DELFT UNIVERSITY OF TECHNOLOGY

MECHANICAL, MARITIME AND MATERIALS ENGINEERING (3ME)
BIOMEDICAL ENGINEERING DEPARTMENT

MASTER THESIS

1 October 2018

The design of an active, under-actuated, prosthetic wrist mechanism based on synergetic relations

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Abstract

Inspired by work of Montagnani et al. (2015), who found that for prosthetic hands a complex wrist mechanism worked functionally equal to a multi-DOF hand mechanism, new work has been set in motion to extrapolate and test this hypothesis. The goal of this work consisted of building a multi-DOF wrist mechanism, while it was crucial to keep the mechanism small, light, and efficient. A study preliminary to this work has found a single, synergetic relational "path" between all degree of freedom of the human wrist, thereby proving a three dimensional, functional output of orientation by a theoretical mechanism, driven by a single input. This work seeks to design such mechanism, capable of following the proven synergy while remaining small, able, and effective.

Starting from scratch, several theoretical mechanism are tested on their ability to create general, non-linear translations. Some of these theories are worked-out into concepts after which a selection is made of the most promising. Further developing these concepts into adequate designs, a set of prototypes, digital and physical, have been used to prove their competence in re-producing the path as found by the preliminary study. Finally, after a fusion of two designs, a final design is developed to a state-of-production. Though the production of a prototype was scheduled, it was not accomplished within the period of this work.

This reports finishes with a final design proven theoretically to be successful in re-creating the theoretical synergetic path through a set of compound mechanics. The mechanism thereby proves the mechanical feasibility of the theoretical synergetic path. Though at a greater cost of size and weight, the mechanism is fully able to function as a prosthetic wrist mechanism as required by two individual partner projects. Due the lack of a physical prototype of this final design, testing and result-checks have been limited to a theoretical and digital environment.

In the discussion, several options of improvements are given, as well as speculations on a parallel, alternative design course for future work. After outlining a set of important decisions made in this design, an alternative set of decisions is mentioned which are hypothesized to work without some of the sacrifices needed in this design, predominately the volume. Whether this alternative design proves successful, if at all feasible, remains to be attempted. Whether the wrist mechanism has benefited from the synergetic approach remains unanswered as well. Due the lack of physical testing several questions around functionality cannot yet be concluded. After the acknowledgement of this design's drawbacks, and the hypothesis of an improved alternative, no statements on the mechanical benefits of the synergetic approach have been made either. After the mechanism succeeds in proving that the theoretical synergetic relation is physically achievable, it is stated that such (alternative) mechanism without the mentioned drawbacks would, in a mechanical sense, be outstanding.

Contents

List of abbreviations

ADL	Activities of Daily Living
(2)DoF	(two) Degree of Freedom
FE	Felxion/Extension
IMU	Inertial Measurement Unit
PS	Pronation/Supination
ROM	Range of Motion
RUD	Radial/Ulnar Deviation
SD	Standard Deviation

1. Introduction

The Biorobotics lab of the Scuola Superiore Sant'Anna university in Pontedera, Italy, worked on two major projects, both involving prosthetic hand mechanisms. After work done by Montagnani et al. (2015), who proved the importance of wrist mechanisms, an interest in such mechanisms expressed itself in a parallel project. The goal of this project was a 9 month development of a new wrist mechanism small enough to fit the requirements of these neighboring projects (see chapter 2). The project was sub-divided into three phases.

This report functions as a thesis report after work done in the last 6 months. It is part of a set containing two other reports: a preliminary study and the literature study.
The literature study focuses on the importance of wrist joints in general, as well as in prostheses. After finding demands from the prosthetic community around a lack of functional wrist mechanisms, a list of general requirements for wrist mechanisms has been set. A state-of-the-art review shows that few adequate wrist mechanisms exist, non of which adhering to all requirements. The study concludes that the requirements of wrist mechanisms can be greatly reduced by applying a "synergetic" approach to their design. The report finishes with the believe that through synergetic work between the degrees of freedom of the wrist a single engine can control all outputs, thereby reducing mass, size, and complexity of control.

This report focuses on a the work done after the preliminary study and the literature study, and consequently deals with the conclusions of both. After the preliminary study found a method of binding the output of wrist orientations (in 3 degree of freedom (DOF)) during activities of daily living (ADL) through a synergetic relation, the literature study advises a further exploration and development of prosthetic wrist mechanism based on such principals. This work focuses on exactly that.

The theory of the preliminary study therefor had to be translated into a physical mechanism able to reconstruct the relation found. Aside from re-creating the 3-DOF output while using a singe engine, the mechanism also had to be designed conform the requirements of the other, neighboring projects, as well as the general requirements as found in the literature study. After designing such mechanism plans continued to have it manufactured and tested.

Designing such mechanism would prove a new type of wrist prosthetic based on a synergetic approach. Being the first to use the new theory of the preliminary study, the design would be unique in proving the use of synergies in its design, and its the benefits.

2. Project definition

2.1 Introduction

A prosthetic wrist mechanism was to be designed at the Institute of Biorobotics of the Sant'Anna Scuola Superiore. The mechanism would be involved in two partner projects: the CECA2020 hand and DeTOP forearm. A big difference between these projects is that for the DeTOP project the wrist mechanism can fit in the forearm, whereas the CECA2020 project requires the wrist mechanism to fit inside the hand. The ambitious goal of the wrist project was set to have a 3-DOF mechanism controlled by a single engine. Due its involvement with the two projects, the mechanism also had to be considerably small. Though both projects should allow the same ROM as defined by the preliminary study (see chapter 2.3.1), the dimensions and environment of the two are considerably different. Ideally, the mechanism can be designed conform the demands and wishes of both projects. However, since the DeTOP project has a deadline set closer to the present, the focus for now will be mainly on those requirements. Nevertheless, volume-wise the goal has been set to fit inside both the CECA2020 hand and the DeTOP wrist.

2.2 Neighboring hardware

Since this work is part of two bigger projects there is important surrounding hardware to keep in mind. Not only does the wrist mechanism need to connect to other hardware such as the frame of the hand and the amputee, it also has to fit inside the hand frame while sharing the space with other mechanism, electronics and cabling.

Some parts of the hand are known in advance. The fingers of the CECA2020 hand have already been designed and house their own mechanics and actuators. This means that the fingers won't take any space inside the palm of the hand, but will need to connect to the final frame of the hand. The thumb of the hand is currently in design. It will have it's actuator inside the thumb but will require some additional space in the palm for a ab-, adduction mechanism. The final frame of the hand has not yet been designed, and will have to fit to all mechanisms inside. This means that connection-wise this project has some freedom of choice.

2.2.1 Hand Frame

The frame of the CECA2020 hand is yet largely undetermined, but the goal has been set to have the volume similar to that of a normal human hand. From Tilley et al. (2001) we find the 50 percentile average for the sizes of the male hand, as well as the 30 and 50 percentile of female hands from Greiner (1991).

