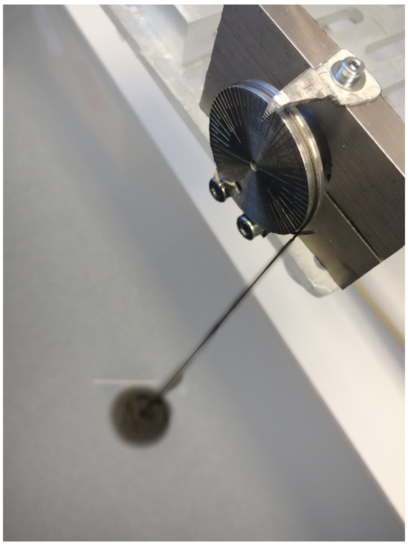


Fig. 11: A cable goes around the wheel to ensure a constant moment arm. by applying different masses the torque on the axle changes.

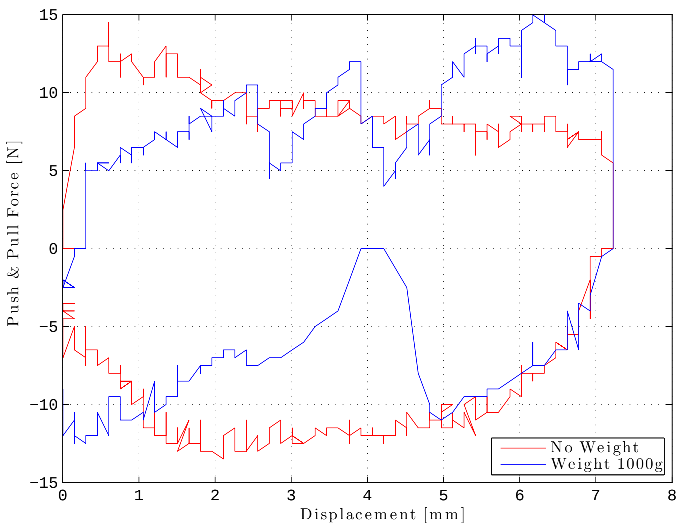
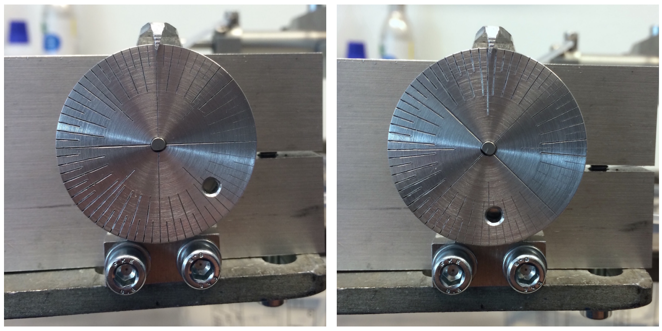


Fig. 12: A datasets without a weight on the wheel is shown, and a dataset with a weight with a mass of 1000g are shown in a hysterese graph of the master cylinder.

[R7] The Range of motion is $90°$ for the motion of rotation. The necessary stroke of the master cylinder to achieve a full range of motion for the vane is calculated as $8.5\,\mathrm{mm}$. This distance is sufficient for $45°$.



(a) The start position of the vane at $0°$.

(b) End position of the vane after a stroke of the master cylinder of $8.5\,\mathrm{mm}$

Fig. 13: A wheel ($\varnothing 20\,\mathrm{mm}$) with $5°$ markings is attached to the axle. A pointer (on top) is used as reference to read the current angle. The vane is located in the middle of its range of motion, i.e. the vane can move $45°$ in either direction.

[R8] Locking the mechanism is intrinsic to the choice of a hydraulic system.

[R9] Easy switching is also intrinsic to the choice of a hydraulic system.

TABLE 8: Overview of the requirements and the results

Requirement		Result
[R1]	Degrees Of Freedom	2
[R2]	Control	Active/ Passive
[R3]	Weight	72.8 [g] (25 [g])
[R4]	Length	52.5 [mm]
[R5]	Diameter	30 [mm]
[R6]	Torque	0 [Nm] (unlocked) 0.1 [Nm] (locked) 0.7 [Nm](glue bond)
[R7]	Range Of Motion	$90°\pm5°$
[R8]	Lockable	Intrinsic
[R9]	Switching control methods	Intrinsic

4 Discussion

It is very unfortunate that the vane cylinder leaked. The vane cylinder did fit the first couple of tries, but the vane could not be moved within its chamber of the shells. Trying to figure out why the vane was not moving, the cylinder has been assembled and disassembled extensively. In this process, the vane has been installed without o-rings. The reason was to figure out if the o-rings caused the jamming. This assembly without o-rings probably resulted in the scratching of the two shells. Using Table 6, it can be seen that, without the gasket, the vane does not fit within the two shells. This can be shown with the following equations:

$$\text{Shell Top} + \text{Shell Bottom} < \text{Vane Height} \tag{2}$$

$$2.35 + 2.41 < 4.789 \tag{3}$$

To solve this problem, a gasket with a thickness of $0.15\,\mathrm{mm}$ is installed between the two shells. Knowing, within the time available, it would not be possible to make new correct parts. Thus the use of this gasket was not intended, and could therefore also be a cause for the leaking. If the vane would have fitted within the shells without a gasket, the bare metal could also have been a problem. But this is not the case with existing vane actuators, besides water did not come out of the vane cylinder through the gap between the two shells with or without the gasket. This would indicate that the o-ring sealing the two shells, and the gasket, doing their work properly. Take note that it is still unclear how the gasket and the o-rings of the vane are interacting, and how well the seal works at that point. Figure 14 shows the possible locations of leaking of the vane cylinder. Thus the vane cylinder could be leaking due to the scratches (green in Figure 14) or at the location where the gasket and the o-ring seals meet (purple in Figure 14). By including the gasket in the mechanism, the vane had enough space to move. Although the compression on the o-rings was well above the intended 8% (16.25-18.75%), bringing a lot more friction, it should not have caused leaking. Taking into account that the vane cylinder leaked more, rotating in one direction than the other, and the scratches being more prevalent on one side on the surface of the shells than the other (Figure 7), it can be stated that the leaking is caused, with a high probability, by these scratches.

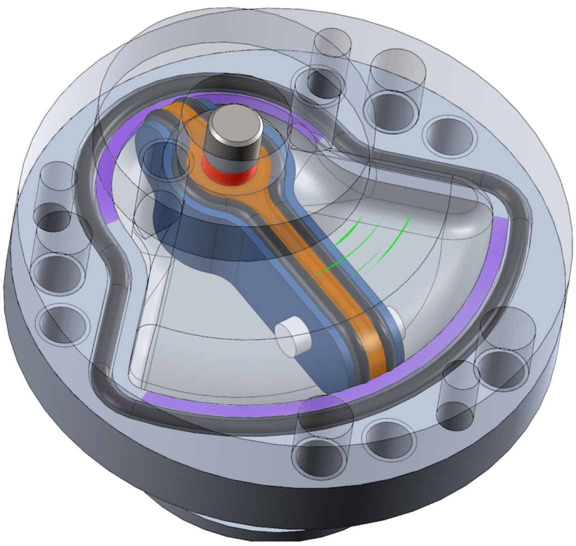


Fig. 14: Possible leaking locations. The shell on top is see through. In red, the location of leaking is indicated. This is observed and can be seen in Figure 6. Orange shows the space between the o-rings where the water is coming in from the system or the air is going into the closed system. Purple shows the location where there is a possibility of leaking due to the gasket used, or the alignment of the two shells relative to eachother. The green lines are the scratches found on the surface of the two shells. These scratches could cause leaking.

The vane cylinder was leaking, but still a lot of other requirements are met. This can be seen in Table 9. These will be discussed now.

[R1] Although only one degree (rotation) is tested, both are accounted for in the design. Thus by proving the working principle of one degree of freedom, the other would give similar results. The testing of two degrees of freedom simultaneously could not be done by this study, but that was also not the goal for this study. But this could be a task for follow-up studies. For instance the research on which control method is best for the control of a multiple degrees of freedom hand prosthesis.

[R2 & R9] This design has the possibility to be of an active controlled as well as a passive controlled mechanism. The tests, with the leaking, where performed bidirectional, thus the vane was controlled both directions when moved. An option for future research, one can remove one connection and replace the hydraulic fluid by air, i.e. an air spring is created. This air spring would result in an automated return of the vane if the pressure was released on the activation stroke of the master cylinder. It is also possible to switch the active control to a passive controlled mechanism. This can be achieved by closing off both connection points of the vane cylinder. This would seal off both chambers, thus by using air instead of a fluid, an air spring is used again. Then the mechanism cannot be controlled actively making it a passive mechanism. This has to be researched, calculated and refined. Thus a clear answer cannot be given in this paper, but this could be a big benefit for this design of a wrist prosthesis, because it gives the possibility to research different control methods for a prosthesis with multiple degrees of freedom without changing much of the prosthesis. If this mechanism would be further developed, it could also be beneficial for the user. It would give the option to switch between the control methods (e.g. making it modular), making it a versatile mechanism.

[R3-5] It is achieved to design the mechanism within the desired dimensions and mass. This would mean that the wrist can fit within the wrist location of a prosthesis of a 4 year old. Making it a more aesthetically appealing wrist mechanism, because there are no parts sticking out or having odd shapes. Making it not excessively heavy is beneficial for the user, since it is dead weight carried around. Making it lighter will make it less of a burden to wear the prosthesis. This is because the prosthesis is carried at the end of the residual limb. Not being a integral part of the support structure, but suspended on the skin, will increase the discomfort if the prosthesis is heavy.

[R6] The maximum torque of $3.75\,\mathrm{N\,m}$ is not achieved by the mechanism in unlocked or locked mode. This is mainly due to the leaking of the mechanism. In locked mode the prosthesis was still able to resist a torque of $0.1\,\mathrm{N\,m}$. For now it can be concluded that the mechanism is not able to resist $3.75\,\mathrm{N\,m}$ in locked mode. If the mechanism is not leaking this value will probably change, but it cannot be said if this value can reach the requirement of $3.75\,\mathrm{N\,m}$. This current torque in locked mode is probably lower than expected also because of the leaking.

Figure 12 shows that there is no noticeable difference in push & pull force on the master cylinder. Which indicates that the vane is leaking, especially knowing that the wheel with weight started moving without moving the master cylinder. This is probably where the sudden drops in force are measured for the second data set. This gives to show that the vane has to be made leakage free before a correct validation can be made for the achievable torque.

The maximum average torque an adult can perform is

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$15\,\mathrm{N\,m}$, which in itself is quite high. Try holding $15\,\mathrm{kg}$, horizontal with an arm of $10\,\mathrm{cm}$ in your hand without rotating. This is quite a task for most, therefore scaling down to $3.75\,\mathrm{N\,m}$ could also be quite a task for the 4 year old. The recommendation would be to have a further look into the average achievable torque instead of the maximum average torque, to lower the expectations of this particular requirement. The reason these current values are quite low is probably due to the air in the system (which is compressible) caused by the leaking, and the leaking itself. Applying a large enough mass would result in the rotation of the vane, because the fluid can bypass the vane with seals.

[R7] Range of motion of 90° for rotation is achieved. Both DOFs are probably capable of 90° movements, because nothing is hindering them to do so. However both vanes cannot move beyond the 90° mechanically. The key to attain this range lies in the master cylinder. Depending on the diameter and the stroke, the displacement volume changes, and therefore the range of motion of the vane cylinder. For the sake of the discussion, let us assume that the master cylinder is capable of this. Then the wrist mechanism with two degrees of freedom is capable of achieving the motion seen in Figure B.3. Although this is not as much as a healthy wrist. It is an improvement compared to most currently available wrists [19], [34], [35]. Since these wrists only have one degree of freedom. It can also be seen that the motion is not half a sphere, but only a part. At this point it cannot be said if half a sphere is desired or that only a part is sufficient. This has to be researched with subjects testing the prosthesis, and would be a point of interest for future research.

[R8] A lockable mechanism is achieved by preventing the fluid from moving, and is therefore intrinsic to the design. Although this mechanism is not fabricated, the current design is tested in locked state by keeping the master cylinder from moving. The torque achievable was only $0.1\,\mathrm{N\,m}$, and could just as well be caused by static friction of the o-rings (since an unexpected higher compression of the o-rings is applied). A higher torque could not be achieved, probably due to the leaking, but given current available methods of locking a hydraulic mechanism, it can be assumed that by blocking the fluid is a legit way of locking the mechanism. For future work a locking mechanism has to be designed and tested specific for this wrist.

In Table 9 the vane cylinder is compared with the requirements. Something more interesting, is the comparison of the vane cylinder with the existing devices. This can be seen in Table 10. The vane cylinder is comparable with the diameter of the pneumatic actuators, but is more than half the length/height and mass. Compared with the hydraulic actuators the vane cylinder is almost five times lighter compared with the Micromatic actuator. The new design is also two and a half times shorter, making it a more compact design. It can therefore be said that this design has potential for a new two degree of freedom wrist mechanism for hand prostheses.

TABLE 9: Overview of the requirements and the results

Requirement		Desired	Achieved/	Measured value
[R1]	Degrees Of Freedom	2	✓	2
[R2]	Control	Active	✓	Active/ Passive
[R3]	Weight	180 [g] 51 [g]	✓ ✓	72.8 [g] (Solidworks) 21.2 [g] (Measured)
[R4]	Length	75 [mm]	✓	52.5 [mm]
[R5]	Diameter	30 [mm]	✓	30 [mm]
[R6]	Torque	3.75 [Nm]	× × ×	0 [Nm] (unlocked) 0.1 [Nm] (locked) $0.7\,\mathrm{N\,m}$ (glue bond)
[R7]	Range Of Motion	90°	✓	90°
[R8]	Lockable	Two directions and Continuous	✓ ✓	Intrinsic
[R9]	Switching control methods	Switching without changing the mechanism	✓	Intrinsic

TABLE 10: Available pneumatic and hydraulic vane actuators in a comparison with the vane cylinder.

	Pneumatic		Hydraulic		
	Festo [29]	Norgren [30]	Parker [31] (double vane)	Micromatic [32] (double vane)	Vane Cylinder
Model	DSM-6-...-P	M/60280	HRN10D	MPR-1x.4	1DOF (Rotation)
Diameter [mm]	29.4	29		35.5	30
Height x width [mm x mm]			55 x 55		
Length [mm]	48	46	95	51.6	20.7
Torque [Nm] (at bar)	0.15 (6)	0.15 (6)	3 (17.5)	0.23 (6.9)	0.1 (-)
Range of Motion (°)	90 & 180	90 & 180	90	100	90
Mass [g]	45	40	1000	100	21.2

4.1 Recommendations and Future Research

It is recommended to do a thorough measurement of all the parts before assembly to make sure everything fits correctly with the correct tolerances. The surface finish of the cylinder should be treated with care, to prevent scratching, thus a possible leak. The stroke of the master cylinder should be kept in mind while testing the mechanism. The reason for this is the mechanical stop of the vane cylinder. If the vane is at its end, the pressure could increase drastically.

The next step for a redesign should look into the shape of the vane. As can be seen in Figure 2b, the vane has a different shape. Giving a larger surface area to the vane. Which would result in a higher achievable torque. While looking into a redesign of the shape of the vane the fabrication process has to be kept in mind. In other words, the mechanism can be optimized for mass/dimensions to torque ratio. Aiming for an as light as possible design with the highest achievable torque output, with a certain comfortable input force.

If the prototype is to be tested with test subjects, an interface between the socket has to be designed. Depending on the terminal device an interface has to be designed for that as well.

After a correct functioning prototype is fabricated, research can be done in the in the control method of multiple degrees of freedom hand prosthesis. Since there is little to no research done in controlling a multiple degrees of freedom hand prosthesis which also concerns about the mental workload, and improve the prosthesis to make it more natural, intuitive, and easy to use.

(measure torque and rotation angle with sensors to correlate between force and position from input)

5 Conclusion

It can be concluded that this hydraulic vane cylinder is a promising wrist mechanism to use in hand prostheses, because it is a small and compact design, although it was not possible to generate a torque in unlocked mode. This was due to leaking of the mechanism at the vane. A short investigation is held to find out where the vane cylinder was leaking. Possible causes were scratches on the surface of the two shells, and the use of a gasket, where the scratches have a higher probability. It was only capable of maintaining position at an applied torque of $0.1\,\mathrm{N\,m}$ (locked mode). Other requirements could still be validated despite this setback. The range of motion, $90°$, for instance could be achieved, only the stroke of the master cylinder had to be increased due to the compression of leaked air. The mass, $21.2\,\mathrm{g}$ (rotation mechanism), the length/height, $20.7\,\mathrm{mm}$, and the diameter, $30\,\mathrm{mm}$, of the mechanism have also been within the range of the requirements. Compared to existing vane actuators this design is far lighter and smaller. The possibility to switch between active and passive control methods, as well as body powered control and externally powered control, is a benefit of this design. Especially for future research conducting control methods for a multiple degrees of freedom hand prosthesis. It is also possible to lock the mechanism. Both of these two requirements have not been tested, but are intrinsic to the choice of a hydraulic system. A couple of improvements can be made, regarding fabrication and design, but this mechanism can be seen as a promising wrist mechanism for a prosthesis and for future research.