Figure 2.1: 50 percentile sizes of human hand (Tilley et al., 2001)

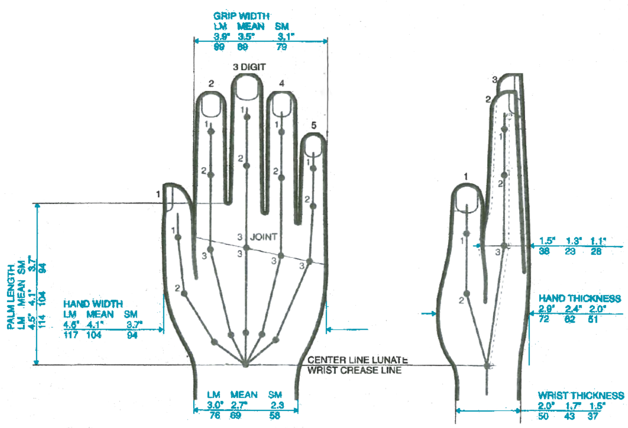
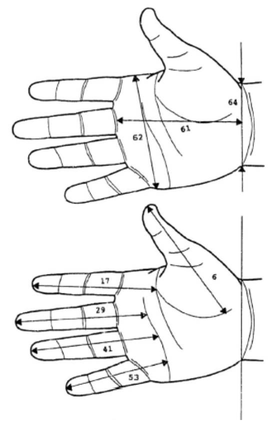


Figure 2.2: Sizes of human hand (Greiner, 1991)



	50^{th} perc. female (Greiner, 1991)	30^{th} perc. female (Greiner, 1991)	50^{th} perc. Male (Tilley et al., 2001)
Palm Length (61)	100.7	97.8	104
Hand Breadth from Digitizer (62)	83.1	80.9	89
Hand Breadth form Wrist (64)	56.9	55.1	69
Thumb Length (6)	110.4	106.8	117
Index Length (17)	100.1	96.9	103 *
Middle Length (29)	100.1	96.9	114
Annular Length (41)	97.1	94.0	107 *
Little Length (53)	77.5	74.7	84 *

Table 2.1: Size overview as corresponding to figure 2.2 where the (*) are measured relatively

After finding the sizes for human hands, Similar statistic have been found on the dimensions of the human forearm. In table 2.2 we see the sizes for the 50th percentile for female forearms. Though the information on the forearm is quite rudimental, we can combine this information with the 50th percentile male hand to find an intersection box.

Male	5th percentile	30th percentile	50th percentile	70th percentile	95th percentile
Wrist circumference	16.2		17.7		19.3
Forearm circumference, relaxed	27.4		30.1		32.7
Elbow-wrist length *	26.6	28.2	29.0	29.8	31.6
Female					
Wrist circumference	13.7		15.0		16.2
Forearm circumference, relaxed	19.9		22.0		24.1
Elbow-wrist length *	23.8	25.4	26.2	27.1	28.8

Table 2.2: Dimensions of the forearm by NASA (1995) and (*) Gordon et al. (1989)

When simplifying the dimensions of the hand and forearm we can estimate their total size as an approximation in the shape of a trapezoid and a cone. For these sizes we take the distance from the wrist joint to the 3^{rd} joint and the total width of the hand as in figure 2.1. The thickness of the hand is decided by the thickness of the wrist moving to the thickness of the knuckles. The forearm is approximated by using a circular circumference. Space for the thumb was approximated as $2/3^{rd}$ of the length and $1/4^{rd}$ of the width.

Figure 2.3: Schematic overview of both hand and forearm approximations

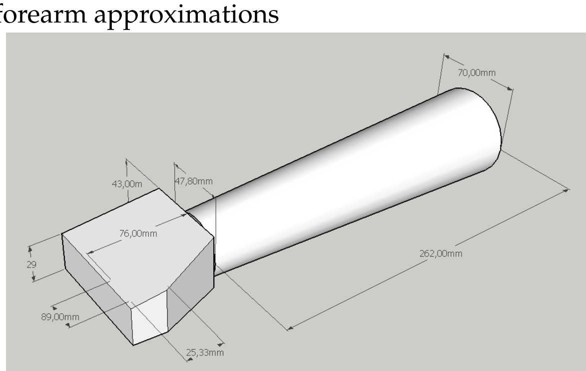
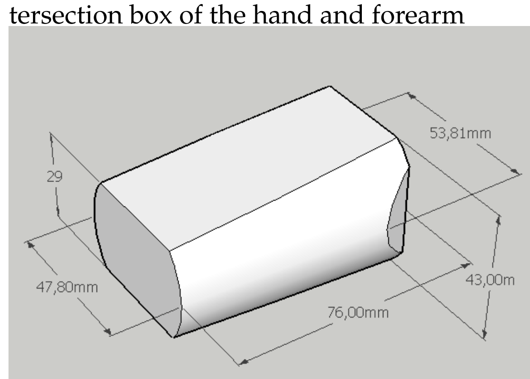


Figure 2.4: Schematic overview of the intersection box of the hand and forearm



In figure 2.4 we see the final approximation of the intersection box. Following these dimensions the mechanism should be able to fit in both the 50^{th} percentile male hand and 50^{th} percentile female forearm. Note that the space allocated for the thumb is barely missing due the width of the wrist from the forearm. This shows that the thumb should have at least $\frac{1}{4}$ of the width of the hand available, plus any space the thumb might use "aside" the hand.

2.2.2 Frame cover

The hand will need a frame to keep all components together. However, since the wrist mechanism will have to rotate the hand, it's frame will have to be build on top of the wrist frame. Because building a frame on top of a frame takes space, it would be better if the wrist frame is partially used as the carrying frame, where the remaining hand frame is build around the wrist frame. This allowed for more space, as the external dimensions become fully available the wrist design.

Aside from a carrying frame the hand also needs a cover for protection and ecstatic reasons. This cover might become yet another layer eating away from the external dimensions leaving less room inside the hand. However, from previous projects it's likely that some thin plastic cover will be used. There are no real constraints on the cover, which means we can strife for the thinnest material with the minimal protection. We can also attempt to use the cover only between the parts of the external frame that would allow the outside to pass, meaning the cover wouldn't induce any extra thickness at all. So far, the cover is expected to be only 1 or 2 mm thick, which will be aided by the use of a glove in case of particular activities (such as involving water).

2.2.3 Thumb

The thumb mechanism had its design period similar to this project. As explained before, the thumb will use its actuator inside its own mechanism, therefor barely taking space inside the hand. It will however need a means of connecting with the hand frame, which includes part of the mechanism allowing ab- and adduction. From the electronic stand point, it is also preferable if the actuators used for the thumb, fingers and wrist are similar in their required control.

2.2.4 Electronics board

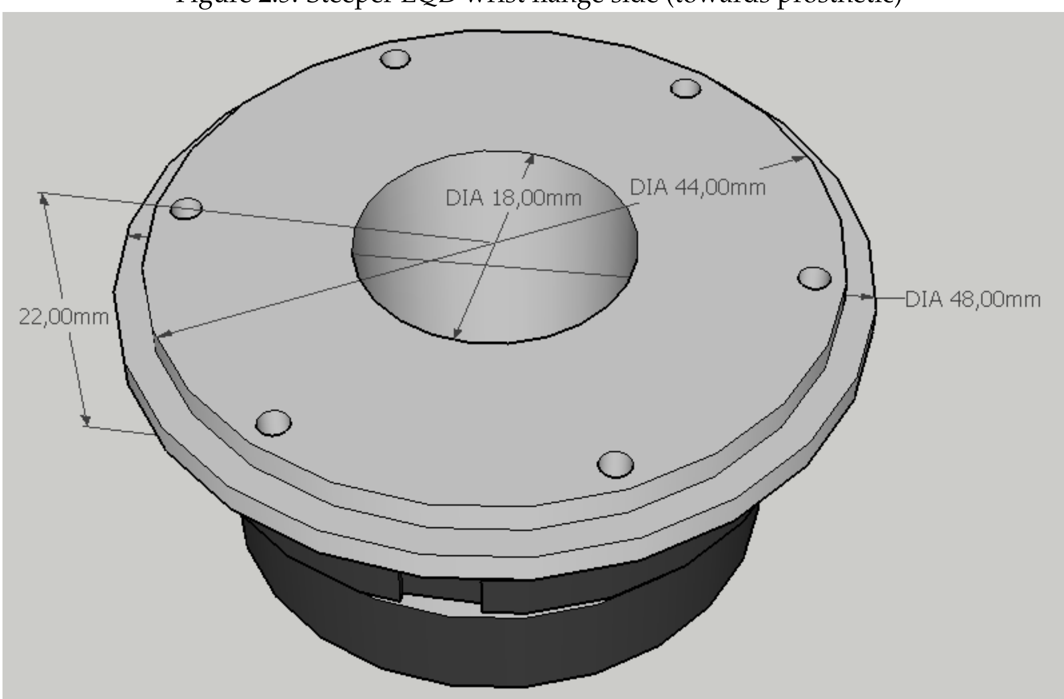
The electronics are so far un-allocated but will need to be present. Part of the control might be placed inside the fingers, but most of it will be a standard chip. The position of this chip is largely unimportant, but it will require some reserved volume, and a connection to the hand frame. The electronics also require a means of control, not just in input toward the engines but a feedback as well. Usually the motors have a decoder connected which allows to keep accounts on the rotations made. For most applications this is enough.

2.2.5 Connectors

Connectors are used as a bridge between the artificial and biological anatomy. The user of a prosthetic hand will often wear a brace around the remaining anatomy which is used as a frame to support the prosthetic. The lab uses Steeper's EQD Wrist which is a standardized connector to connect the bebionic3 Hand to any sort of frame worn by the user. On the prosthetic side it uses a simple flange with six screw-slots in a total diameter of 50[mm], with in the center room for multiple holes to allow cables to run though. On the other side the EQD Wrist is fitted with a radially symmetric tooth-like geometry used to lock into by any sort of driver. The outer rim is fitted with a ball-bearing to allow smooth rotation around PS.

This connector is used to fit as a stand-alone connector where the hand might rotate freely or where the DOF is locked in a preferred position. Using BeBionic's wrist rotator the wrist can be actively driven while the connector supports the free rotation.
The design of this connector has been done with an order of hand-connector-rotator in mind, where the rotator is mounted on what's left of a trans-radial amputation. In this project however, the goal was set to fit the rotator (wrist mechanism) inside the hand, which reverses the order of components. In our case we have a hand-rotator-connector order. Using this connector is therefor probably unnecessary, however, the general design on the connecting flange is still relevant.

Figure 2.5: Steeper EQD wrist flange side (towards prosthetic)



2.2.6 Motors

To select a motor the project will refer to Maxon Motor's which is the lab's primary choice and source for electrical engines. In general, an electrical engine is combined with a gearbox and a controller. Electrical engines tend to focus on high speeds with relatively low torque, which makes them ideal for high ratio gearboxes and precision work. This combination, however, easily adds to the total size and weight of the engine, which is desired to be kept low. It is important that the engine has the right torque to handle whatever mechanism is designed, while having sufficient final speed (after reduction of the gearbox) to make the mechanism move at an acceptable rate. These two ends (speed and torque) will have to be balanced.

Aside from the required output of the engine, the mechanism as a whole is also required to be non-backdrivable. This means that the engine can set the mechanism's orientation, but that external forces should not be able to do so. consequently, external forces should not be able to rotate the engine either. This can be achieved in multiple ways. Dedicated non-backdrivable mechanisms can be used between the engine's output and the mechanism, thereby preventing the mechanism to change its orientation. These mechanism's take space however, and will complicate the engine's output and size. Some mechanisms have an inherent non-backdrivable effect, ususally meaning that it is simply difficult to drive the mechanism from the other end. Gearboxes and lever systems are examples of this. It is likely that the engine will require a gearbox, and the required wrist mechanism is likely to have lever, or other, effects. By a clever design therefor, the non-backdrivability of the mechanism as a whole is trivial.

2.3 Requirements

2.3.1 Weight, strength, torque and velocity

Aside from reaching the right orientations the wrist also has the responsibility to carry the hand. This means that the final joint of the mechanism has to be strong and sturdy enough to support the hand and its applications.

Weight
The weight of the hand has been set to target roughly 700 grams. This is the full weight of the hand, meaning it might include the wrist mechanism as well. Since the final design of the mechanism, or any other part of the hand, are not known yet, the true weight of the full hand is yet undetermined. For now, however, we take the 700[g] as the expected value. Naturally, this requires the mechanism to have a weight as low as possible.
Second to this requirement comes the goal of the hand to hold objects up to 5[kg]. It is obvious that the wrist will have to support both, meaning a sum of 5.7[kg].

Strength
The wrist mechanism will be designed as a means of orienting the hand. This *does not* include dynamic behaviour. This means that the wrist is not required to change the orientation of the hand while an object is being held. The mechanism itself will therefor only have to overcome the weight of the hand alone. The mechanism, and particularly the final output shaft rotating the hand, will have to be strong enough to hold the total weight of 5.7[kg] in any orientation of both the wrist and the hand in a global reference frame.

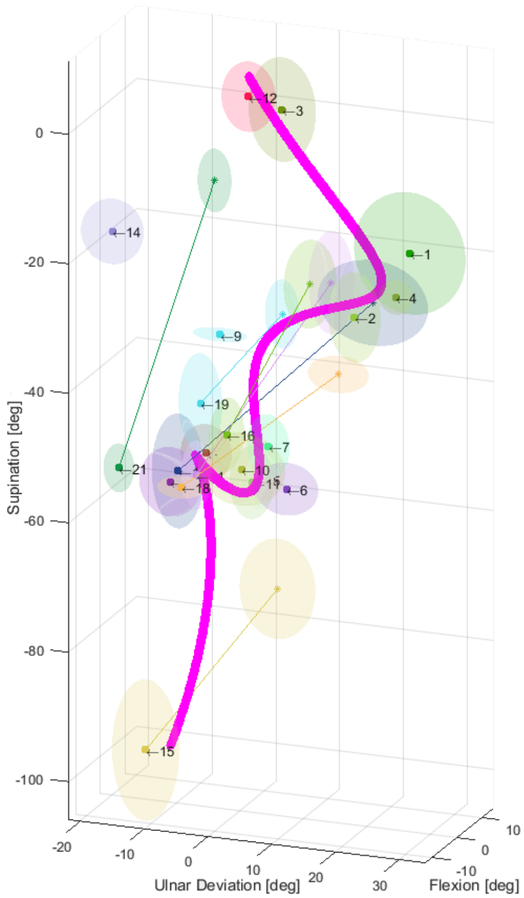
Torque and velocity
As said before, the wrist does not require a particular output torque beyond what is required to orient the hand. Neither have any requirements been made for the velocity by which the mechanism orients. It is however useful to have a sense of perspective, for which we can refer to other, similar wrist rotators. Keep in mind, however, that none are as complex as the mechanism developed in this work.