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APPENDIX A
CONCEPTS

In this section the three concepts are walked through with general formulas and calculations.

A.1 Curved Cylinders

Figure A.1a shows the mechanism for a curved cylinder.

Calculations

First

$$P = \frac{F}{A} \tag{4}$$

where P is the pressure in the system, F is the force applied or received, and A is the surface area on which the pressure is acting. For the straight cylinder, the surface area is given by the following equation:

$$A = \pi \cdot D \tag{5}$$

The volume however

$$V = A \cdot S \tag{6}$$

Now the path for the curved cylinder has to be calculated to get the angle of rotation. If $90°$ is desired, then S should be the circumference. This can be done with the following equation:

$$S = \frac{1}{4} \cdot 2 \cdot \pi \cdot r = \frac{\pi \cdot r}{2} \tag{7}$$

The torque can be calculated as

$$T = F \cdot r \tag{8}$$

A.2 Rack & Pinion

Figure A.1b shows the principle mechanism of a rack and pinion. This mechanism can also be made with two cylinders, that are parallel and on opposite sites of the pinion. This will reduce the total height of the mechanism.

Calculations

The same as Curved Cylinders:

$$P = \frac{F}{A} \tag{9}$$

For the straight cylinder in the rack & pinion configuration, the surface area is given by the following equation:

$$A = \pi \cdot D \tag{10}$$

$$V = A \cdot S \tag{11}$$

For the rotation of the pinion, the same equation as for curved cylinders can be used.

$$S = \frac{\pi \cdot r}{2} \tag{12}$$

The torque can be calculated as

$$T = F \cdot r \tag{13}$$

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A.3 Vane Cylinder

Figure A.1c shows the principle mechanism for the vane actuator.

Calculations

Figure A.2 shows that the vane actuator has two surfaces on which the hydraulic pressure acts. The moments are in opposite direction of each other around the main axis. The equations are as follows:

$$A_n = h \cdot l_n \tag{14}$$

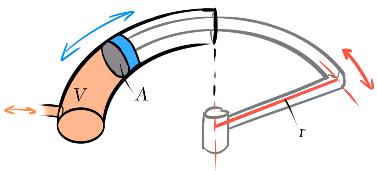
where n is 1 or 2 and stands for one of the two sides of the vane (Figure A.2), h is the height of the vane, and l is the length. The entire surface can be taken since the areas cancel each other out.
Then

$$F_n = P \cdot A_n \tag{15}$$

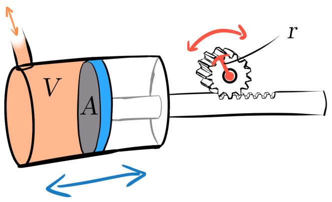
$$T = \Sigma(F_n \cdot r_n) \tag{16}$$

And the total volume that needs to be displaced for $90°$ should be:

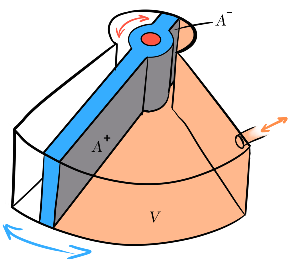
$$V = \frac{h \cdot pi \cdot ({l_1}^2 - {l_2}^2)}{2} \tag{17}$$



(a) Curved Cylinder.



(b) Rack and Pinion.



(c) Vane Cylinder. The plus and minus indicate positive and negative relation of the areas to the torque. The leverage arms can be seen in Figure A.2

Fig. A.1: Three different hydraulic concepts. V is the volume with hydraulic fluid, A is the surface area on which the pressure of the hydraulic fluid acts, r is the leverage arm of the torque.

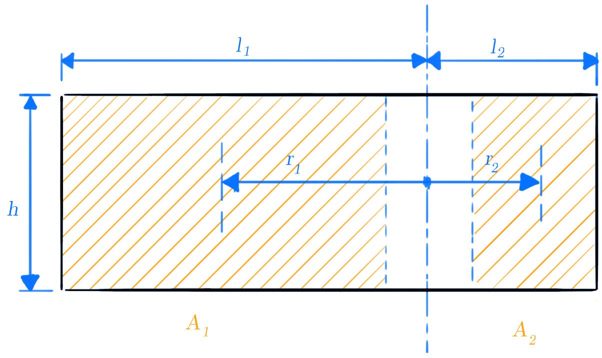


Fig. A.2: First initial schematic scetch of the side view perpendicular to the surface on which the fluid pressure acts on the vane

Appendix B
Vane Cylinder Embodiment

After the decision has been made to use the vane cylinder. Solidworks is used to make a 3D model of a two degree of freedom active wrist mechanism. Figure B.1 shows a full render of the entire mechanism with two degrees of freedom. The prosthetic hand can be attached to the grey platform. The bottom part has to be attached to the socket or interface on the residual limb. Figure B.2 shows a section view of the same wrist mechanism. The mechanism is made such that it will fit within the 30 mm diameter circle. The length is tried to make as short as possible, since a shorter prosthesis would cover more patients with a transradial amputation. The movements are designed in a specific way. Rotation proximal to flexion. This way the motion of the platform (shown in grey) and therefore the terminal device becomes a section on a sphere, Figure B.3.

Fig. B.1: Shown is a 3D render of the full design of the wrist mechanism with two vane cylinders (actuators), and therefore two degrees of freedom. The rotation movement is accounted for in the lower part of the design. Where flexion is in the top part. The grey part is in a flexed position of the top vane cylinder.

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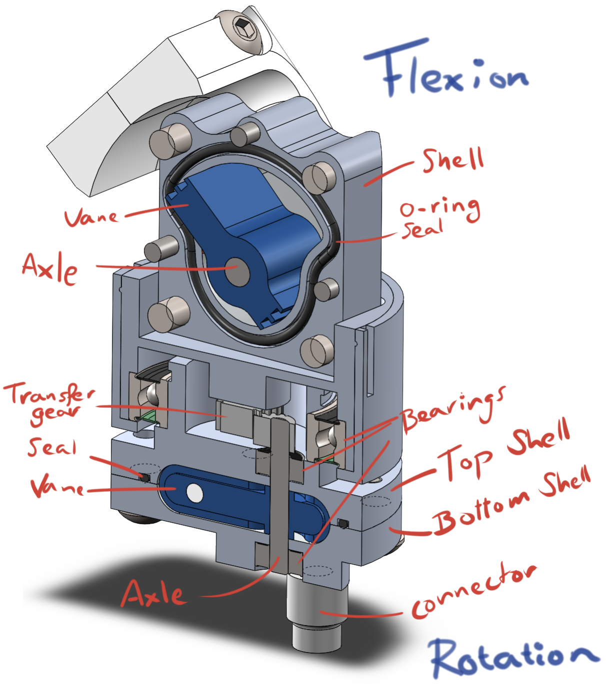

Fig. B.2: Section view of the full design of the wrist mechanism. In blue are the two vanes and the corresponding movements. Indicated in red are the different parts of the wrist mechanism. The pins sticking out at flexion are bolts and dowel pins.

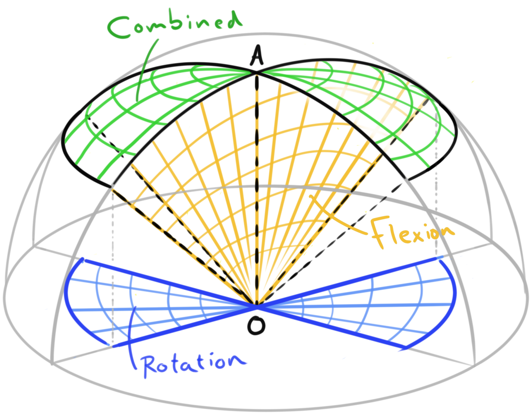

Fig. B.3: Visualization of the combined motion of the two degrees of freedom, both 90°, of the wrist mechanism.

The embodiment is a result of the dimensions and the parts necessary in the design. The vane, for instance, is shaped because of the axle going through it, and the o-rings necessary to seal the cylinder. This specific kind of sealing is chosen since it will require less seals for the same sealing effect. A curvature is needed for the o-rings so they will still be able to seal and don't buckle at sharp edges.The size of the vane is altered slightly since an o-ring is also used to seal the two shells in which the vane is seated, seen in Figure B.4. The axle for the rotation movement is off center. This gives a larger moment arm for the vane, thus a higher torque. Therefore there also has to be a gear transfer to the center of the wrist. This gear ratio is 1:1.

In the next section the bearings, seals and locking mechanism are elaborated.

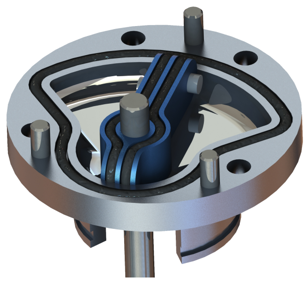

Fig. B.4: Render of a open vane cylinder for the rotation motion. The vane is depicted in blue and sits in its chamber of one of the shells. Around this chamber a groove is visible. This groove is there for the seal that seals the two shells.

B.1 Bearings

There are three locations where bearings are needed. The first two are those of the axles of the two vanes (a total of 4 bearings). The third is to establish the motion of rotation (between the flexion and rotation vane, Figure B.2), and is relatively large. Initially the first two locations are thought to only guide the axle, thus no high radial forces would act on the bearings. Later it is seen that the bearings used to guide the axle for the flexion motion do have a radial force acting on it. For now only the rotation vane cylinder is fabricated to test, so this has to be a point for future work, i.e. to figure out which bearings are needed for the flexion vane.

To continue, the large bearing is picked out such that it would have the largest diameter possible. And would still fit within the 30 mm parameter. This would be a ball bearing from NSK, with part number 6803 [36]. With outer diameter of 26 mm, inner diameter of 17 mm and a width of 5 mm. Then calculations are made to see if it would hold under the loads of usage by a child. An extreme example would be a handstand. Although it is a whole different subject if a toddler of 4 years old can achieve such a thing, but it can be used as a good measure. The average mass of a 4 year old is 15 kg [37], [38]. If a child would do a perfect handstand on one hand, the loads of the weight would be axially on the bearing. As an initial calculation, according to RBC bearings and SMB bearing, the axial load capacity is $20-25\%$ of the static loadrating of the bearing [39]–[41]. The dynamic and static loadratings of the bearing are $2630\,\mathrm{N}$ and $1570\,\mathrm{N}$ respectively. Thus the following calculation can be made to calculate the maximum mass on the bearing in axial direction:

$$m = \frac{20\% \cdot \text{Static Loadrating}}{g} = \frac{0.2 \cdot 1570\,\mathrm{N}}{9.81\,\mathrm{m/s^2}} = 32\,\mathrm{kg} \quad (18)$$

This is twice the mass of a child of 4 years. So it seems this is sufficient as a bearing. Although dynamic loads of usage are not taken into account, it does give a good indication.

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B.2 Seals

The seal picked for the prototype of the vane are from ERIKS:

$$\text{Hardness} = 70°\text{sh.}$$
$$\text{Cord thickness } d_s = 1\,[\text{mm}]$$
$$\text{Inned diameter } D_i = 13\,[\text{mm}]$$

The squeeze of the o-rings are important, since that determines the friction of the cylinder. According to Plettenburg [42] a compression of 8% is needed. The following formula is taken for the piston groove diameter:

$$D_p = D_c - 2 \cdot d_s \cdot \left[1 - \frac{a}{100}\right] [\text{mm}] \tag{19}$$

$$\begin{aligned} \text{where: } D_p &= \text{piston groove diameter [mm]} \\ D_c &= \text{cylinder bore diameter [mm]} \\ d_s &= \text{O-ring cross section width} \\ &= 1\,[\text{mm}] \\ a &= \text{O-ring squeeze} \\ &= 8[\%] \end{aligned}$$

This holds for a piston that is circular. So only the latter part is taken to determine the dept of the groove in which the o-ring lies. So it can be applied to a non-circular o-ring groove. Figure B.5 shows a cross section of the o-ring and the groove. An o-ring is chosen with a cord thickness d_s of 1 mm and a compression a of 8% gives:

$$h = d_s \cdot \left[1 - \frac{a}{100}\right] = 1 \cdot \left[1 - \frac{8}{100}\right] = 0.92\,[\text{mm}] \tag{20}$$

The width of the groove should be [42]:

$$w = 1.1 \cdot d_s = 1.1 \cdot 1 = 1.1\,[\text{mm}] \tag{21}$$

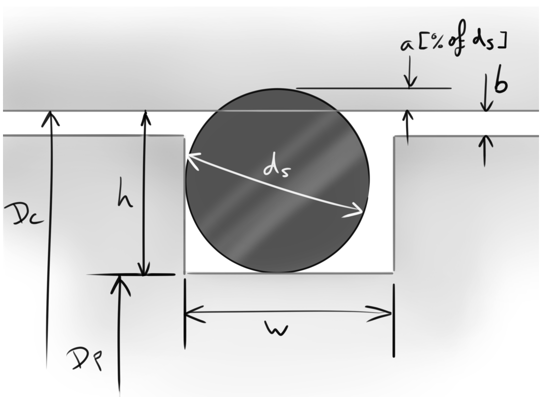

Fig. B.5: Cross section of o-ring (dark grey) and o-ring groove for equations 19-22. The top grey part is the cylinder and the bottom grey part (with groove) is the vane.

The calculations for the friction are made for an circular cylinder. The outer diameter of the o-ring is taken for further calculations. Table B.1 shows the result for a range of pressures. The friction forces are as follows:

$$F_f = [f_c \cdot L] + [f_h + A] \tag{22}$$

$$\begin{aligned} \text{where: } F_f &= \text{O-ring friction force [N]} \\ f_c &= \text{friction factor due to O-ring compression} \\ &= 0.1[\text{N/mm}]\ [42] \\ f_h &= \text{friction factor due to fluid pressure} \\ &= \text{see Table B.1 } [\text{N/mm}^2] \\ D_c &= \text{cylinder bore diameter [mm]} \\ &= D_i + 2 \cdot d_s - 2 \cdot \frac{a}{100} = 14.84\,[\text{mm}] \\ D_p &= \text{piston groove diameter [mm]} \\ L &= \text{length of seal rubbing surface} \\ &= \pi \cdot D_c[\text{mm}] \\ A &= \text{projected area of seal} \\ &= \frac{\pi}{4} \cdot \left[{D_c}^2 - {D_p}^2\right] [\text{mm}^2] \end{aligned}$$

TABLE B.1: O-ring friction for a circular cylinder for a range of pressures. The dimensions of the o-ring chosen for the vane are used.

Input						
Pressure [bar]	10	20	30	40	50	60
f_h [N/mm^2] [42]	0.08	0.11	0.14	0.17	0.20	0.22
Output						
F_f [N]	8.0	9.2	10.4	11.6	12.9	13.67

The results from Table B.1 show a quite a large friction force. The exact value will be different since the o-ring is not circular in the vane, and is also rotating about an axis. But it will give a good indication.

B.3 Locking Mechanism

The locking mechanism can be a simple plunger or piston that will block the hydraulic fluid. Another option is the use of a ball valve, Figure B.6. This is currently not designed, since it does not have priority. Therefore it is also a point for future work while optimizing the vane cylinder, and designing connection points. Making it a complete wrist prosthesis.

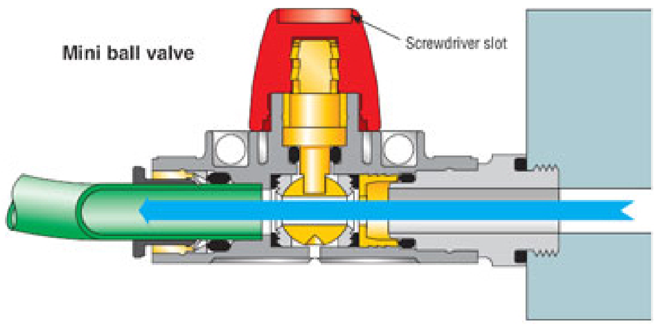

Fig. B.6: Example of a simple hydraulic valve. The blue arrow shows the flow. The yellow parts show a miniball valve. When this ball is rotated it blocks the flow, therefore locking the system. http://hydraulicspneumatics.com [Date accessed: 17 November 2015]

B.4 Switching

The problem with switching between control methods normally would be changing the actuator within the wrist. With this hydraulic design that is not needed anymore, but it shifts the problem to the manipulator, i.e. master cylinder. A solution is found within the motorcycle racing circuit. There they use a so called 'quick disconnect brake line', Figure B.7. This mechanism allows a decoupling of the brake line without removing other parts or draining the system of the hydraulic fluid. Which means that there is no need for bleeding the system.

The same as the locking mechanism holds for the switching mechanism. It is not yet designed. It is therefore recommended to take it in the design for a complete prosthesis, or only for a specific research where switching is necessary.

Fig. B.7: Image of a quick disconnect mechanism used for brake lines in motorcycles, to quickly disconnect the brakeline such that (front) wheel can be changed quickly. Original image from https://spieglerusa.com/media/catalog/category/brake-disconnect.jpg

APPENDIX C
VANE CYLINDER CALCULATIONS

The following Tables (C.1 and C.2) show the used values of the variables needed for revised calculations of the vane cylinder. With the aid of solidworks the surface areas on which the hydraulic pressure is acting and the maximum and minimum volumes (Figure C.1) are measured.

TABLE C.1: Values for the master cylinder according to measurements in Solidworks of the vane cylinder.