		RIC Wrist	Ottobock Wrist Rotator	Motion Control MC Wrist	ProWrist	Kyberd et al.	Roose	Mahmoud et al.	Zinck et al.
Rotator:	Speed	500	81	143	168	175			246
(PS)	Torque	2.2		1.7	1.7			0.216	0.06
	Mass	236	96	168	168				87
Flexor:	Speed	450				150			
(FE)	Torque	2.5				0.073	0.321	0.927	
	Mass	153							
Devator:	Speed								
(RUD)	Torque							0.216	
	Mass					200	95.4		
Load (kg)				22	22				
Voltage (v)		14.8		7.2	7.2	7			

Table 2.3: Overview of multiple brands statistics (with speed in deg/sec, toque in Nm, and mass in grams)

3. Preliminary research

Figure 3.1: Least-squares polynomial fit through the tasks, where task 14, and 22 are ignored



Prior to the design of the mechanical wrist as described in this report, a preliminary study on the usage of the human wrist during activities of daily living (ADL's) has been done (Lenssen et al., 2018). A total of N = 10 subjects have been asked to perform a set of tasks chosen to represent common ADL, including standardized abstract tasks from the SHAP test and performing self contact with the hand. The subjects were asked to wear a total of four IMU's which were able to detect the motion of the wrist, elbow and shoulder, giving insight in the orientation of the joints during the tasks.

Figure 3.1 shows all tasks in a three dimensional space where each dimension represents a DOF of the wrist. The tasks gain their position by representing the average orientation of the wrist for each task, with the center as the mean and the bubble as the STD. From this graph a 7'th order polynomial has been fitted to the tasks using a least-squares method, where task 14 and 22 were regarded as outliers, and has been plotted as the magenta line. Using the derivative of this line-fit, a set of 8 specific points have been regarded as "must have" to minimally represent the motion of a human wrist, though the full line-fit is available as a set of the exact polynomial numbers.

These points, referred to as "locs" (short for locations) together make up the essential features of the path. In table 3.4 the locks are outlined in terms of each DOF.

Locs:	1	2	3	4	5	6	7	8
Ulnar deviation:	2	20	5	0	-8	4	-5	-8
Extension:	-2	6	8	6	4	-3	0	-6
Supination:	8	-23	-32	-40	-53	-56	-72	-95

Table 3.4: Orientations of the locks, as decided by smoothing re-arrangement

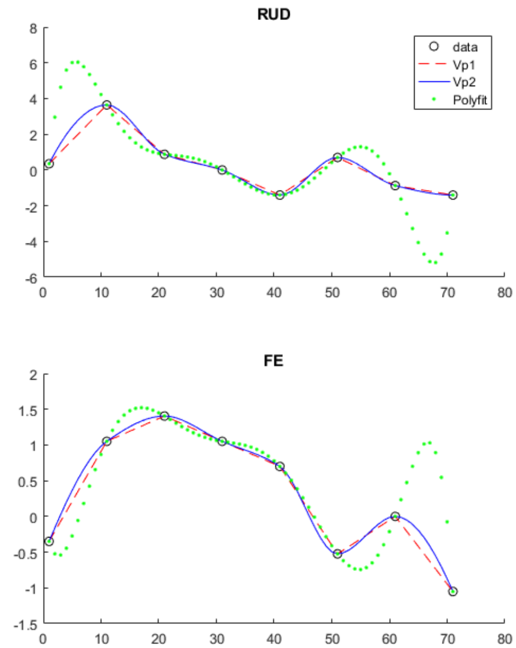
The reason for this necessity comes from the fact that the PS dimension is not entirely monotonic, a problem that cannot be allowed by the single actuator demand on the mechanism. The Lock points have therefor been found as a skeleton to re-design a fitting line that passes all points.

3.1 Re-defining the path

The preliminary report already concluded a set of new locs which were monotonic in PS. Here, we use those points to re-create the path for all DOFs using another polynomial tool. Where in the first works it was important to use an averaging tool to find the mean-fit path through the data, in this case it is important to find the best fitting plot that *does* reach each point. Moreover, once the plot reaches the points, no over- or undershoot should be allowed so as to truely best fit the path as defined. Any deviation from the originally intended path will obscure the work done before.

Using Matlab's interpolation technique with the 'pchip' command the eight remaining points were used to create a new set of lines each containing 360 points. In figure 3.2 Vp2 (blue, solid line) indicates the final chosen method.

Figure 3.2: Re-design of the two dependent DOFs



For the purpose of designing the mechanisms that will have to re-produce this path, it is usefull to know the total ROM of each DOF. PS ranges from 6° to -95°, making a total of about 100°. Furthermore, the ROM of the two dependent DOFs came to 25° to -11° flexion, 11° to -9° ulnar deviation. This shows that the driven DOF is rather limited in rotation (about 28% of a full rotation) while the largest angle required by the dependent DOFs comes to 25°.

4. Usable theoretical mechanisms

4.1 Theoretical requirements

From the requirements as defined by the project combined with the findings of the preliminary study a set of new requirements can be made. This chapter focuses on theoretical mechanisms able to translate the found path from the preliminary study into a realistic, physical re-creation. To start the search for feasible mechanisms a set of theoretical requirements has to be set-up. Knowing what the mechanisms must be able to perform helps with selecting viable designs.

The preliminary study has given a 3-DOF path through the relating PS with the two remaining DOFs through a set of three polynomials. In section 3.1 these have been translated in thee arrays of each 360 points in 3D space. A difficulty with these paths is that they are highly non-linear and can have steep, and sharp curves. PS was designed to be the leading DOF, and has therefor been made monotonic. The remaining, dependent DOFs however are not, making their behaviour quit complex.

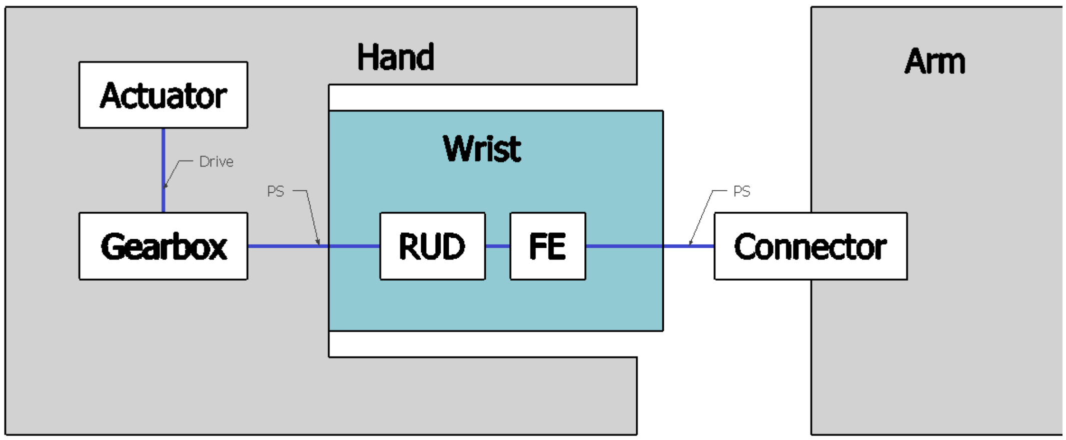
Though the DOF each have their own path, the final axis needs to be influenced by all three. The mechanism will have to re-create all orientations for all DOFs, and be able to combine them in the end. A common way to achieve this is to simply stack individual mechanisms on top of each other. In this case, the two dependent DOFs could stack while both being driven by the PS axis, which then somehow has to protrude through the mechanism along with its orientations. Having PS "come out" at the other end creates the third and last DOF, which at this point should be influenced by the two previous DOFs. This means that the mechanisms should not only be repeatable, but flexible enough that they can be build on top of a moving reference frame.

The input is likely to be an electrically driven engine with a rotating output. Though there are many ways to translate rotary mechanics to other translations, every mechanical translations will cause friction, loss of torque, speed, momentum or energy in general. Keeping the number of translations low is generally good for the efficiency of the system. Therefor it is good to search for mechanisms specifically able to deal with a rotary input and some sort of angular orientation as output.

One of the design demands requires the wrist mechanism to be non-backdrivable. This is a property that can be achieved through a non-backdrivable axis between the mechanisms and its output. However, when translating one mechanical output to another there is often a mechanism available that transfers energy as such that it takes a large sum of energy to drive the mechanism in reverse. This, then, also causes a non-backdrivable property on the total design, simply by choice of mechanism, which then requires no further mechanism to ensure this property.

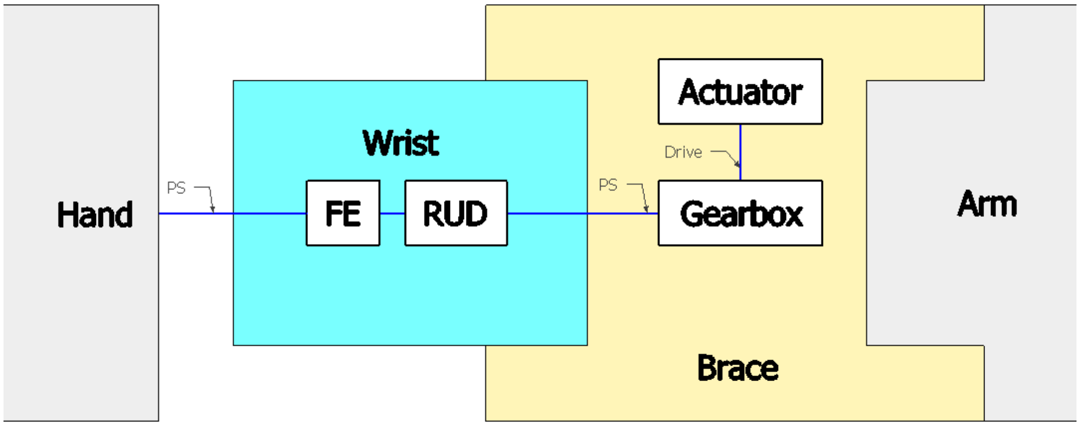
Last, the PS axis will have a double role. It needs to both drive the other DoF and influence the orientation of the hand relative to the arm. We can do this by maintaining a Actuator-PS-Wrist-Connector order, where the PS axis drives the wrist mechanism and binds to the connector to rotate the entire hand relative to it. This means that the PS axis needs to connect to the other DOF systems and somehow protrude through them to reach ”the other side” of the mechanism. Every rotation done by the mechanisms of either RUD or FE needs to let the PS axis pass through.

Figure 4.1: Schematic of the wrist and its driven axis realtive to the hand and connector



In figure 4.1 we see a schematic overview of the needed drive from the actuator to the arm, concerning the PS axis. The drive needs to arrive to the connector as the PS which means it needs to pass a gearbox. Since the RUD and FE are defined as depending on the PS it's useful to translate the drive to PS as soon as possible, right after the actuator itself. In this case the gearbox might be the motor self, as many types of motors (stepper motor, servor motor, DC motor) often include this in their design. A second option is to place the gearbox after the wrist mechanism, which might give the RUD and FE mechanisms the drive from the engine directly. In this case the missing translation from drive to PS should be included in the mechanisms for the RUD and FE.

Figure 4.2: Schematic of the wrist as driven from the arm



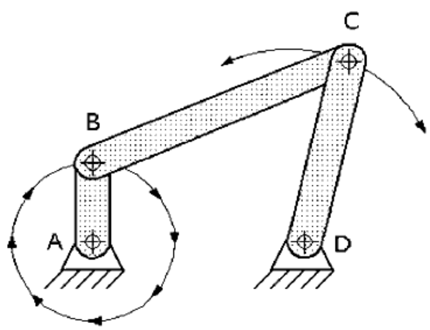
In figure 4.2 we see the same schematic of the wrist mechanism when applied in the arm instead of the hand. Since the wrist mechanisms will be used for both features, the goal of the design is to make the mechanism as such that it can be used on either side. This requires that on the outside of the mechanism the frame has to be compatible with both the inside of the hand and a general brace/sleeve as worn by the amputee. Secondly, the connection from the mechanism's final axis to the connector/hand is preferably the same (see section 2.2.5). When designing the hand, it would ideally have the same flange as the EQD wrist form Steeper.

4.2 Selection of mechanisms

As in the previous section, a discussion on the theoretical requirements of the mechanism has been set-up, now follows the selection of theoretical mechanisms able to produce such features. These mechanisms have been selected by their ability to produce complex, non-linear, non-monotonic outputs with often a rotation as input. The following images are from a source-book by Sclater and Chironis (2007).

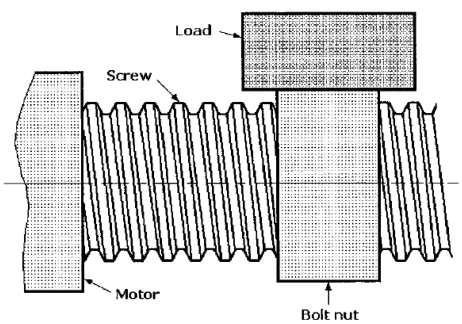
4.2.1 Driving mechanisms

Figure 4.3: Schematic of a complex bar linkage



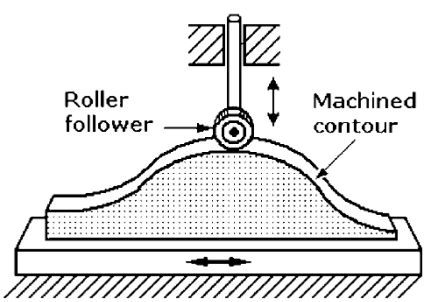
A complex bar linkage construction is theoretically able to make any shape and motion. Driven on one side and constrained by a combination of multiple secondary bars, the system as a whole can have a complex output able to drive another system. Bar linkages use many parts however, and usually require many joints which will need maintenance or costly bearings. These systems also usually work in a plane, and become extra complex when a three-dimensional output is required.

Figure 4.4: Schematic of a bolt-nut connection



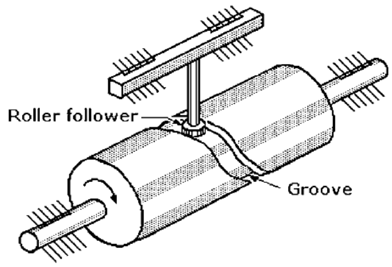
Screw-nut connections are a nice way of driving translation with accuracy while using a rotation as input. Usually These screws are symmetric in their threading, causing a linear relation between the translation and the number of rotations. However, a custom made screw part could translate the nut non-linearly, so long as the nut is guided properly.

Figure 4.5: Schematic of roller-hill guide



The roller-hill guide is a customizeable, non-linear way to turn a static motion into a dynamic motion. When the "hill" is wrapped circularly we can drive this in a rotational motion, while the roller remains its up-down motion. This can then be used in a lever concept, where the angle of the mechanism is pushed back and forth.

Figure 4.6: Schematic of a pin-groove connection



Like the roller-hill connection this pin-groove connection directly works with rotational input, and is able to push and pull, making it no longer require a return mechanism.