	Rotation		Flexion	
Diameter	12	[mm]	14	[mm]
Stroke	17.1	[mm]	18	[mm]
Area	37.7	[mm^2]	44.0	[mm^2]
Volume	644.7	[mm^3]	791.7	[mm^3]

TABLE C.2: Values for the vane cylinder according to measurements in solidworks of the vane cylinder. Figure A.2 is used as a reference for the values in this table.

	Rotation		Flexion	
Positive leverage arm; r_1	9.2	[mm]	7.2	[mm]
Negative leverage arm; r_2	4.9	[mm]	4.9	[mm]
Positive Area; A_1	48.9	[mm^2]	85.0	[mm^2]
Negative Area; ; A_2	6.0	[mm^2]	21.7	[mm^2]
Postive Volume	793.0	[mm^3]	1218.0	[mm^3]
Negative Volume	149.0	[mm^3]	434.0	[mm^3]
Δ Volume	644	[mm^3]	784	[mm^3]

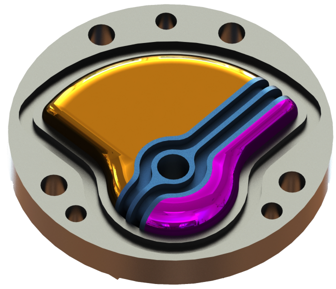

Fig. C.1: A render of the vane actuator. In orange/gold the maximum volume is shown, and in purple the minimum volume is shown. The maximum volume minus the minimum volume gives the volume that needs to be displaced by the master cylinder to get the full range of motion. All these volumes can be seen in Table C.2

Revised calculation are performed with the more accurate values measured with Solidworks. This is done with Matlab, where the code used can be seen in Appendix E. The results can be seen in the table below (Table C.3), it can be seen that the maximum torque is one third of the initial calculations. This is quite significant, it will be a even lower when friction is taken into account. When looking at the maximum pressure in the system when the system is locked and 3.75 Nm is applied, it can be seen that it is quite a high pressure. These values have to be compared to the results of the test, with a vane cylinder that is not leaking.

TABLE C.3: Results from the revised calculations, with more accurate values for the variables used.

Moving Vane				
	Rotation		Flexion	
Max. Torque of the vane; T_v	0.558	[Nm]	0.575	[Nm]
Pressure	13.263	[bar]	11.368	[bar]
Pressure at 3.75 Nm torque for a locked system				
	Rotation		Flexion	
Pressure	78.100	[bar]	52.085	[bar]

C.1 Vane Attachment to Axle

Two ways of attaching the vane to the axle have been tried. Gluing and an interference fit. Calculations for both can be seen in the subsections below.

But after assembling the prototype the result was the jamming of the vane in the shells. The axle probably fitted a bit askew while it was laid down to dry. Therefore a interference fit was used next. This will a more straight alignment between the vane and the axle. But after trying this, the vane still got stuck between the shells. Later it was concluded that the vane was not jamming due to a misalignment of the vane with its axle, but that the chamber in the shells for the vane was too small. Next a gasket is used, to slightly raise the two shells from each other. Also the interference fit would not hold between the vane and the axle. Therefore small grooves where made in the axle, before glue was applied again, having again glued the vane with the axle.

C.1.1 Gluing of the Axle and Vane

The calculations for gluing the that are as follows:

$$A = \pi \cdot D \cdot h \tag{23}$$

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$$T = A \cdot \tau \cdot \frac{D}{2} \tag{24}$$

with

$$\begin{aligned} D &= 3 \text{ mm} && (25)\\ h &= 5 \text{ mm} && (26)\\ & && (27) \end{aligned}$$

Shear strength pin and collar (0.02mm gap) of Threebond 1373B:

$$\tau = 30 \sim 40 \text{ N/mm}^2 \tag{28}$$

gives:

$$T = 2.12 \sim 2.83 \text{ Nm} \tag{29}$$

Which is less than the initial requirement of $3.75\,\mathrm{Nm}$. But as can be seen in the results, the current maximum torque is $0.6\,\mathrm{Nm}$, which does not come close to the maximum torque the glue can take.

C.1.2 Interference Fit between Axle and Vane

From Van Beek [43] the transmission torque for an interference fit can be calculated. The opposite is desired, therefore the formulas are rewritten as (Figure C.2 shows an illustration of how the variables are used):

$$F = 2\,T/d = 2 \text{ [N]} \tag{30}$$

$$p = \frac{F}{\pi d L\ \mu} = 0.0707 \text{ [GPa]} \tag{31}$$

where

F	[N]	Interference force
$T = 3$	[Nm]	Maximum desired torque
$d = 3$	[mm]	Nominal diameter of interference
p	[GPa]	Pressure at interference
$L = 5$	[mm]	Height of contact area
$\mu = 0.61$		Friction coefficient [44]

$$\delta = pd\left(\frac{1}{E_o}\left(\frac{(d_o/d)^2+1}{(d_o/d)^2-1}+\nu_o\right)-\frac{1}{E_i}\left(\frac{(d_i/d)^2+1}{(d_i/d)^2-1}+\nu_i\right)\right) \tag{32}$$

$$= 5.9[\mu\text{m}]$$

With the following variables:

$d_i = 0$	[mm]	Inner diameter axle
$d_o = 7.2$	[mm]	Outer diameter vane
$E_i = 210$	[GPa]	Young's modulus steel axle [45]
$E_o = 71.7$	[GPa]	Young's modulus aluminum vane [46]
$\nu_i = 0.29$		Poisson's ratio steel axle [45]
$\nu_o = 0.33$		Poisson's ratio aluminum vane [46]

δ is the minimal overlap needed of the interference fit. According to the ISO fit system that would be 3 S4/g6 [47]. A commonly used fit would be S7/h6 [48], which also holds for the minimal overlap.

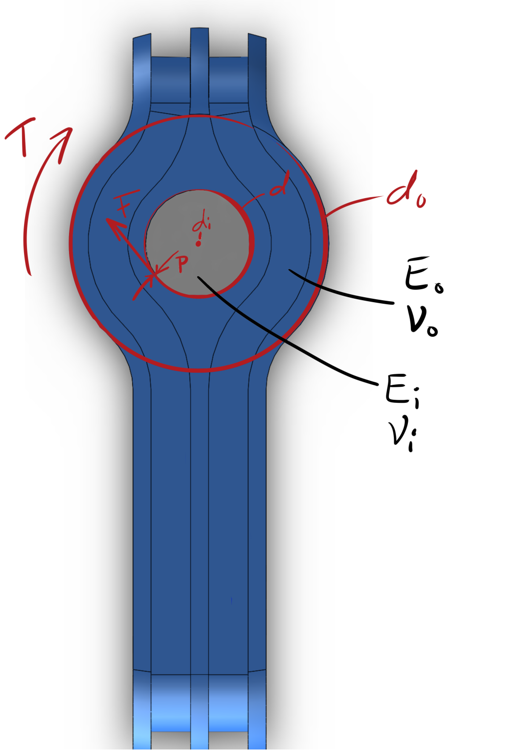
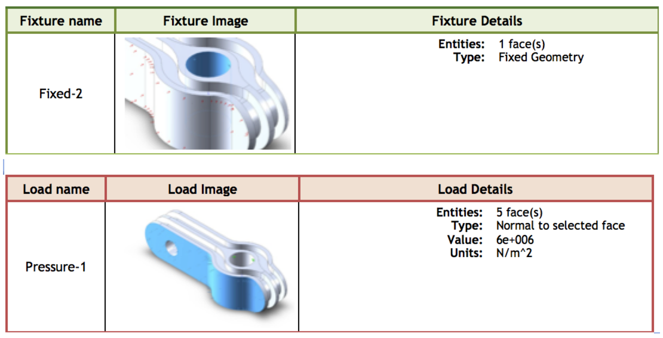


Fig. C.2: Top view of the vane and axle. Shown are the variables used to calculate the obtainable torque with the used interference fit.

Appendix D
Vane Cylinder SimulationXpress Study

The SimulationXpress Study of Solidworks is used to analyze the stresses of the vane under the circumstances found in the preliminary results, where a maximum of 78.100 bar (Table C.3) was calculated. A pressure sensor is used, that has the specifications of a maximum of 60 bar, therefore this value is used within this simulation study. Here it is applied on one side of the vane, and the hole for the axle is used as a fixture. Both can be seen in Figure D.1. The deformation of this study can be seen in Figure D.2, and the VonMises stress study results can be seen in Figure D.3. It can be seen from these results, that the deformation and the stresses do not exceed the allowable values (yield strength). Therefore this vane can be used with these loads, without deforming.



Fixture name	Fixture Image	Fixture Details
Fixed-2		Entities: 1 face(s) Type: Fixed Geometry

Load name	Load Image	Load Details
Pressure-1		Entities: 5 face(s) Type: Normal to selected face Value: 6e+006 Units: N/m^2

Fig. D.1: Loads and fixtures of the van in SimulationXpress Study of Solidworks.

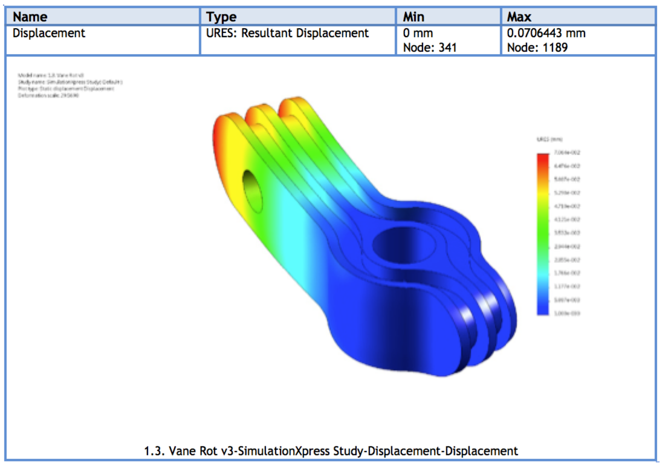


Fig. D.2: The deformation of the vane in SimulationXpress Study of Solidworks.

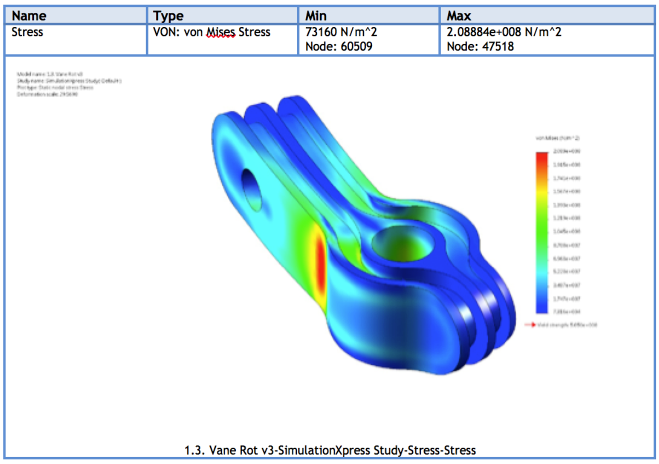


Fig. D.3: The VonMises values of the vane in SimulationXpress Study of Solidworks.

Appendix E
Matlab code

Here the Matlab code is shown for the revised calculations of the vane cylinder of the 3D model in Solidworks.

Listing 1: Matlab code to calculate the torque and range of motion for the current design.

```
clear all
clc

f = 50;          % [N]  Maximum Force exerted ...
    by operator
s = 50;          % [mm] Maximum Stroke of ...
    operators force range

%%   MASTER CYLINDERS ESTIMATION
%                            Rot   Flex
C =             [            12    14;   % [mm] ...
    Diameter
                           17.1    18]; % [mm] ...
                 Stroke
C(3:4,1:2)=[         pi*C(1,1)   pi*C(1,2);   % [...
    mm2] Area
                pi*C(1,1)*C(2,1)  pi*C(1,2)*C...
                    (2,2)]; % [mm3] Volume

%%    SYSTEM OPERATING PRESSURE
%       Rot          Flex
p = [f/C(3,1) f/C(3,2)]*1e1; % [bar] Max ...
    Pressure (dyn)

%%    VANE ACTUATORS MEASUREMENTS
%         Rot      Flex
X =    [  9.22     7.205; %[mm]  pos leverage ...
    arm
          4.945    4.945; %[mm]  neg leverage ...
             arm
         48.87    85.04;  %[mm2] pos area
          5.98    21.69;  %[mm2] neg area
        793.0   1218.0;   %[mm3] max volume
        149.0    434.0];  %[mm3] min volume

%%    SYSTEM OPERATING TORQUE
F =   [  p(1,1)*X(3,1) p(1,2)*X(3,2);        %[N...
    ]
         p(1,1)*X(4,1) p(1,2)*X(4,2)]*1e-1; %[...
             N]

T =   [  X(1,1)*F(1,1) X(1,2)*F(1,2);
             X(2,1)*F(2,1) X(2,2)*F(2,2)]*1e...
                 -3;
Torque = [T(1,1)-T(2,1) T(1,2)-T(2,2)];

%%    SYSTEM LOCKED PRESSURE @3.75Nm

P =    [3.75/((X(1,1)*1e-3)*(X(3,1)*1e-6) + (X...
    (2,1)*1e-3)*(X(4,1)*1e-6))...
    3.75/((X(1,2)*1e-3)*(X(3,2)*1e-6) + (X...
        (2,2)*1e-3)*(X(4,2)*1e-6))]*1e-5;

%% Display values and results
disp('Master cylinder values:')
disp( '            Rotation        Flexion')
disp(['Diameter:   ' num2str(C(1,1)) '   [mm]  ...
        ' num2str(C(1,2)) '   [mm]'])
disp(['Stroke:     ' num2str(C(2,1)) '[mm]  ...
        ' num2str(C(2,2)) '   [mm]'])
disp(['Area:       ' num2str(C(3,1),'%.1f')  '...
    [mm2]     ' num2str(C(3,2),'%.1f') '[mm2]'...
    ])
disp(['Volume:   ' num2str(C(4,1),'%.1f') '[...
    mm3]    ' num2str(C(4,2),'%.1f') '[mm3]'])
disp(' ')
disp('Vane cylinder values measured from ...
    solidworks:')
disp( '                                      ...
    Rotation     Flexion')
disp(['Nositive leverage arm (r_1):     ' ...
    num2str(X(1,1),'%.1f') '[mm]        ' ...
    num2str(X(1,2),'%.1f') '[mm]'])
disp(['Negative leverage arm (r_2):     ' ...
    num2str(X(2,1),'%.1f') '[mm]        ' ...
    num2str(X(2,2),'%.1f') '[mm]'])
disp(['Positive area:                  ' ...
    num2str(X(3,1),'%.1f') '[mm2]      ' ...
    num2str(X(3,2),'%.1f') '[mm2]'])
disp(['Negative area:                   ' ...
    num2str(X(4,1),'%.1f') '[mm2]      ' ...
    num2str(X(4,2),'%.1f') '[mm2]'])
disp(['Maximum volume:                  ' num2str...
    (X(5,1),'%.1f')  '[mm3]   ' num2str(X(5,2)...
    ,'%.1f') '[mm3]'])
disp(['Minimum volume:                  ' num2str...
    (X(6,1),'%.1f')  '[mm3]    ' num2str(X...
    (6,2),'%.1f') '[mm3]'])
disp(' ')
disp('Difference between positive and ...
    negative volumes:')
disp(['Rotation desired volume: ' num2str(X...
    (5,1)-X(6,1)) ' mm3, to get the desired ...
```

```
    motion'])
disp(['Flexion desired volume: ' num2str(X...
    (5,2)-X(6,2)) ' mm3, to get the desired ...
    motion'])
disp(' ')
disp('Moving vane:')
disp(['Rotation Torque: ' num2str(Torque(1),'...
    %.3f') ' Nm'])
disp(['Flexion Torque:  ' num2str(Torque(2),'...
    %.3f') ' Nm'])
disp(' ')
disp('Pressure for these torques:')
disp(['Rotation Pressure: ' num2str(p(1),'%...
    .3f') ' bar'])
disp(['Flexion Pressure:  ' num2str(p(2),'%...
    .3f') ' bar'])
disp(' ')
disp('Pressure at 3 Nm torque for the locked ...
    vane:')
disp(['Rotation Pressure: ' num2str(P(1),'%...
    .3f') ' bar'])
disp(['Flexion Pressure:  ' num2str(P(2),'%...
    .3f') ' bar'])
```

Appendix F
Technical Drawings

Not available to the public.

II

Literature Study

ABSTRACT

Literature concerning upper extremity prostheses, wrist function is an aspect often not meeting the user's demands. Wrist movement, control, and functionality are often perceived as inadequate. This results in inconvenience when used, which could lead to abandonment of the prosthesis. This literature study aims to gain an understanding of prosthetic wrist function and the problems with current solutions, resulting in requirements for a new prosthetic wrist design. Relevant literature was collected via a search of PubMed, Scopus and Google Scholar with a broad variety of keywords. The search to reach the requirements was divided into four stages: *1.Healthy wrist function.* Within a healthy wrist two degrees of freedom (DoF) where identified. Forearm rotation was also desired as a DoF for prosthetic wrists. Values where identified for active- and functional range of motion (RoM), joint torques, and joint stiffnesses of the healthy wrist joint. *2.Existing Devices.* Commercially available wrist devices where found for passive and active prostheses, both body-powered and externally powered. These devices are available for all DoF's for passive prostheses, and for one and two DoF's for active prostheses. A question arose while searching for wrist devices: why is there still this demand for (better) devices? This question remained unanswered. *3.Prosthesis control.* Several control methods where identified along with their advantages and disadvantages. One of these control methods is hybrid control, but little research is found regarding this subject. Extended physiological proprioception was found to be the biggest advantage, and is present in body-powered prostheses. Furthermore mental workload and intuitive control are found to be important aspects of prosthesis control that should be of primary concern when the number of independent simultaneous DoF's controlled is increased. *4.Mechanism considerations* are found for the order of DoF's and compensation mechanisms. Also the validation of prostheses by an assessment tool is found. In conclusion, this study found very limited results for hybrid control solutions; therefore possibilities in hybrid control should be investigated, and are seemingly promising. A list of parameters and considerations is constructed and should be used when designing a prosthetic wrist. The control of prostheses with multiple independent simultaneous DoF's should be focused on, with cosmetics and comfort kept in mind. Future research is recommended to focus on identifying the reason of user dissatisfaction towards prosthetic wrist devices with current supply of commercially available devices.

1

INTRODUCTION

1.1. BACKGROUND

Throughout history mankind has tried to provide replacement arm/hands for people with an arm defect. One of the oldest known examples dates back to about 300 B.C. [1]. Since then many different designs were developed to aid people with a limb defect. Other recorded examples date back from medieval ages, as can be seen in Figure 1.1. But the most progress was made through aftermaths of war [1].

There are two main causes for limb loss, congenital limb deficiency and amputation. The latter can either result from traumatic injuries or diseases [2]. These two causes leave the affected to opt for a prosthetic device that replaces the limb. The loss or absence of a limb is going to affect the efficiency in completing activities of daily living. A patient with a prosthetic hand regains some functionality. But the prosthesis does not only have a mechanical function. There also is an appearance and social function to the prosthesis [3]. In any case, the person has to alter their lifestyle. Be it from the beginning of their life, in an instant, or gradually.

A brief explanation about different kinds of upper arm prostheses is needed to understand further information and literature. There are two kinds of prostheses: passive and active prostheses. Within the active prostheses there are body powered prostheses (BP) and externally powered prostheses (EP). BP are prostheses that obtain their control and actuation from another part of the body, e.g. by means of a harness and a cable to harness the movements of the shoulder. EP are prostheses that obtain their actuation from an external energy source, e.g. battery or pressurized gas in a cylinder. Some passive prostheses have the ability to manipulate the hand (fingers or gripper). This is done with the other hand or an object.

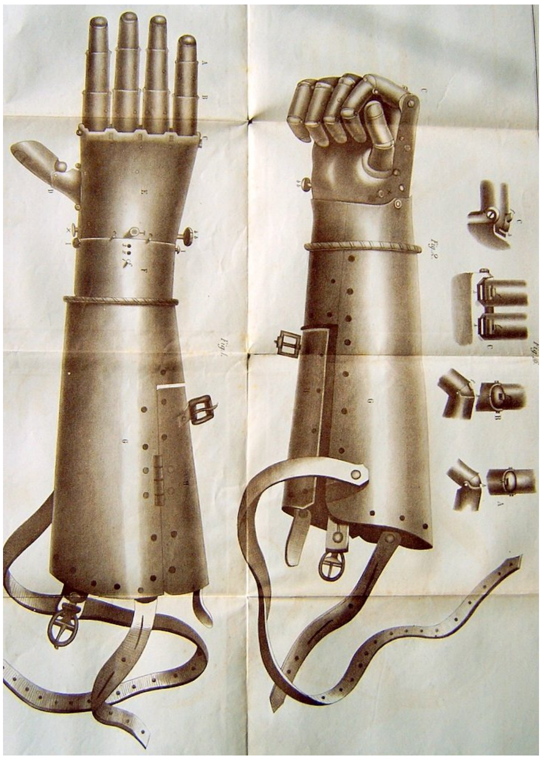


Figure 1.1: Artificial hand owned by Götz von Berlichingen [1480-1562]. A German knight, who lost his right hand in battle and replaced it with a iron hand. `http://en.wikipedia.org/wiki/Götz_von_Berlichingen#/media/File:Götz-eiserne-hand1.jpg`

1.2. USER DEMANDS

Literature found regarding evaluations, user satisfaction, and rejection rates [4–10] for the upper extremity prostheses were summarized by Biddiss and Chau [11]. The summary shows that mean rejection rates are found of 48% and 35% for BP and EP respectively for pediatric devices. Lower rates (26% BP and 23% EP) where observed in adult devices. Biddiss *et al.* [4] also performed their own survey where the rejection rates were 39%, 53%, and 50%, for myo-electric hands, passive hands, and body-powered hooks respectively. Solutions to tackle these rejection rates might be found in three basic needs of the patient, mentioned by Plettenburg [12, Chapt. 3.4 & 4]: Cosmesis, Comfort and Control.

Whether one should wear a prosthetic replacement of the limb is entirely up to him/herself. However giving the option to choose, it can be expected that the prosthesis should be beneficial (increase their quality of life [11]) to wear. Because of this, the user demands should be focused on development of the prosthetic hands [4, 12, 13]. You wouldn't buy a tennis racket without strings, for this would not meet your demands of a tennis racket. Then why would you buy a prosthesis that would not meet your demands? For instance if you desire a realistic appearance, you wouldn't buy a non-anthropomorphic looking hand prosthesis (e.g. a hook).

Other literature was found not included in the summary of Biddiss and Chau [11]. Where for instance LeBlanc [14], Roeschlein and Domholdt [15], Kyberd and Wartenberg [16], who all pointed out that function of the prosthesis is an import aspect for further development. Also natural moving, pleasant appearing, inconspicuous prosthesis, and movement- and grip function where mentioned in various literature. Other literature always seems to be in accordance with the three main categories mentioned before. Namely cosmesis, comfort, and control. Various aspects that where found in the literature [17–19] that would fit within the demands described below. These demands always seem to return (papers in Biddiss and Chau [11] are already summarized):

- Appearance (Cosmesis) [11, 14, 19]
- Comfort of harness for BP [11, 13, 14],
  weight of the prosthesis (for both but more so for EP) [11, 13, 17]
  and perspiration discomfort [18].
- Improved and ease of control [4, 7, 11, 13]
- Overall function [13, 14, 17, 19, 20], where wrist movement/control [4, 11, 17, 20, 21],
  (wrist) mobility and increased range of wrist motion [16, 21] of the prosthesis are desired.

These demands can all be put in the three categories mentioned by Plettenburg [12]. The first item falls under cosmesis, the second item under comfort and the last two can be categorized under control. From the literature it can be concluded that each category is just as important, but may very in importance on individual preferences. Adams *et al.* [22], Franko *et al.* [23], and Bland *et al.* [24] all have performed a clinical study to evaluate functional decrease of the hand with a restricted or absent range of motion (ROM) of the wrist. All these studies conclude that the function of the hand decreases with increasing restriction of the ROM of the wrist. From these studies regarding impaired wrist motion resulting in decreased hand function [22–24], it can be concluded that a prosthetic hand would also benefit from a sufficient functional ROM of a prosthetic wrist. Since it would not matter if it concerns a real hand or an artificial hand for a desired increase in hand function.

Now the goal for this literature study can be formulated:
Obtain an understanding of prosthetic wrist function and the problems with current solutions, resulting in requirements for a new prosthetic wrist design.

Now that the goal has been identified, the structure of this literature study is mapped out. The first subject of interest is wrist function of healthy wrists. This should give insight on the functionality of healthy wrist. This could then be used as a comparison measurement tool for wrist prostheses. The next step is to look into existing devices, since they show what has already been done in the field of wrist prostheses and what is currently commercially available. After that the control of prosthesis and mechanisms is studied. So that a full spectrum of the use and control of a prostheses can be identified.

1.3. METHOD

1.3.1. LITERATURE SEARCH

The relevant literature was collected via a search of Pubmed, Scopus and Google Scholar using the Keywords seen in Table 1.1. An example of the use of the keywords is: *Wrist movement AND (prosthesis OR prostheses OR prosthetic) NOT surgery NOT implant* etc. (where * is a wild card in Pubmed).* Google has been used to find commercially available devices. These devices are available for the patients and therefore would be

Table 1.1: Used and excluded keywords

<table>
<tr><th>General keywords
Keywords used in most searches</th><th>Optional keywords
Keywords depending on the search</th><th>Excluded keywords
Keywords used to exclude certain fields of research</th></tr>
<tr><td>• Prosthesis OR prostheses OR prosthetic
• Upper limb OR upper extremity
• Wrist OR hand</td><td>• Body powered
• Externally powered
Introduction
• Abandonment
• Problem
• Evaluation
• Survey
• Satisfaction
Wrist function
• Function
• Motion
• Movement(s)
• Rotation(s)
• Activities of daily living (ADL's)
• Active/Functional range of motion (ROM)
• Compensat(-e, -es, -ion, -ory)
• Torque(s)
• Moment(s)
• Coupling between wrist flexion–extension AND radial–ulnar deviation
Existing Devices
• Unit
• Device
• Design
Control of the prosthesis
• Control
• Coupl(-e, -ed, -ing) movements/motions
• Hybrid(-s) (system)
• Combined/mixed control (methods)
• Myoelectric
• Intuitive
• Simultaneous & sequential
• Underactuated</td><td>• Surgery
• Arthroplasty
• Implant(-ed, -s, -ings, -ation)
• Fracture(s)
• Computer
• Dental
• Radiation
• Bone(s)
• Cell(s)
• Cancer</td></tr>
</table>

more likely to appear in a general search engine like Google. Worldwide Espacenet and United States Patent and Trademark Office are used to look into patents. Since patents could provide devices, principles or mechanisms that aren't commercially available yet and produced by businesses and/or companies without scientific research papers.

Another method used to find relevant papers is the use of references in useful and relevant papers. Further the different search engines have the option to find so called "cited by"- papers. This way it is also possible to find papers that were published after a particular paper. If an author seemed to be a useful source of contributing information to this study, other research papers of that author would be looked up and selected.

1.3.2. SELECTION CRITERIA

These last methods yielded more results than the use of keywords. Probably due to the very limited research done in the field of wrist function of prostheses. The results of the search with keywords was manually filtered by excluding papers that where in any way about, decoding or improving EMG (Electromyography) sensor signals, improving grip patterns of externally powered hand prostheses, and any papers about wrist prosthesis that mean implants, surgical papers about surgery, arthroplasty, fractures, dental papers, radiation or about computers that weren't filtered by the excluded keywords options in the search engines.

2

WRIST FUNCTION

The goal for this chapter is to get an understanding of a healthy human wrist and its function(s). Where it is focused on movements and joint torques, instead of the anatomy. This way the desires from the user can be seen from the perspective of the lost functionality of a healthy wrist.

The human wrist technically has two degrees-of-freedom (DoF); Flexion/extension and radial/ulnar deviation. Rotation (Pronation/supination) of the wrist comes forth from the forearm, but is seen as a desired wrist function for this study. To make no misunderstanding in terms used throughout different literature, the definitions of the standard position of the wrist and forearm are used from Wu *et al.* [25], which is visualized in Figure 2.1. The angular movements seen in Table 2.1 (from Taylor [26]) are partially different from the definitions used by Wu *et al.* [25]. The motions of the wrist are visualized in Figure 2.2, where P-S (Figure 2.2a) denotes the rotation about the EW-axis, F-E (Figure 2.2b) is the rotation of the hand about a vertical axis at W, and R-U (Figure 2.2c) is the rotation of the hand about a horizontal axis perpendicular to the EW-axis. These terms used throughout this paper can be seen in Figure 2.3.

2.1. ACTIVE RANGE OF MOTION

Active range of motion (RoM) is the motion that is allowed by the anatomy of the wrist. This RoM varies per person, but can be averaged. This has been done and the values for the active RoM are found by Arnold and Grajek [28], seen in Table 2.2. They retrieved the information from:

Norkin, C., White, D. (2009). Measurement of Joint Motion. A Guide to Goniometry.

Other angles of active RoM are found by Ryf and Weymann [27], Taylor [29], Braune and Fisher [30], and Carlson [31], also seen in Table 2.2. These values are similar and therefore any of them can be taken.

2.2. FUNCTIONAL RANGE OF MOTION

The functional range of motions, are the motions that are used to perform functional activities, thus only a portion of the maximum available range of motion (active RoM) could suffice for certain tasks. Meaning that the value of the functional RoM depends on the task, and therefore can vary heavily per task. Functional

Table 2.1: Principal Components and Motions of the Upper-extremity System. After Taylor [26]

Segment	Bones	Axis	Angular movements
Shoulder	Clavicle, scapula	OH	Flexion-extension, elevation-depression. Rotation neglected.
Arm	Humerus	HE	Flexion-extension, elevation-depression, medial and lateral rotation.
Forearm	Radius, ulna	EW	Flexion-extension, pronation-supination (wrist rotation)
Hand	Carpals, metacarpals, phalanges	WK	Radial and ulnar flexions, volar and dorsal flexions. *(Radial and ulnar deviation, flexion and extension [25])*

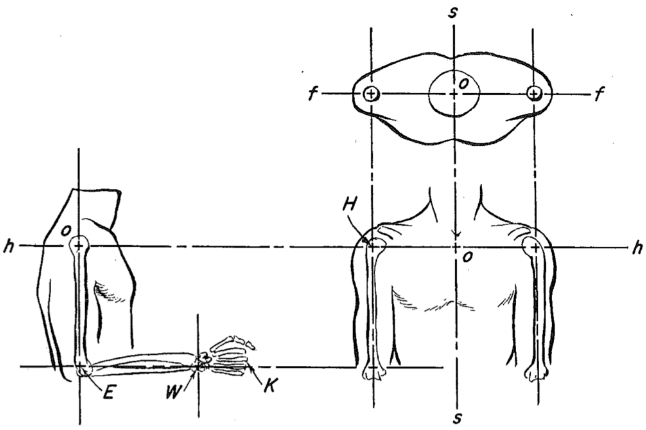
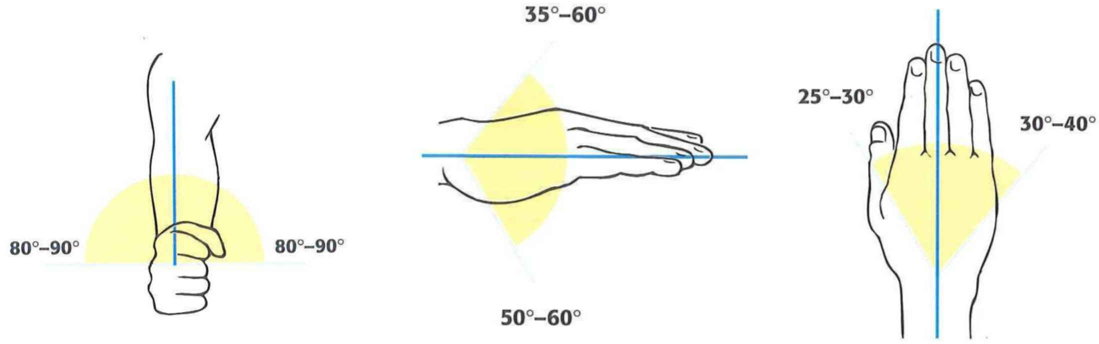


Figure 2.1: "Upper-extremity system in standard position. Body reference planes: ss, sagittal; hh, horizontal; ff, frontal (coronal). The radioulnar wrist axis is vertical through W" - Taylor [26]



(a) Pronation and supination *(b) Flexion and extension* *(c) Radial and ulnar deviation*

Figure 2.2: Visualization of the active range of motion [27]

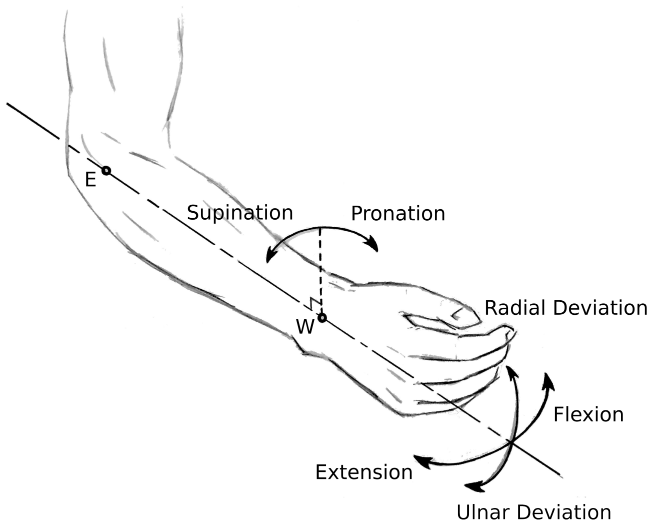


Figure 2.3: Movement terms of the wrist and forearm in the natural position, where the elbow is denoted with E and the wrist with W. The natural position of the forearm [25](the radius relative to the ulna) is when the elbow is flexed 90° and the thumb is pointing to the shoulder (up). The natural position of the wrist [25](natural flexion/extension and natural radial/ulnar deviation) is when the third metacarpal longitudinal axis is parallel to the longitudinal axis of the radius.