Figure 4.7: Schematic of a cam with rotating lever

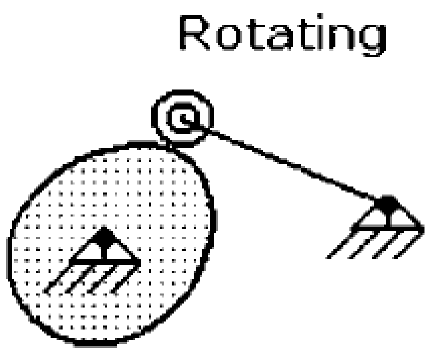
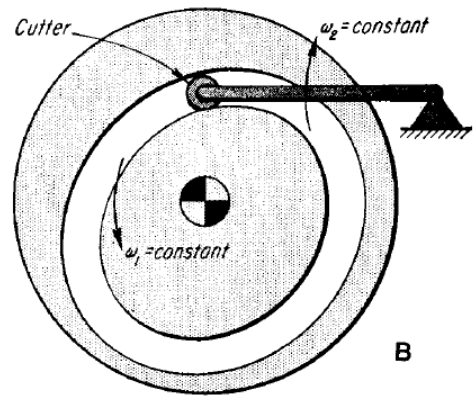


Figure 4.8: Schematic of a disk groove with rotating lever



Like the pin-groove connection a cam-lever connection can be used to translate a pin due rotational motion in a close-environment, controlled way. Here the translation of the pin is radial to the input axis.

Figure 4.9: Schematic of a double interlocking cam

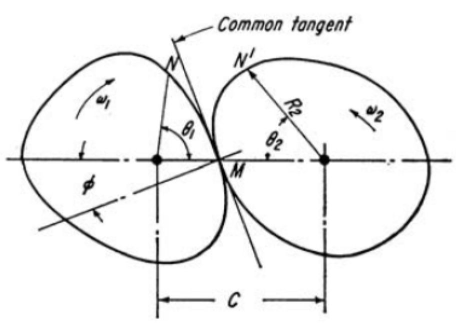
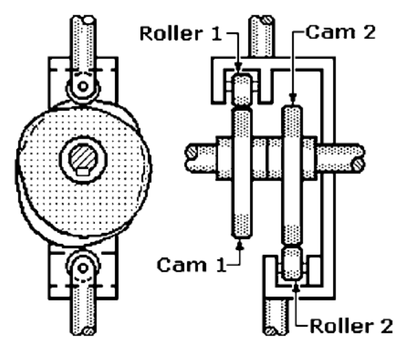


Figure 4.10: Schematic of a double cam with translating frame



Double cams can be applied in two ways. In figure 4.10 we see two cams translating the same frame up and down. Both cams are driven by the same axis, and their mirrored non-symmetry guides the frame both up and down, allowing no other movement. Secondly, the interlocking cams in figure 4.9 have another property. One of the cams will be driven so that the other is actuated. Since the cams are identical they will always interlock. However, due their non-symmetry the static drive of one cam will cause a dynamic rotation of the other, causing a non-linear relation in the roational velocity.

4.2.2 3D axis connectors

Figure 4.11: Theory of a 2DOF link

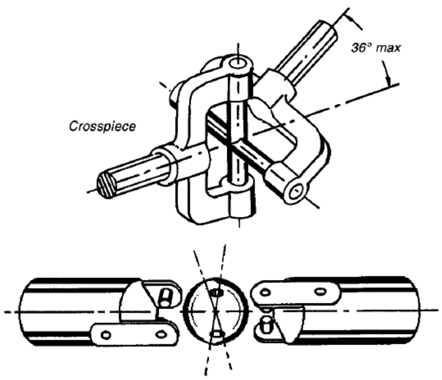


Figure 4.12: Theory of a double 2DOF link

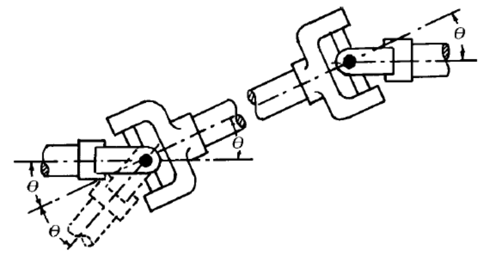


Figure 4.13: Schematic of a 2DOF joint

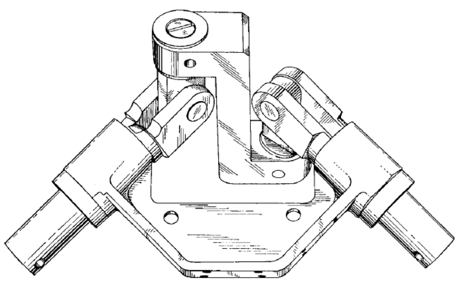


Figure 4.14: Schematic of a double 2DOF joint

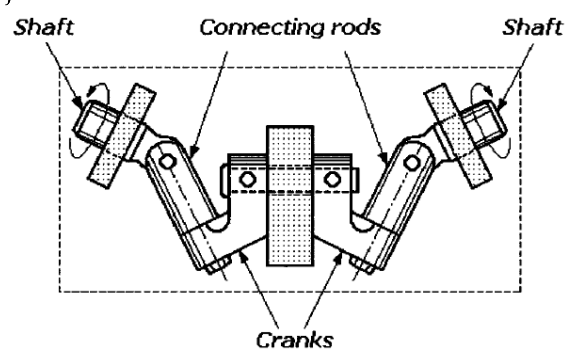


Figure 4.11 to 4.14 show the theory of a double 2DoF joint link. These will likely be important to use, since the mechanism required will have to rotate over two axis while the third axis (PS) has to pass through them (see section 4.1). Links like these have the ability to allow the transfer of rotation while the driver gets bend in two places along its axis.

4.3 Sketches of mechanism concepts

From the theoretical mechanisms a set of concepts can be derived as a first orientation on real, physical models. Though the sketches will be rather minimal, an overview of possible devices helps in comparing and eventually choosing which concept to pursuit.

Figure 4.15: Sketch of the ”Parallel Column”

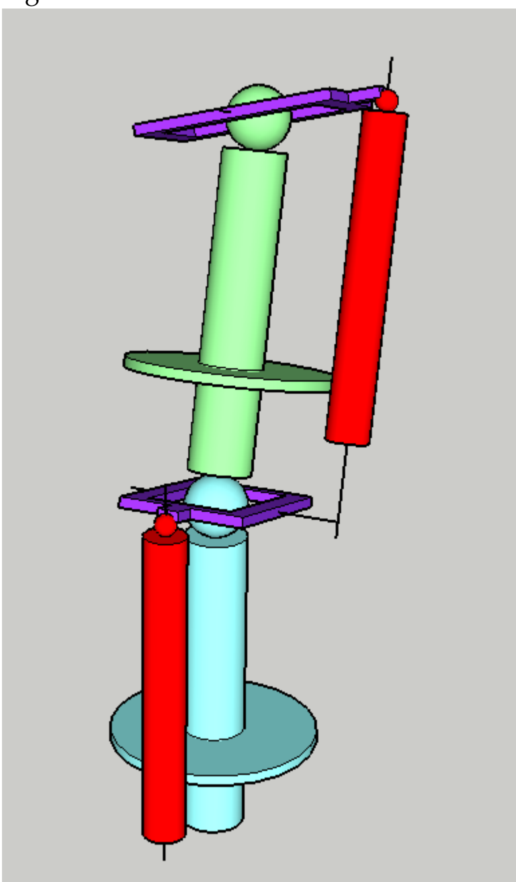
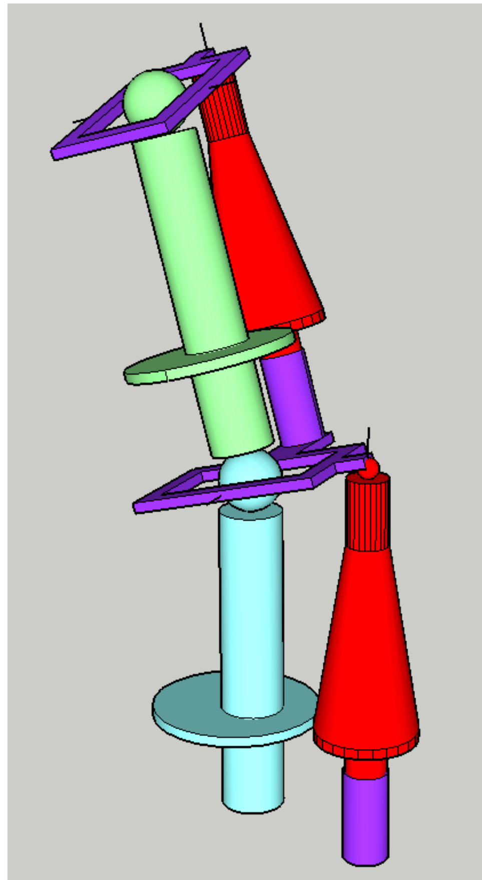