Table 2.2: Active Range of Motion of the wrist [27–31]

Movement		Neutral position		
Rotation	Pronation		Supination	
	84° – 76°	0°	80°	[28]
	90° – 80°	0°	80° – 90°	[27]
	90°	0°	80°	[29]
	71°	0°	84°	[31]
Deviation	Radial		Ulnar	
	25° – 20°	0°	30° – 39°	[28]
	30° – 25°	0°	30° – 40°	[27]
	27°	0°	27°	[30]
	19°	0°	33°	[31]
Flexion	Flexion		Extension	
	80° – 60°	0°	60° – 75°	[28]
	60° – 50°	0°	35° – 60°	[27]
	84°	0°	84°	[30]
	73°	0°	71°	[31]

RoM is more important than active RoM since the full range of motion is seldom used while performing tasks where wrist motion is needed. Literature found of the functional range of motion shows that this is true; smaller angles of RoM suffice in most activities/tasks. This can be seen in Table 2.3. It also shows for which activities of daily living the ranges apply. A more clear table with the same but combined/summarized values is Table 2.4. These values compared to the values of active RoM in Table 2.2 indeed show that lower ranges of motion suffice. The movements with the wrist-joint angle frequency plot by Taylor [26], seen in Figure 2.4, gives more insight on the distribution of reached maximum angles during activities of daily living (ADL).

As one can see in Figure 2.4a, motion between 0° and 60° pronation is most frequent used for activities of daily living. These motions happen more frequent than motions (angles) of pronation and supination that lie outside this bandwidth. The same applies for extension of the wrist (dorsal flexion in the figure) in Figure 2.4c, for angles of motion between 0° to 30°. Figure 2.4b shows that for radial and ulnar deviation quite a small bandwidth of angles suffices. The values from Table 2.2 & 2.4 coincide with the frequency plots of Figure 2.4. Therefore it may be assumed that this distribution of angle frequency can be used for further analysis.

An interesting research paper was found which showed that with wrist movements, extension is used more frequently in combination with radial deviation and flexion more often combined with ulnar deviation [32]. Which is basically the movements a dart thrower makes with his wrist while throwing a dart. This is confirmed by Crisco *et al.* [33] (with 6 cadaver wrists) and by Li *et al.* [34] and Formica *et al.* [35] (both with 10 alive subjects). They all concluded that the mechanical axes of the wrist are orientated obliquely to the anatomical axes. The coupled movements coincide with the stiffnesses of the wrist. Where the wrist is coupled in the direction of flexion with ulnar deviation, and extension with radial deviation (seen in Figure 2.5a); the wrist is stiffer in the direction of flexion with radial deviation, and extension with ulnar deviation [33, 35–38] (seen in Figure 2.5b). This basically shows that these directions of least and most amount of passive stiffnessess of the wrist are orthogonal to each other, and therefore it can be concluded that the motion of least resistant is most frequently used. This could be useful if it is desired to combine the motions of flexion/extension and deviation in the design of the wrist prosthesis. In the thesis of Charles [39] it is concluded that for 2 DoF (flexion/extension and radial/ulnar deviation) tasks, the test subjects where using three DoF's (including pronation/supination). Questions asked where "Does it reflect an attempt to straighten paths? Or perhaps to follow a 'path of least resistance' in an effort to minimize stiffness torques?". This also reflects the use of the coupled motions.

2.2.1. ACTIVITIES OF DAILY LIVING

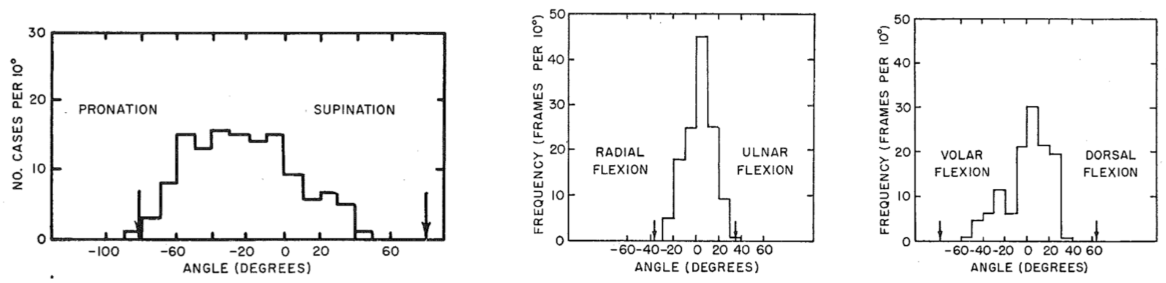
Movements often used can be taken from a list of activities of daily living. These ADLs can be used as a measurement of functional RoM of a prosthesis. If more than one ADL cannot be performed or it takes longer to perform this ADL with a prosthesis than without, it can be imagined that the prosthesis is unlikely to be

Table 2.3: Maximum values for the functional Range of Motion of the wrist, where the motions are from neutral position (0°) [31, 40–43]

Source	Activities of Daily Living (ADL)	Motions	
Brumfield and Champoux [40]	Personal care	Flexion 10°	Extension 15°
	Eating, drinking, using a telephone, reading	Flexion 5°	Extension 35°
Palmer *et al.* [41]	Normal functional RoM	Flexion 5°	Extension 30°
	Normal functional RoM	Radial dev. 10°	Ulnar dev. 15°
Ryu *et al.* [42]	Maximum motion	Flexion 54°	Extension 60°
	Maximum motion	Radial dev. 17°	Ulnar dev. 40°
	Majority of tasks with 70% of max. RoM	Flexion 40°	Extension 40°
	Majority of tasks with 70% of max. RoM	Radial dev. 20°	Ulnar dev. 20°
Morrey *et al.* [43]	Tie a shoe, dressing and hygiene	Pronation 0°	Supination 50°
	Eating, using a telephone and opening a door	Pronation 50°	Supination 50°
Carlson [31]	Suggested minimum ranges of motion required for normal daily activity	Pronation 60°	Supination 30°
	Suggested minimum ranges of motion required for normal daily activity	Flexion 20°	Extension 30°
	Suggested minimum ranges of motion required for normal daily activity	Radial dev. 0°	Ulnar dev. 0°

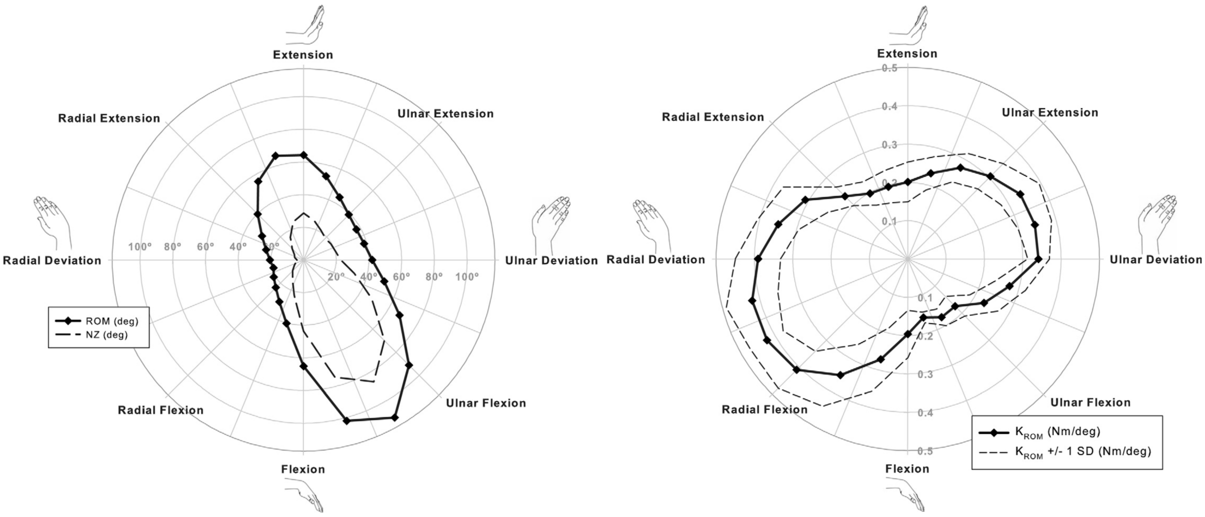
Table 2.4: Combined maximum values of functional Range of Motion of the wrist, where the motions are from neutral position (0°) [31, 40–43]

Pronation 50° – 60°	Supination 30° – 50°
Radial deviation 0° – 20°	Ulnar deviation 0° – 20°
Flexion 5° – 54°	Extension 15° – 60°



(a) Pronation and supination. *(b) Radial/ulnar deviation.* *(c) Flexion and extension.*

Figure 2.4: Frequency plot of wrist-joint angles. "Histograms obtained from analysis of 128 frames taken from kinematic studies of one nonamputee subject performing 51 daily-living activities." – Carlson [31]



(a) Combined wrist RoM. *(b) The mean values for wrist stiffness.*

Figure 2.5: Images after Crisco et al. *[33]. The resulting stiffness envelope from 2.5b is essentially orthogonal to the range of motion and neutral zone envelopes of 2.5a.*

used for those activities. If the activities stack up for which the prosthesis takes longer to perform those tasks, it is more likely to be left at home. This is also mentioned by Doeringer and Hogan [44]:

> "Many arm amputees (particularly those with one sound arm) feel that a prosthesis offers too little cosmetic benefit or functional advantage to compensate for the discomfort and inconvenience of wearing the device."

This can easily be deducted, for instance if a task can be faster/cost less energy without a prosthesis, why bother wearing it? Thus most of the time the prosthesis is used is in bi-manual tasks. Since both hands are needed to perform these tasks. Roley *et al.* [45] produced a list of general Activities of Daily Living which have been reduced to bi-manual tasks according to own reasoning. This is shown in the following summation:

- Dressing
- Feeding
- Personal device care
- Personal hygiene and grooming

These items show that for an activity to be bi-manual something is held by one hand and subsequently the other hand performs another task necessary to complete the overall task, e.g. putting toothpaste on the toothbrush, closing a zipper, or cleaning your glasses. A list of activities of daily living focused on prosthesis use, can be taken from the survey conducted by Jang *et al.* [19]. The following list shows the ADLs by Jang *et al.* [19] arranged in the categories by Roley *et al.* [45] for bi-manual tasks:

Personal hygiene and grooming:
- Washing face (getting soap from the soap bottle)
- Brushing teeth (opening toothpaste and putting it on a toothbrush)
- Caring for nails (remaining hand)

Dressing:
- Putting on and taking off underwear
- Buttoning shirts
- Closing zipper (of pants, jacket, or even a bag)
- Wearing socks
- Tying shoe laces

Feeding:

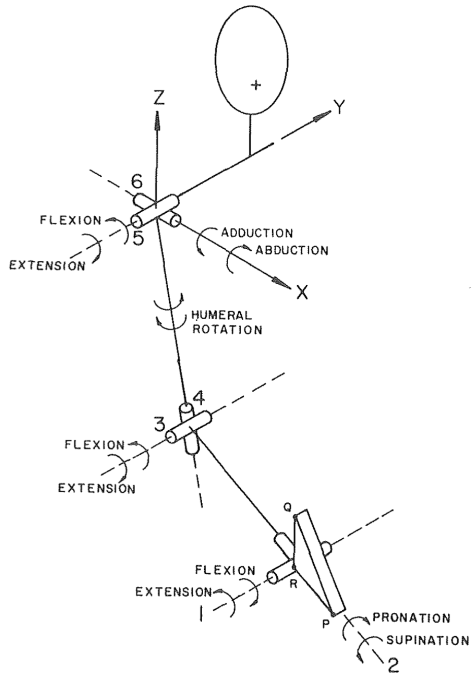


Figure 2.6: Kinematic model of the upper arm by Carlson and Hock [46]. Here the head is depicted as a circle, and the hand is depicted as a triangular block. Also the palm of the hand is facing down (pronated position from established neutral position), since flexion is downwards and extension is upwards.

- Eating with knife and fork
- Opening and drinking caned beverages
- Opening and drinking bottled beverages

Personal device care:

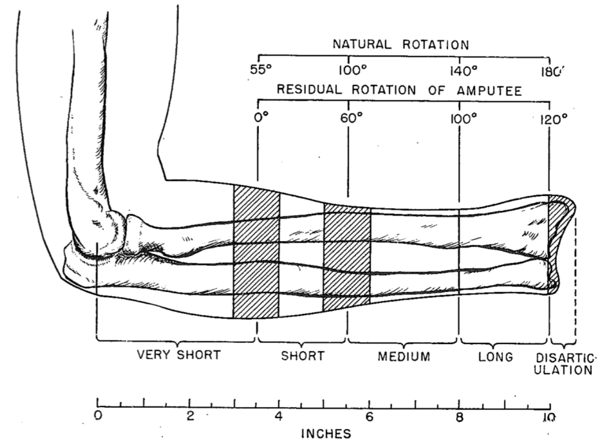
- Putting on and taking off prosthesis on your own
- If applicable, cleaning glasses

Other:

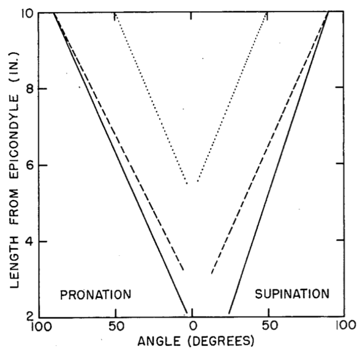
- Using scissors
- Opening door by turning door knob (when holding something)
- Opening envelopes
- Turning steering wheel (driving in general)

2.2.2. BODY ENGLISH

When one is lacking one or more DoFs in a joint, other joints will compensate for this motion. We all can, in some way, give an example of this effect. For instance a sprained ankle will result in a different walking gate, and may give more sway from side to side while walking. These compensatory motions are called "Body English" by Carlson and Hock [46]. For lack of wrist movement the same principle applies; other body parts will compensate [47–50] in movement for a lost degree of freedom. In Figure 2.6 it can be seen that if there is no more pronation/supination the only other way to rotate the hand is by lifting the upper arm up (abduction of the humerus). If flexion/extension was limited or unavailable, depending on the rotated position, various other joints can be used to get the desired angle. The compensation for the absence of a DoF shows that even though the prosthetic wearers are able to perform certain tasks while compensating, the tasks could be more difficult to perform. This is shown by Carey *et al.* [47]. Here three groups (able bodied, able bodied with a wrist brace, and prosthesis users) where examined in four ADLs. This research shows that the prosthesis users show more compensating movements than the able bodied, but the able bodied with restricted wrist motion (with a brace) showed similar compensatory movements as the prosthesis users. Thus the loss of wrist function will result in a more limited set of motions available to the user, which could lead to inconvenient compensatory movements.



(a) Below elbow amputee achievable rotation on the basis of residual limb length.



(b) Forearm rotation. Solid lines, radial-ulnar rotation range of a skeleton; dashed lines, mean torsion of flesh in five non-amputee subjects; dotted lines, estimated socket rotation, based on six amputees.

Figure 2.7: Pronation/supination of the residual limb. After Taylor [26]

Taylor [26] shows that, for pronation/supination, with decreased residual limb length the angle of rotation will decrease dramatically (Figure 2.7a). Where non amputees can rotate the full 180°, amputees can only rotate their forearm 120°. That translates roughly to one third loss in range of motion. When the length of the forearm is less than 60% of the full length, the rotation of the stump has no more effect on functional rotation. This can be seen in Figure 2.7b, at that length the skin will prevent the rotation of the bones be translated to functional rotation of the socket (dotted line). Thus if certain movements would require rotation of the wrist, the movement would have to come from some other place than the forearm.

2.3. JOINT TORQUES

Not only the motion of the wrist are important, also the torques able to be generated are important. Table 2.5 shows the found wrist joint torques for all the degrees of freedom. It can be seen that very limited information is available about the torques of the wrist joint, and the way of measuring wrist torque is done in various ways. But none have measured joint torques about their mechanical axes, explained in Chapter 2.2. The most frequent used mechanical axes are oblique to the anatomical axes of rotation. The wrist joint torques are measured around anatomical axes. In Table 2.5, wrist torque values for neutral position are shown by Taylor [29]. Taylor [26] showed values for full range of pronation/supination. Seo *et al.* [52] measured values for wrist flexion/extension torque while exerting a grip force for a range of grip strengths. Delp *et al.* [51] probably did the most extended research, where torques for different motions are measured in the most frequent reached range of that particular motion. But none did an evaluation of the wrist torque about the coupled range of motion. The relevance of this detail is probably a minor detail, since the values of the torques are most likely

Table 2.5: Wrist joint Torques

Movement	Torques [Nm]		
Rotation	Pronation	Supination	
	12.4*	13.0*	[29]
	9.9 – 14.7*	9.0 – 14.7*	[26]
Deviation	Radial	Ulnar	
	14.7*	16.9*	[29]
	7.9 – 15.3	5.9 – 11.9	[51]
Flexion	Flexion	Extension	
	22.6*	15.3*	[29]
	5.2 – 18.7	3.4 – 9.4	[51]
	9.1 ± 4.5 – 12.2 ± 5.5	6.0 ± 2.8 – 6.6 ± 3.3	[52]

* Values converted from lb-in to Nm

to be in the same range, or somewhere in between.

2.4. DISCUSSION

Relating back to the goal of this chapter (to get an understanding of the healthy human wrist and its functions), it is clear that the main function of the wrist is to position the hand. The range of motion to do so, can be divided in active and functional range of motion. Where active RoM is the maximum achievable RoM allowed by the anatomy, and the functional RoM is most used RoM for activities of daily living. The other function is to apply torques. Summarized values for these functions can be found in Table 2.6. The values for this table should be used as requirements for a new prosthetic wrist design. The suggestion is to use the functional RoM for the range, but use the active RoM to know the full range of motion. For the Torques it can be said that the values in Table 2.6 are rather high for an active prosthetic wrist, but nonetheless should be kept as a desired.

Table 2.6: List of Requirements for wrist function

Movements		Maximum range values		Unit
		Pronation	Supination	
Rotation	Active RoM	71 – 90	84 – 90	[°]
	Functional RoM	50 – 60	30 – 50	[°]
	Torques	10 – 15	9 – 15	[Nm]
		Flexion	Extension	
Flexion	Active RoM	50 – 84	35 – 84	[°]
	Functional RoM	5 – 54	15 – 60	[°]
	Torques	5 – 23	3 – 15	[Nm]
		Radial	Ulnar	
Deviation	Active RoM	19 – 30	27 – 40	[°]
	Functional RoM	0 – 20	0 – 20	[°]
	Torques	8 – 15	6 – 17	[Nm]

The following considerations should be used as aids for designing a prosthetic wrist, since they give insights on the functionality and the usage of a healthy wrist.

- **Bi-manual activities** of daily living are most likely where a prosthesis is used. A list is found in Chapter 2.2.1.
- **Combined DoFs**, due to passive stiffnessess for Flexion/Extension and Radial/Ulnar Deviation (Figure 2.5), could be used to combine DoFs in the prosthetic wrist to simplify the design and/or control.
- The distribution of the **frequency of RoM**, Figure 2.4, gives more insight on the functional RoM. This could therefore be used as an aid while designing a prosthetic wrist.

3

Existing Devices

This chapter will focus on existing devices. To see what is commercially available to the patients. Making a categorization of these devices will help to see which demands are fulfilled and where improvement is necessary. This categorization can be seen in Figure 3.1.

Existing prosthetic wrists are put in earlier mentioned categories: passive, body powered and externally powered. These are put against the same categories for the prosthetic hands. The difference with hands/hooks is that prosthetic wrists are used to orientate the terminal device. Which is the soul purpose of a wrist. So now possible combinations are filled in with the existing devises. These devices where found by Roose [53] and can be seen in Table 3.1. The devices Roose [53] found are expanded with new found devices to fill in the gaps, as shown in Table 3.2 (For completeness patents also have been looked into, but didn't result in different working principles). Note that it became clear that the DoFs have an order of importance. Since there where no devices available for single DoF of deviation. And hardly any devices for a combination of flexion and deviation. So from most to least important/desirable it would be, rotation, flexion, and then deviation.

Table 3.2 shows the devices available categorized in the control of the wrist prosthesis and the degrees of freedom controllable by the user of the wrist prosthesis. It can easily be seen that not all combinations are available. For either the externally or the body powered prostheses. The next sections try to answer the question of why these gaps are there. They further analyze the differences and functionality of these devices, using the same categorization as used in Figure 3.1.

Table 3.1: Existing devices found by Roose [53]. The motions of the devices are added.

Category	Name	Company	Motions	
Passive	i-limb ultra flex	Touch Bionics	Rotation, discrete flexion	[54]
	MC multi-flex	Motion Control	Discrete flexion	[55]
	Omniwrists	Liberating Technologies	Bending (flexion and deviation)	[56]
Externally Powered	Wrist rotator	Liberating Technologies	325∘ rotation	[56]
	MC Wrist rotator	Motion Control	360∘ rotation	[55]
	Electric Wrist rotator 10S17	Otto Bock	360∘ rotation	[57]
Body Powered	4-Function wrist	Hosmer	360∘ rotation (discrete), discrete flexion	[58]

3.1. Passive Prosthetic Wrists

Passive prosthetic wrists are the most common wrists for prosthetic use. There are two types of functional passive wrists: friction and locking wrists [64]. Both are manipulated by the other sound hand. The first is a wrist that is, for all the degrees of freedom, adjustable for their entire intended range in a continuous matter and the end position, when used for an activity, can either be held by the friction itself or by a locking mechanism, that will clamp the movable part in a fixed position. This way the wrist can be used without moving during the activity. An example is the MyolinoWrist 2000 10V51 [63] (Formerly VASI omniwrist). The other wrist type is lockable in predetermined positions, and therefore is labeled as discrete. I-limb ultra flex

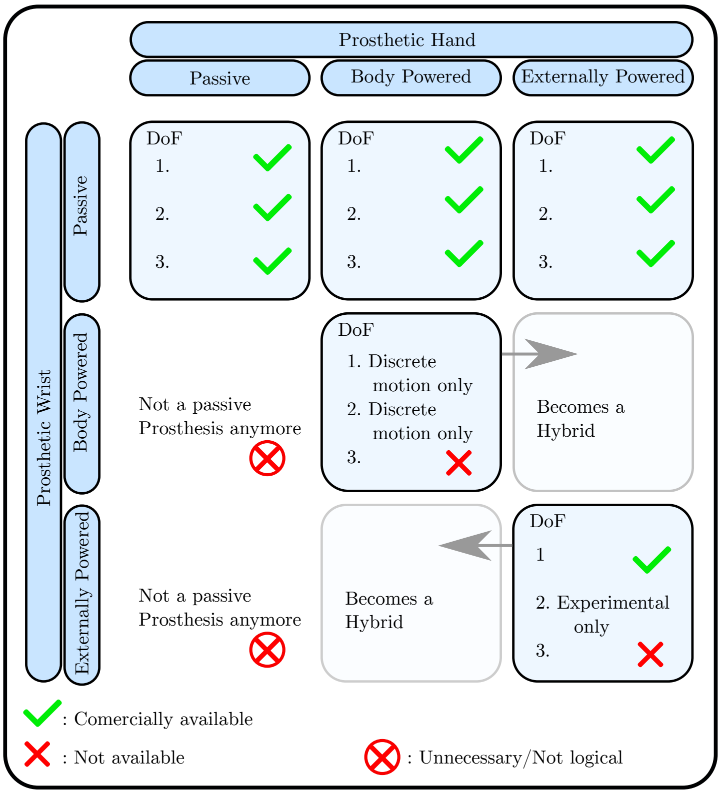


Figure 3.1: Schematic overview of the available combinations of prosthetic hand control and prosthetic wrist control. The degrees of freedom (DoF) are the total number of DoF for a wrist prosthesis. Two and three DoF body- and externally powered wrists can have combination of passive and active motion combinations. The arrows show that the same devices can be used for an alternate prosthetic hand, but that would mean the overal prosthesis becomes a hybrid. This schematic overview is composed with the wrist devices displayed in Table 3.2

[54] is an example of such a discrete passive device for wrist flexion. The advantages and disadvantages of a passive prostheses are summarized with the user demands (Section 1.2) kept as a guideline.
Advantages:

- Simple in design
- Simple control (easy control actions needed)
- No harness (comfort)
- No batteries, motor needed (light weight)

Disadvantages:

- Extra motions are needed, with other hand, to control. This could be a big nuisance since the sound hand is occupied with the control of the wrist. Plus the user needs to cognitively think about the wrist movement and/or position, because of the separate control of the sound hand.

Kyberd [20] showed that overall function of a externally powered prosthetic hand with wrist function increased for just a passive wrist. Kyberd concluded that wrist flexion had a positive impact on the function and it enabled some tasks to be performed with less difficulty and faster completing times. Deijs *et al.* [65] on the other hand concluded that manual functioning and satisfaction did not show positive effects of flexible wrists. But they suggest that flexible wrist units decrease compensatory movements (Body English). So in both cases, the passive wrist already increases overall functionality of the prosthesis.

3.2. EXTERNALLY-POWERED PROSTHETIC WRISTS

As seen in Figure 3.1, externally and body powered prosthesis do not have devices available for all three degrees of freedom. One degree of freedom active externally powered wrist is found at Liberating Technologies [56]. For more DoFs combinations can be made between passive and active degrees of freedom, i.e. not all degrees of freedom need to be of one control/actuation method. For instance the i-limb ultra flex [54] can be equipped with a passive or an active rotator (wrist flexion stays passive for both the rotators). It can be

Table 3.2: Possible combinations between control and degrees of freedom for the prosthetic wrist. (D/C): Discrete/Continuous, and [A/P]: Active/Passive (Applicable for active wrist devices)

Wrist Degrees of Freedom		Prosthetic Wrist Control		
		Passive	Active	
			Body Powered	Externally Powered
1	Rotation	WE Friction Wrist [58] WedgeGrip Wrist [58]	Rotation Wrist (D) [58]	Wrist rotator [56]
	(D/C) Flexion	MC multi-flex (D) [55]		
2	Rotation & (D/C)[A/P] Flexion	i-limb ultra flex (D) [54]	4-Function wrist (D)[P] [58] N-Abler V Series (D)[A & P] [59]	2 DoF Pneumatic (C)[A] [60] 2 DoF Electric (C)[A] [61]
	Flexion & Deviation			Tendon 2 DoF Electric[62]
3	Rotation, Flexion & Deviation	MyolinoWrist 2000 10V51 [63]		
Can be used for Prosthetic Hands:		Passive, Body Powered Externally Powered, Hybrid	Body Powered, Hybrid	Externally Powered, Hybrid

imagined that there are a lot of combinations possible. Way to many to discuss them all. But from the devices found, not all combinations are out there. This has probably something to do with the order of importance of some aspects. One of them is already pointed out earlier: the order of importance of the motions.

Another thing that became clear is that there are prostheses with continuous and discrete motion of the DoFs. With this in mind, knowing that this extra variable increases the amount of combinations of DoFs a device can have, it is easier to first write down the advantages and disadvantages of the active devices. And use these variable combination parameters as recommendations.

The list of advantages and disadvantages, just as for the passive devices, can be summarized with the aid user demands. Since Biddiss and Chau [11] has put down a good summation, this will be used to obtain the advantages and disadvantages for the externally powered prostheses, and later on also for the body powered prostheses. The advantages are [11]:

- Appearance
- Increased pinch strength, better grasp of heavy objects compared to BP
- Ease of operation
- Lack of harness

The disadvantages are [11]:

- Increased maintenance
- Higher cost
- Higher weight
- No sensory feedback [12](explained in 3.3). Although discussed that greater feedback is obtained due to auditory feedback from motor and vibrations through the fitting. But this can be dismissed as it will be disproved at the next section, section 3.3.

Literature was found that seemingly showed good results for EP prostheses [66]. They compared a self developed EP wrist with a "common body powered wrist", but nowhere is stated which common BP wrist is used, nor which socket is used for either prosthesis. There is no reason given why they compare it to a BP and not an existing EP wrist. Therefore this paper is not included in the establishment of the discussion of this paper.

Kyberd *et al.* [61] are the only ones (besides Roose [60]) that developed a two DoFs externally powered wrist prosthesis for the upper extremity. But as can be seen in Table 3.2, these two wrist devices are only in experimental use only. Thus beyond these developments, there are no devices available with two or more DoFs. Which is strange if functionality and natural movements are user demands. So there is this gap between supply and demand. And why this gap is there, has not been answered by this literature search. There is a more elaborate discussion at the end of this chapter.

3.3. BODY-POWERED PROSTHETIC WRISTS

The body powered wrist prostheses are the last category to be discussed. Currently only discrete body powered wrist prostheses are available for patients (Table 3.2). The following advantages and disadvantages are for the overall prosthetic devices but reflect on the wrist unit, and therefore can be used for wrist devices as well. Generally speaking body powered prostheses have an edge over externally powered prosthesis when it comes to [11]:

- Lower weight
- Better finger position feedback (extended physiological proprioception [44]) and object visibility
- Better manipulative and overall function
- Less inadvertent activation, and less effort required to open slightly

Disadvantages [11]:

- Harness discomfort and/or breakage
- Excessive wear temperatures
- Abrasion of clothes
- Wire failure
- Unattractive appearance

Carey *et al.* [67] compared externally powered prostheses with body powered prostheses for a selection of activities of daily living. Findings are that, in order to eliminate the harness with its suspension system, the externally powered prosthesis has to have higher trimlines of the socket. Which in turn limits the elbow motion relative to the body powered prostheses users. Thus that point is debatable in whether it is an advantage or a disadvantage.

The previous Section 3.2 of no sensory feedback continues here. **Extended physiological proprioception** (EPP) is first mentioned by Simpson [68]. EPP is the extension of the intrinsic proprioception of the body. Proprioception according to Doubler and Childress [69]:

> It implies that the manner in which a mechanical device is controlled or used can be such that the operator is able to perceive its static and dynamic characteristics through naturally arising proprioceptive sensations. By eliciting proprioceptive sensations, the device becomes an artificial extension of the operator, part of the functioning person. The feedback information may be fundamentally important in itself or important as a means of monitoring the activity of the device.

So it is the sense of force and position of your limbs. Thus with EPP, the sense of force and position of your limbs is extended beyond the body. The best way to explain is via the cane of a blind man, or the tennis racket of a tennis player. The length and shape of the object, that is held, is learned and by the biological sensors in the joints and tendons, the orientation and position of the cane's end point and the racket is known without looking at it. This is achieved with the proprioceptive sensors of the joints. The extension out the body into the held object is therefore called extended physiological proprioception. The results of the study conducted by Doubler and Childress [69] showed that a prosthesis mechanism with an EPP control of wrist rotation and elbow flexion/extension had functional characteristics comparable to those of the physiological elbow and wrist as defined by tracking capabilities.

This feature cannot be achieved with EP since there is no direct correlation between the input and the output of the control of the prosthesis. A brief explanation in chapter 3.2 says that a disadvantage of EP is no sensory feedback. There are ques from the motors as vibrations and auditory feedback, but this does not give the level of feedback as the EPP obtained from BP.

A way to get around this obvious disadvantage of EP is by expanding the prosthesis with a mechanism that explicitly puts feedback in a mechanism which can be sensed by the user. Here BP takes a big advantage, because it does not need an extra feature to give feedback to the user.

3.4. DISCUSSION

It becomes clear that each type of prosthesis possesses its own benefits but all comes down to personal preferences towards those advantages and disadvantages. For instance playing tennis or table tennis. They are similar yet different, i.e. they have similar rules yet require different gears to play. This difference is purely a personal preference in sport choice. The same holds for prosthetic devices. It is evident that there are wrist devices for prosthetic hands available. Despite this knowledge, from chapter 1.2, it clearly shows that there is a demand for more/better wrist motion/control/function/mobility/range of motion. A question arises for this apparent gap in supply and demand. Something in those prosthetic wrists is not sufficient for the user. This could have a couple of reasons. The simplest most obvious answer could be ignorance, but with current information available seems unlikely. Another one is that the wrist device/unit is not offered as an option for patients that conducted in those surveys. Then it is clear why there is this complaint. But then again, it is also easy to obtain the desired prosthesis via other methods than the prosthetist.

Another reason could be that the control and/or movements are not natural or intuitive enough. This would result in frustration by the user for not being able to control the prosthesis properly. Or it takes to much Body English to control or obtain certain movements.

If this apparent gap cannot be explained by the available surveys conducted, which concluded wrist function is inadequate, a survey should be held specifically targeting the wrist movements of prostheses. Another way to obtain information and complementing the conducted survey is by conducting an experimental setup, where different wrist motions are constrained, with various ways to control (passive/active, continuous/discrete). This way, all the commercially available prostheses can be weighed against the user demands. Biddiss [70] provided the questionnaire in the conducted survey about user experience with upper extremity prostheses. This questionnaire did not provide a clear answer. Other than a statement about the satisfactory wrist movements of a prostheses nothing else was giving answers of why the (current) wrist devices are not sufficient.

Further there is the discussion about all the combinations possible between the degrees of freedom for the wrist prostheses. First the three categories: passive, BP, and EP. These categories can individually control one degree of freedom for a multi-degree of freedom device (e.g. EP rotation with BP flexion). And the motions can be continuous of discrete. The list of all the available combinations will be enormous, and therefore left out. But from the available wrist prostheses an estimate can be established for the order of importance of each option. This can be seen in Table 3.3.

First	⇒	Last
Pronation/supination	Flexion/extension	Radial-/Ulnar deviation
Continuous	Discrete	
Active	Passive	

Table 3.3: Importance of different options for the wrist prostheses. With less DoF's available in a wrist prostheses than three, combinations for movements are available (e.g. pronation with flexion or pronation with deviation). Each motion can be continuous/discrete and active/passive. This table shows an order of importance for each option.

From Table 3.3, new questions arise whether or not continuous/discrete prostheses have an order of importance, or is it also pure subjective preference by the user? What is the limit of discrete intervals where the user cannot distinguish between continuous and discrete motion in the feedback? The same holds for active/passive wrist prostheses, since most of the time the prostheses is used when there is a task that requires both hands (bimanual). This means that users might not mind manipulating the wrist with their sound hand, since the hands are already close together.

But with this knowledge, why is there still this gap in demand and supply? If they wouldn't mind manipulating a passive wrist for bimanual hands, why do the current devices not suffice. Maybe more insight can be obtained in the next chapter.

Lastly extended physiological proprioception is a term used, which provides an understanding of the importance of feedback. To what extend this advantage of EPP benefits BP over EP is unclear and can be a subject of interest for further research.