Figure 4.16: Sketch of the ”Parallel Column Cam”



The Parallel Column (figure 4.15) uses a combination of the bolt-nut and pin-groove principle. The red columns use custom threading to move the purple frames with respect to their driver column, blue and green, which will be the PS axis. Here the driving concept is a pin-groove connection between the columns. This design requires the PS axis to bend twice and builds one frame on top of the other.

In figure 4.16 we see the cam edition, where we replace the pin-groove connection for a twin-cam version. In this case the driving axis and columns have a non-symmetric cam connection which will rotate the columns with a dynamic rotational speed. The columns are then held by the frame via a standard threading (see the purple ”sleeve”) which will force the columns to move up and down due the rotation. The variable speed of the rotation will cause variable translation of the columns, and thus variable orientation of the frames.

Figure 4.17: Sketch of the "Gramophone"

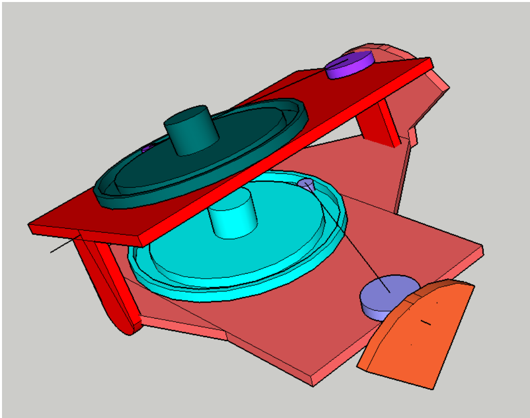


Figure 4.18: Sketch of the "Twin Gears"

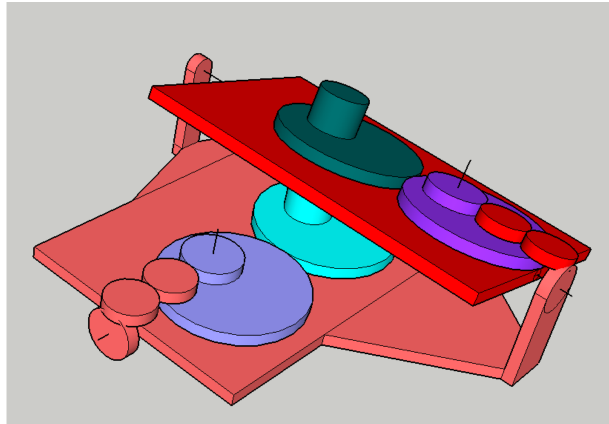


Figure 4.17 shows **the Gramophone** concept based on a cam-disc driving a rotating lever. As the lever rotates it can orient a tooth-gear, which, when interlocked with a tangent gear can rotate the orientation of the entire base-plate relative to some axis below. The figure shows a simplified, extreme version of the frame, though it's likely for this mechanism to require much space, specifically a large cam-disc to keep the rotation of the tooth-gear large enough. Systematic problem with this design is that the PS-axis requires space for a joint either above or below the cam-disc, which means the axis of rotation for the plate (which has to be in the same place) needs to be lower than the plate itself, causing an unfavorable relation between the drive gear and frame gear (the pie-shaped gears, see the orange).

The Twin Gear concept from figure 4.18 can better deal with this problem since it requires several transitions between the drive gear and the frame gear. This concept uses twin non-symmetric cam gears to transfer the static rotation of the PS-axis into dynamic rotation for the drive gear. It's unlikely however that this frame will be smaller.

Figure 4.19: Sketch of the "Cam Shifter v1"

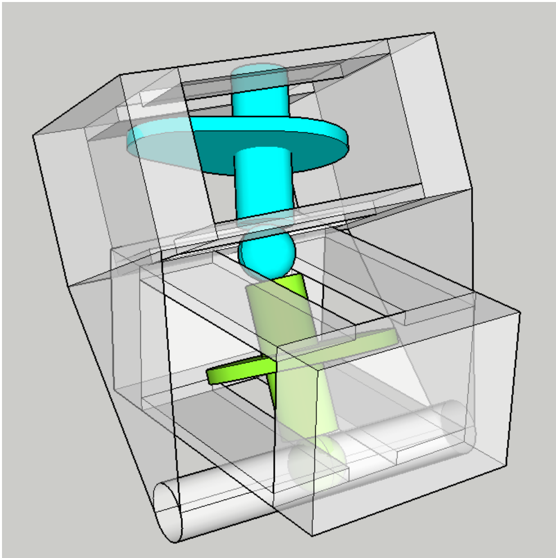
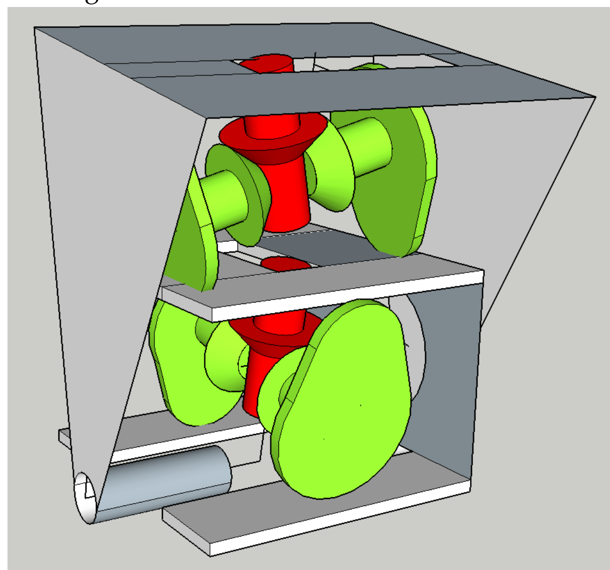