4

Control of the Prosthesis

Mentioned by Simpson [68], it is more important to examine the choice of the method of control of the limb rather than expediency or novelty. Therefore the control of the prosthesis is going to be investigated. From the literature in Chapter 1.2 the coordination of multiple joints and multiple DoF's can be seen as desirable. It can be understood that with more independent (and simultaneous control) DoF's the mental load on the operator becomes excessive (for instance a helicopter pilot or an operator of an excavator). With prostheses it is the same [31]. For instance in the beginning of controlling an excavator or a helicopter all of your attention is spend towards the controls themselves. Eventually when the movements and controls are learned, the actual control requires less mental focus. Now other activities can be performed in parallel. For the coast guard pilot that could be communication, searching for castaways, or commanding the crew. This can only hold if there is feedback in the system, other than visual feedback. Since if it requires visual feedback (e.g. the operator of the excavator needs to look where the bucket is digging, since that is the goal of an excavator), it takes a lot of mental work load. Wickens and Hollands [71] show that increasing the control of more DoF's increases the mental workload. It also takes more control sites of a prosthesis if there are more DoF's to control. It takes all the pilots limbs to control a helicopter. Therefore adequate control sites for these extra DoF's for the wrist need to be found.

Desirable is control of a prosthesis that is of low mental work load (low conscious control effort) and have a natural and intuitive control [72]. This way, the attention can be put somewhere else, instead of the control of the prosthesis.

Passive control is the control of the wrist with the other hand or an object. Thus the prosthesis is manipulated from outside the prosthesis. Although it is interesting how a passive wrist affects the overall performance of the prosthesis, but no literature has been found on passive wrist control.

4.1. Active Control

Then there is active control. For this part, control of a prosthesis in general is looked at, since there is more literature about the control of a prosthesis than a specific DoF, e.g. wrist prostheses.

Keep in mind that there is a difference between control and actuation. Although with BP the control is also the actuation, with EP control is separate from actuation. This can be explained with a control method other than body powered control or externally controlled. Cineplasty [73, 74], where in Figure 4.1 an example is given, is a good example of this difference. The method of control can be seen, a tunnel is created with a muscle looped around that tunnel. If the muscle is contracted the tunnel will move, and a force can be exerted on a rod that is inserted through the tunnel. As for the difference between actuation and control, cineplasty is a control method, and can be used for either BP or EP prostheses. Where for BP the cable is directly attached mechanically, and for EP the control cable is used as an input for an external energy source to actuate the prostheses.

Another method of control is called peripheral nerve interfacing. This method uses the connection between the prosthesis and the peripheral nerves [75, 76]. What this method does, is have inserted electrodes connected to nerves. This way signals from the nerves can be used as an input to actuate the prosthesis. In the future signals also might be send back into the nerves. This would close the loop, and proprioceptive feedback can be achieved. But this is still in development and the question is how long it will take before this

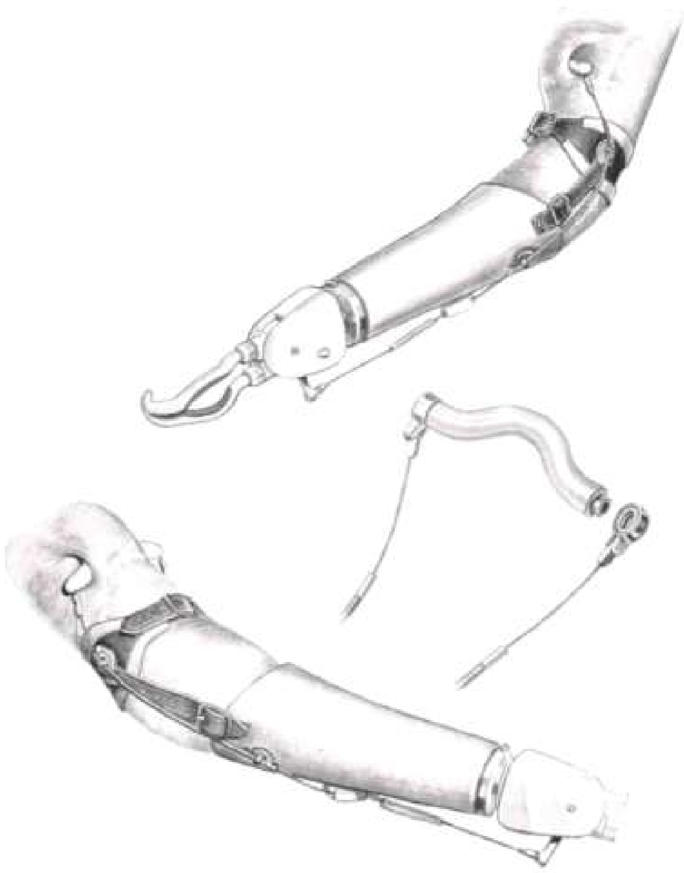


Figure 4.1: Bicep cineplasty example [`http://www.oandplibrary.org`]

is achieved. Navarro *et al.* [77] also shows that there are disadvantages to this method:

- Nerves can be damaged by the implanted electrode Implantation requires delicate surgical procedure, depending on the accessibility of the nerves
- Reverse order of recruitment of motor units during electrical stimulation leading to fast-fatigue production
- Selective stimulation requires careful testing after implantation given the variability infascicular architecture of each peripheral nerve

Another way is rerouting the nerves to unused muscles to amplify the signals coming from the nerves, and is called targeted muscle reinnervation (TMR) by Kuiken *et al.* [78]. After rerouting the signals from the activated muscles are picked up with EMG sensors, or with sensors implanted within the muscles. This method is very similar to myoelectric control of externally powered prostheses (the most common control method for EP prostheses). The same advantages and disadvantages also apply for TMR. Another disadvantage is to use TMR the user also needs to go through surgery.

These three methods of control are invasive procedures which come with their disadvantages, because there are always the risks that come with surgery itself, and the chance of infection or rejection/infection of a foreign material in the body. Other than that, they are still in research or clinical practice status [77]. Cineplasty is not very appealing, cosmesis wise, and might not be practiced anymore for that reason. Peripheral nerve interfaces and targeted muscle reinnervation are only in research or clinical practice status. This research is in full process and especially the peripheral nerve connection shows promise when it comes to idea of human robot interfaces. The idea that merely by thinking of a movement (as we do with our sound arm) and the prosthesis performs that movement "perfectly" (taking into account there should not be any risk or safety hazard for the user), could be said to be the ultimate achievement. But since the research is ongoing, and not achieved yet, the two most common control methods, body control and externally control, are further looked into.

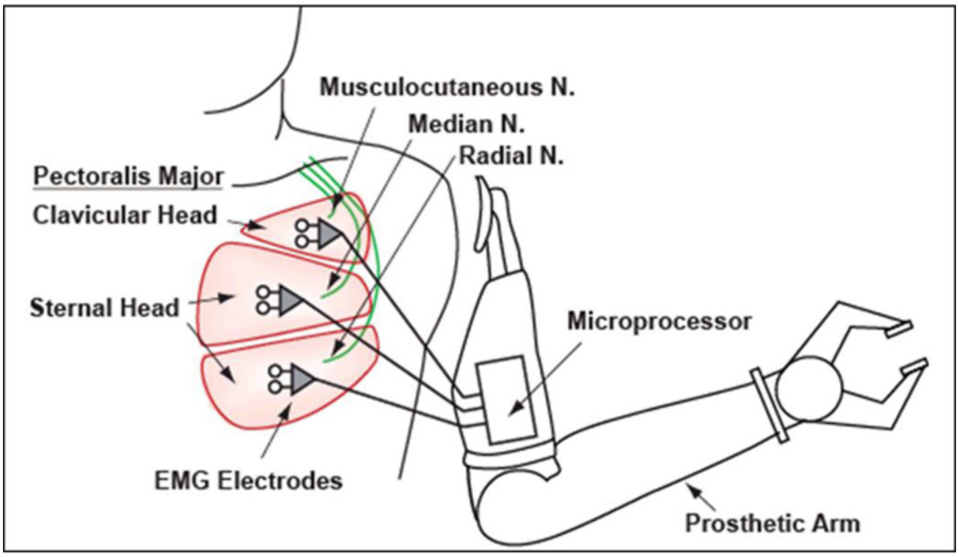


Figure 4.2: Vizualisation of targeted muscle reinnervation [79].

4.1.1. EXTERNALLY CONTROLLED

Looking at Figure **??** and the difficulty to control these machines, it should be clear that the control of a prosthesis cannot be too complex, or else the user would not wear it. Kyberd *et al.* [80] confirm that the control should be simple, also for EP. Since it requires a high level of concentration to control multiple inputs simultaneously. Kyberd *et al.* [80] talk about the control complexity of a multi-DoF EP hand. If an EP hand as multiple grasping functions, with multiple DoFs to control it becomes very complex very fast. If the DoFs of the wrist are then added it becomes almost impossible. If we only look at te wrist, it can be imagined that if the DoFs of the wrist can be reduced to two instead of three, the amount of control effort will be reduced as well. With the knowledge of the coupled wrist DoFs from Chapter 2.2 this could be achieved.

Myoelectric control is the most used control method of EP control and is researched as early as 1948 by Reinhold Reiter [81]. This method uses electromyography (EMG) signals, which records electrical activity of muscles. Signals are taken from nonfunctional skeletal muscles that are contracted. These nonfunctional skeletal muscles are muscles in the residual limb that are unused, e.g. an forearm amputee has muscles left in the forearm that have no more function. These EMG signals are used as input signals for the control of a prosthesis. This control can either be binary control (on-off control or bang-bang control) or proportional control. where proportional control derives its name from the principal where an input is proportional to the output.

Fougner *et al.* [82] states that the debate about proportional control and the necessity and appropriateness is still going. But whether proportional or binary control is taken they both have the disadvantages of being affected by changes in skin impedance, sensitive to placement on the muscle, and require amplification and electrical shielding [77]. Even though the binary control system is less influenced by noise, current systems lack the proprioceptive feedback [83] often achieved with the use of simple body-powered devices. Although research is done to overcome this apparent problem [83], it is no guaranty of success and it still is in the research process of solving this problem. It is also not the only problem. One is signals aren't robust enough after donning and doffing (research trying to solve this is done by Boschmann and Platzner [84]). Another problem is that recalibration is needed every day when the myoelectic prosthesis is used (research trying to solve this is done by Liu *et al.* [85]). One other problem is that limb position influences the performance of a prosthetic device [86]. This means that the control of the device is not consistent throughout the range of motion of the limb. These researches show that there are a couple of disadvantages to this type of control, apart from the earlier mentioned disadvantages in Chapter 3.2.

Atzori *et al.* [87] state that there are three main disadvantages for myoelectric prostheses, which they try to solve. The first is limited DoFs to control. This would result in limited functionality. But this desire would work against the difficulty of controlling multiple DoFs simultaneously. Therefore the controls should be as intuitive and natural as possible. The second disadvantage says exactly that, that there is a lack of intuitive

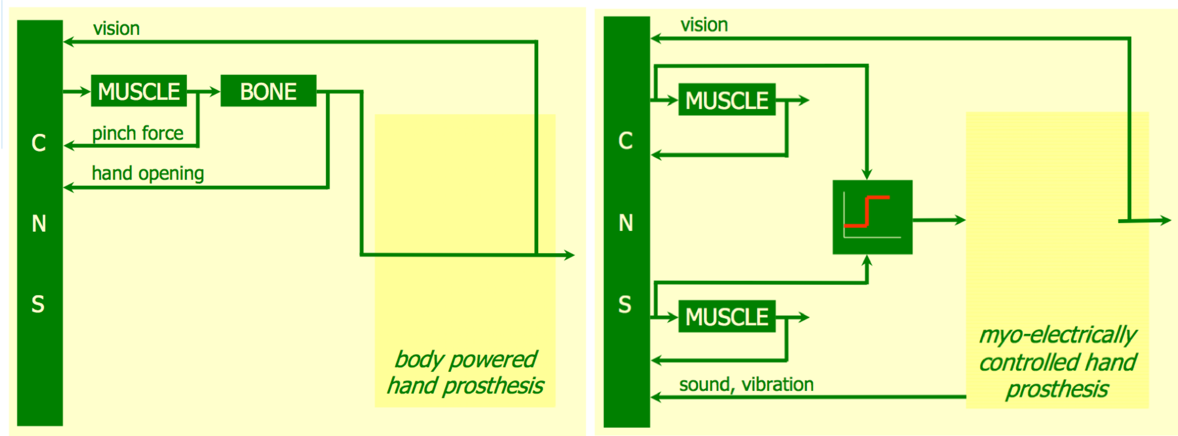


Figure 4.3: Schematic overview for BP and myoelectric prostheses. In accordance to Plettenburg [12]: "In the use of prostheses the feedback is limited. In BP prostheses some feedback is possible through the body parts that control and activate the prosthesis. In myoelectrically controlled prostheses only the visual feedback is left."

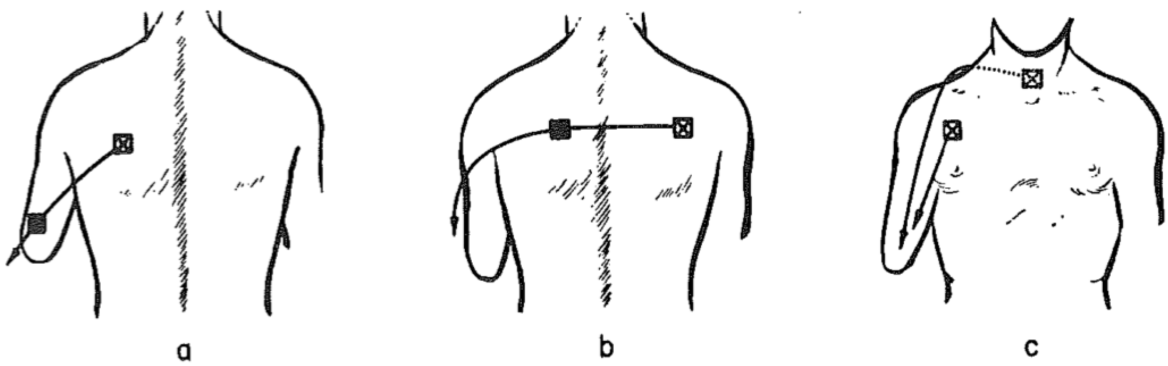


Figure 4.4: Above the elbow harness control sites. In accordance to Taylor [26]: "a, arm flexion control; b, shrug control; c, arm extension control; ⊠ stablization point; ■ attachment piont; → control path to prosthesis."

and natural control. And third, the myoelectric prostheses require long and complicated training procedures. Research recently published by Hahne *et al.* [88] state that these problems described above are still relevant. They are working on solutions to the problem of shifted EMG sensors due to daily donning and doffing for proportional control use. The lack of feedback other than sound and visual feedback is also still a problem for EP, as is visualized by Plettenburg [12] in Figure 4.3.

Thus this type of control should be avoided as a control method when feedback is desired. For other types, e.g. switches, this control method could be used since they do not require direct feedback, and the advantages of myoelectric control and externally powered prostheses can be used.

4.1.2. BODY CONTROLLED

The most common control method is the use of a bowden cable. This cable controls and actuates the functions of the prosthesis. Two points of attachment are needed, so that the change in length between those two points results in the lengthening or shortening of the cable. Which actuates the mechanism of the prosthesis. In Figure 4.4 three examples of control sites can be seen for above the elbow amputees. Control site **a** is used for above- and below- elbow amputees [29]. Where the stabilization point of **b** also can be used, with this the shrug of the (contralateral) shoulder also can be used. Site **b** for forequarter, partial shoulder disarticulation, and humeral-neck amputees [29]. And site **c** is used for above-elbow amputees.

If more DoFs need to be controlled, more control sites need to be located. There are various ways to do so. One option is to simply ad more control sites. The problem of this is just as described above. More simultaneous controlled DoFs require more mental load of the user. Plus there is limit to the amount of control sites that can be added. Another way of control is by using one control site to switch between functions for

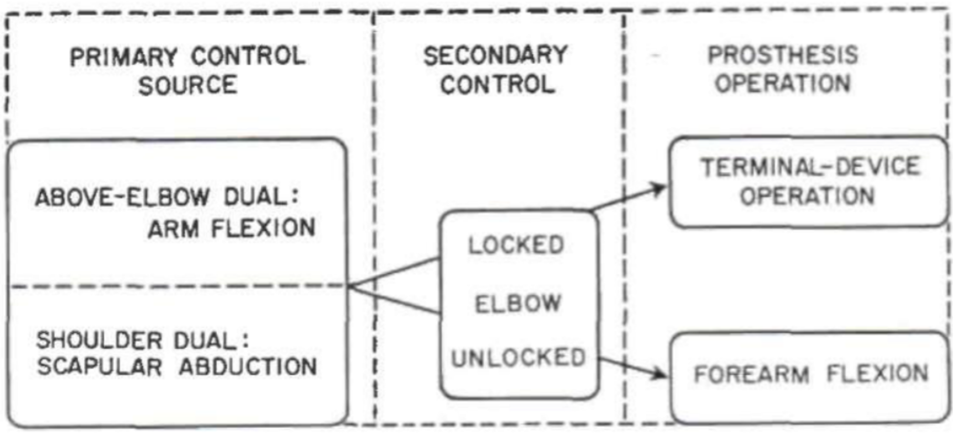


Figure 4.5: Operation of above-elbow and shoulder dual controls [29]. One primary control source controls both outputs: elbow and terminal device. The secondary control is used to lock one of the DoFs, so that the other DoF can be actively controlled.

the other control site [89]. This is visualized in Figure 4.5 and originates from BP control. It is used for an above the elbow amputee with two DoFs; the elbow and the terminal device are controlled with this principle. The drawback of this system is that the two controlled functions cannot be controlled simultaneously, only sequentially.

Therefore it is also important to look at different control sites. Van Mil *et al.* [90] have researched the possibilities in different control sites for BP prostheses. It is concluded that only shoulder protraction and elevation are considered suitable when using a Bowden cable. The other movements, shoulder elevation, shoulder pro- traction, trunk flexion, trunk rotation and toe flexion, where considered suitable when a wireless control system would be introduced. This is a system where the position of the limbs and joints is measured. Those measurements are then used as input signals for an externally powered prosthesis. The feedback loop can be closed by transducer.

But the feedback in the BP prostheses is also not optimal [12]. Improving the feedback [91] and the efficiency in the operating cables [92] where also developed. LeBlanc [93] used hydraulics instead of a bowden cable to increase the efficiency even more. Just as for EP prostheses the same applies for BP prostheses. There are still developments to improve the control method for BP prostheses. Also studies conducted on the feasibility of a BP prosthesis for children [94] shows that more efficient prostheses need to be developed.

A specific wrist control method for rotation is to split the prosthesis, so that the residual forearm uses its own pronation and supination [95]. The functional part of the prosthesis is still at the end and is attached via straps to the other part of the prosthesis, which secures the entire prosthesis on the residual limb. But this solution can only be used with long residual limbs. For shorter residual limbs, the problem arises described in Figure 2.7. Because this control method is very specific it cannot be used for other DoFs and is therefore not looked further into.

4.1.3. HYBRID CONTROL

A different approach could be a hybrid solution. Literature found about hybrid prosthetic devices is diverse. Losier *et al.* [96] use the word hybrid by means of different attachment locations of the EMG sensors for myoelectric prostheses. With this, for instance, the shoulder muscles can be added for control of a prosthetic device. Another way of the use of the word hybrid is for different EMG signal decoding, e.g. hard and soft [97]. The most general way to interpret the word hybrid is by means of the human with a "robotic" prosthesis as a whole is a hybrid [98].

The intended definition of a hybrid prosthesis is given by Billock [99] and Childress and Billock [100]. Both defined a hybrid as a prosthesis with components of different control methods. For instance an electric hand/hook and BP elbow [99] or vice versa [100]. By doing so, more variance in prostheses control can be made available to meet the demands of the user. But as Billock [99] also points out, the manufacturers of the components need to make their components with interchangeable connection points. This combining of different control methods was also discussed in Chapter 3.2.

This hard line between components for control does not need to be defined as one control method for one

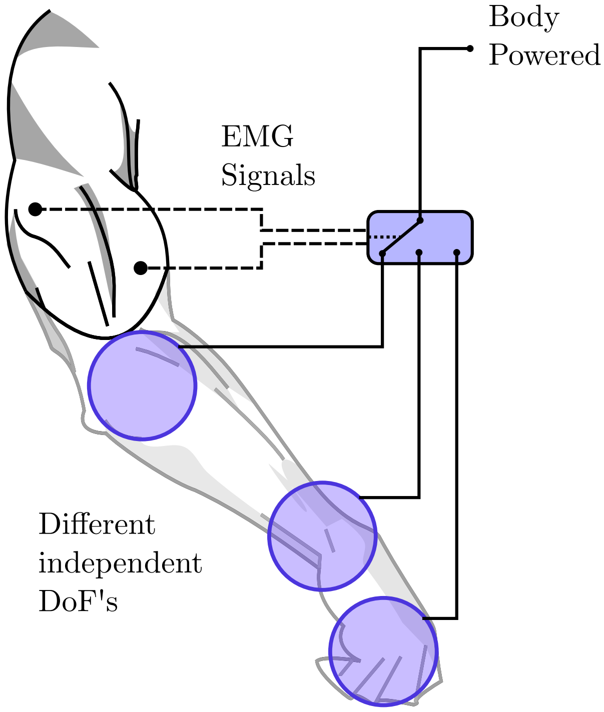


Figure 4.6: Visualisation of a hybrid control scheme for an above the elbow amputee. EMG signals are used to switch the body powerd control flow between different degrees of freedom.

degree of freedom. For instance electric switches in series with bowden cables for the control of EP prostheses [72]. However this kind of control setup comes with both the disadvantages of a BP (harness) and EP (weight, battery) prosthesis. A different approach is to use the principle as seen in Figure 4.5, but instead of a BP cable to switch, this switch could also be (myo)electric, and the control still be BP control. This is one example of a broad variety of different combinations and control setups. This specific example has not been found in the literature nor in patents. Further no literature was found on any one of this kind of hybrid control (BP and EP combinations).

Other literature about a different hybrid system was found in a patented method of control [101], where they used voice- and myoelectric control. Which is clearly an example of a hybrid control.

An entirely different way, which could be interpreted as a hybrid. Briefly discussed at Chapter 4.1.2, it is with the use of transducers. With a myoelectric prosthesis, that uses the signals of sensors on the shoulder as an input for the actuation [102]. While feedback is fed back via these transducers to the shoulder of the user. Where the biological sensors close the loop and send the information to the brain. Thus the proprioceptive feedback of shoulder can be used. Although the components are all from the EP prosthesis, the method of feedback control is from the BP prosthesis. If it is by definition a hybrid is debatable, but the method to obtain feedback is interesting nonetheless.

These hybrid control methods show that there is a lot more to discover in the control of prostheses. Especially it there is not that much literature found on this subject.

4.2. COUPLED MOVEMENT CONTROL

Within the range of control methods, coupled movements can be combined with other control methods. Coupled movement control utilizes the movement of other body parts to control a certain motion of the prosthesis, which is most of the time not the terminal device. WILMER elbow control is an example of a different location to of BP control to manipulate the terminal device [103]. The WILMER elbow control uses the flexion-extension movements of the elbow as a control input instead of a shoulder harness. The working principal can be seen in Figure 4.7. With this type of control the obstruction of wearing a harness is worked around. But the obvious drawback is that the movement, as the chapter title indicate, are coupled. Thus moving the elbow, in case of the WILMER elbow control, the terminal device is also put in motion. Even when this is not desired.

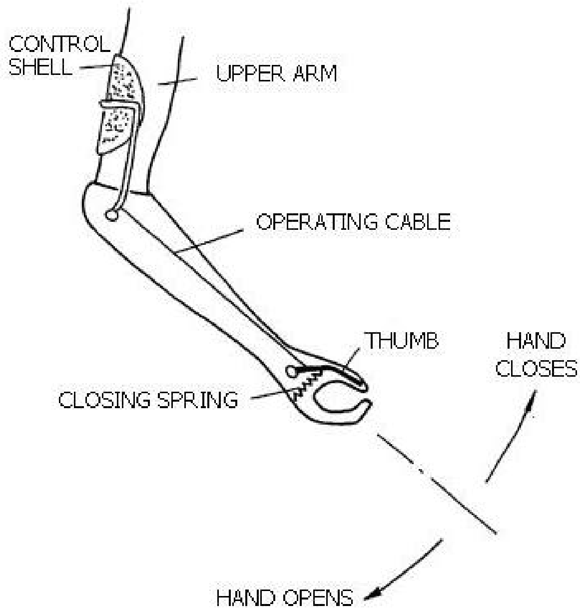


Figure 4.7: WILMER elbow control [103].

Carlson and Hock [46] shows a list of ten prosthesis with coupled mechanisms up to 1977. Three groups where established. The first group has wrist pronation-supination coupled to elbow flexion. The second group has wrist flexion-extension coupled to elbow flexion. And the third and last group has elbow flexion coupled to shoulder flexion. The biggest drawback is described above. There is also an advantage; because of the coupling, the mental workload decreases, because the movement is not independently controlled. And therefore the movements can be learned and done "without" thinking of activation of the movement itself.

4.3. DISCUSSION

No literature describes an optimal solution for control. Probably because there is not an optimal solution, and it all relates back to individual preferences. But, the users are not the ones to design a better control method or strategy. Therefore it is still desired to look for better solutions that keep the desires and needs as guidelines. Besides all these methods are still in development, and it all depends on the desired function of the control or desired controlled movements of the prosthesis.

For the wrist control, multiple questions arise. For instance: Which DoFs need to be simultaneously and which sequentially? It probably is just as in the discussion in the previous chapter, simultaneous is more desired than sequential control. In the Myoelectrical development research and advancements, the possibility of simultaneous control is further researched and picked over sequential control [104, 105]. This thus contributes to the desire of simultaneous over sequential. But low mental workload and intuitive control should be considered first, since these give the user the ability to focus on other things. To which extend this is beneficial, or where the turning point lies of how many DoFs can be controlled simultaneous and independently without increasing the mental workload or decreasing the natural feel of control is not clear.

With the kind of control where a hybrid control is used, the advantages of both BP and EP could be obtained with various combinations. For instance the feedback of a BP, and the multiple DoF's control of myoelectric control (sequential), e.g. the BP is used for the main control, and the myoelectric control for the switching between control functions, as seen in Figure 4.5. Research in this area of hybrid control is very limited for the combined control and should be further investigated. Research currently conducted by A.N. Vardy (Delft University of Technology), in some sense, incorporates hybrid control in a similar way as Barton [102].

Coupled movements, for instance humeral abduction, could be used for wrist rotation since it is a different location of rotation in the same plane, provided that the standard position is used. The forces of the wrist device could be lower than that of the terminal device since the wrist is a motion, with hardly any demand for force/torque manipulation. But when rotation is coupled to humeral abduction, but no rotation is desired while lifting the arm, it could lead to undesired situations. Where even more Body English is needed. And precisely this is the biggest drawback. The advantage is that the mental workload can be reduced. Thus could give a possible (sub)solutions since a mechanism for decoupling is also an option. Hence coupled motions should be kept in consideration while designing. The requirements and goals for the control of a prosthetic hand when designing an active prosthesis from this study is also summarized by Childress [72]:

- Low mental loading or subconscious control.
- User friendly or simple to learn to use.
- Independence in multifunctional control.
- Simultaneous, coordinated control of multiple functions.
- Direct access and instantaneous response.
- No sacrifice of human functional ability.
- Natural appearance. If possible, the control system should be operated in ways that have a nice aesthetic appearance.

As can be seen, a multiple points are already discussed. Others can be used from this list or are already in other categories (natural appearance in cosmesis). These considerations are put together in the following Table:

Table 4.1: Considerations for Control

Considerations
• Low mental workload • Natural or intuitive control • Simultaneous and independent control • No sacrifice of human functional ability

5

MECHANISM

This chapter is here because there are some aspects found in the literature that could be useful in the development in the design process for the mechanism. Not actual mechanisms are described here, only principles.

For instance Smit *et al.* [106] used a compensation mechanism for the stiffness of the material of the cosmetic glove. This should be taken into account when designing, since the cosmetic glove interacts with the movements and could cause problems.

5.1. BIO-INSPIRED

Looking at the actual wrist could be insightful for the development for a mechanism. Sarrafian [32] made clear that the flexion of the wrist is a combination of multiple rotation axis in the same plane, i.e. multiple bones rotate with smaller ROM. These smaller ROM combined are described in Chapter 2.1. Also the rotation of the forearm biologically differs from mechanical rotation mechanisms.

5.2. ORDER

The order of DoF's is important. If the order changes, the range of motion changes. This can be seen in Figure 5.1, where only two degrees of freedom (flexion and rotation) are used as an example. As can be seen, comparing Figure 5.1a and 5.1b, putting rotation proximal to (before) flexion, covers an area that the terminal device can cover (point a in the Figure 5.1a). If rotation is put distal to (after) flexion, the terminal device can only operate on a circular path, but it can rotate on that path (Figure 5.1b).

5.3. MEASURING AND EVALUATING THE MECHANISM

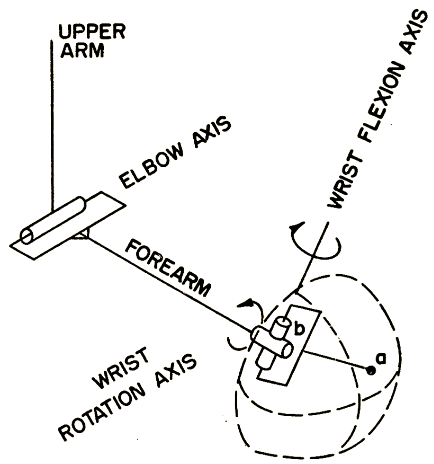
Light *et al.* [107] introduced the so called SHAP (Southampton Hand Assessment Procedure) method. This evaluation method could be used for evaluating the wrist mechanism. It uses several methods to evaluate a total prostheses. Some of these methods also evaluate wrist movements.

5.4. DISCUSSION

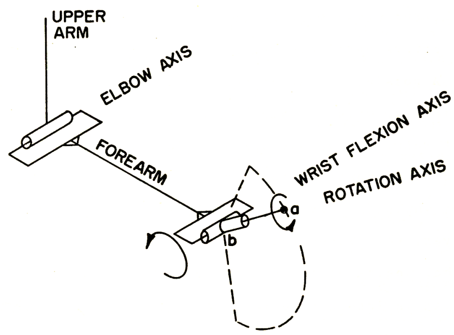
Design considerations that should be kept in mind can be seen in the following Table 5.1:

Table 5.1: Mechanism considerations

Considerations
• The use of Bio-inspired concepts could give new solutions • Order of DoFs is important • Compensations mechanism could be useful



(a) Wrist flexion distal to rotation.



(b) Wrist flexion proximal to rotation.

Figure 5.1: Visualization of the order of rotation axis [31]

6 CONCLUSION

From the user demands in Chapter 1.2 the goal for this literature was formulated as: **Obtain an understanding of prosthetic wrist function and the problems with current solutions, resulting in requirements for a new prosthetic wrist design.** This conclusion summarizes the most useful found information of the chapters' discussions.

The functional ROM should be held as a requirement first. Secondary the active ROM, since it still gives insight in the full range of motion of the wrist. Reducing the workload of the user, the total number of DoF's should be brought down from three to two. Which is contradictory, since more independent DoF's are desired, for natural movements. With the current status we are not capable of controlling to many independent DoF's simultaneously. With the knowledge of coupled movements (dependent DoF's) between wrist flexion and deviation, this could be achieved via a rotated flexion axis obliquely to the anatomical flexion axis. Which is the natural (most used) movement of the human wrist.

Considering the biggest advantage of BP prostheses, EPP, it is the first choice of control method. Controlling the prosthesis could however, be a combination multiple control methods, making it a hybrid solution. This approach is not researched extensively enough, and should be further investigated for future developments. Because it opens possibilities to develop new control methods with hopefully less disadvantages.

A table of requirements and design considerations is constructed (Table 6.1), to give an overview of all the found information that could be used for the design of a prosthetic wrist. This table can be seen below, which combines all discussions of all chapters.

Table 6.1: List of Requirements for wrist function

Movements		**Maximum range values**		**Unit**
		Pronation	Supination	
Rotation	Active RoM	71 – 90	84 – 90	[°]
	Functional RoM	50 – 60	30 – 50	[°]
	Torques	10 – 15	9 – 15	[Nm]
		Flexion	Extension	
Flexion	Active RoM	50 – 84	35 – 84	[°]
	Functional RoM	5 – 54	15 – 60	[°]
	Torques	5 – 23	3 – 15	[Nm]
		Radial	Ulnar	
Deviation	Active RoM	19 – 30	27 – 40	[°]
	Functional RoM	0 – 20	0 – 20	[°]
	Torques	8 – 15	6 – 17	[Nm]

The following considerations should be used as aids for designing a prosthetic wrist, since they give insights on the functionality and the usage of a healthy wrist.

- **Bi-manual activities** of daily living are most likely where a prosthesis is used. A list is found in Chapter 2.2.1.

- **Combined DoFs**, due to passive stiffnessess for Flexion/Extension and Radial/Ulnar Deviation (Figure 2.5), could be used to combine DoFs in the prosthetic wrist to simplify the design and/or control.
- The distribution of the **frequency of RoM**, Figure 2.4, gives more insight on the functional RoM. This could therefore be used as an aid while designing a prosthetic wrist.
- **Extended Physiological Proprioception**
- Order of importance; Pronation/supination, Flexion/extension, Radial-/Ulnar deviation
- Order of importance; Continuous control,Discrete control
- Order of importance; Active control, Passive control
- **Low mental workload**
- Natural or intuitive control
- Simultaneous and independent control
- No sacrifice of human functional ability

As mentioned before at Chapter 3.4 extended physiological proprioception is a term used, which provides an understanding of the importance of feedback. To what extend this advantage of EPP benefits BP over EP is unclear and can be a subject of interest for further research.

Also as discussed briefly at Chapter 4.3 follow-up steps could include investigating the control of multiple DoFs simultaneous and independently while looking at the mental workload. This then could be used as a basis to start designing a prosthetic wrist.

As for the next steps for this thesis is to develop concepts of control with the requirements and considerations as guidelines. This eventually will lead to a wrist prosthesis which can be used as a basis to start researches with for further developments in the control of prostheses.

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