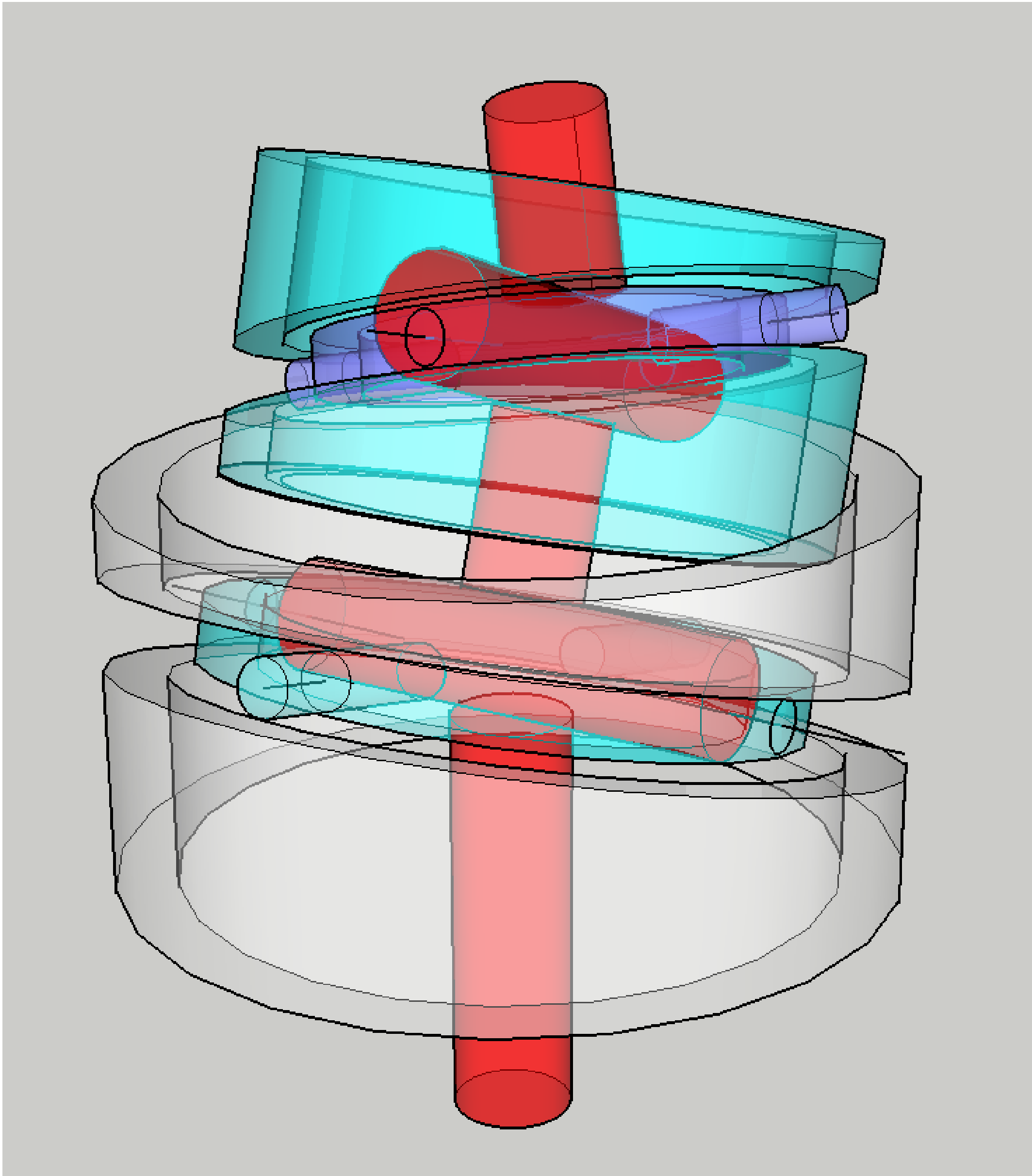
Figure 4.20: Sketch of the "Cam Shifter v2"



The Cam Shifter concept uses two cam-discs on the driving PS-axis to push the axis in diagonal orientations relative to their frame, where the stacked frame follows along. Version 1 uses a single cam which pushes the axis sideways, while version two uses a cam-pair to push up and down. Version 2 becomes more complex, and will require an extra frame to connect the cams with the PS-axis, though this frame might be useful (perhaps necessary) to connect the PS-axis to the external frames (white) which need to follow along.

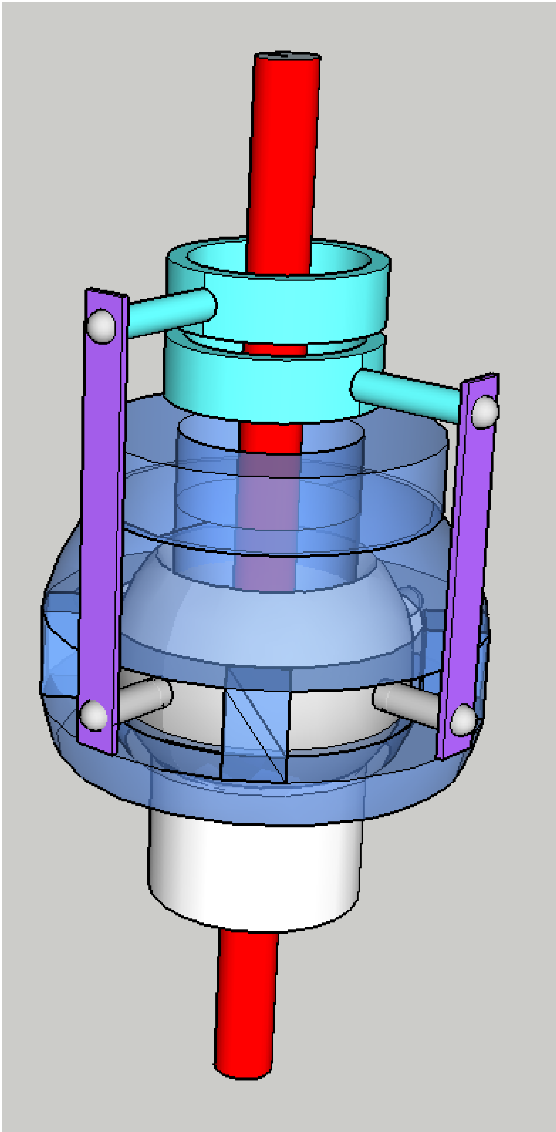
Though in theory this is one of the simplest designs, unfortunately the external frame of the mechanism is here build on the PS-asix rather than vice versa. This should cause some concern around the strength of the mechanism and the strength required of the engine in terms of friction and such.

Figure 4.21: Sketch of the ”Walled Gyro”



In an attempt to integrate the pin-groove/roller-hill guide **the Walled Gyro** was designed. The mechanism consist of two frames like has been the case so far. The outer-bottom frame (white) consists of a cylinder with a groove in the inside. A disk-frame (cyan) inside the outer frame uses pins to lock into the groove which will decide it's orientation as it rotates. This ”inner” frame will carry a second ”outer” frame (dark blue) so as to repeat the mechanism inside using the second disk-frame. Both blue and cyan frames are driven by the PS-axis (red) which will need a joint in the center of each disk-frame. This might well be one of the most compact mechanisms but it relies heavily on the pin-groove concept which is prone to friction. The friction here becomes an extra problem since the frame needs to hold the weight of the entire hand, the force of which will come directly on the pin-groove connection. Secondly, the second inner frame (dark blue) needs to move independent from the first inner frame (cyan), meaning the PS axis (red) needs a transition between them, whether lowering or speeding up the rotational velocity between them.

Figure 4.22: Sketch of the ”Ball in One”



After seeing a repeating problem of the need to stack the frames of the two independent DOFs a way was sought to avoid the problem all-together. Two frames, the white and glass, form a ball-joint connection. The white frame has two pins protruding through the glass frame which can be moved up and down to orient the joint in both DOFs separately. Inspired by the Walled Gyro, in this case the cyan frames with a custom threading (pin-groove) connection to the PS-axis (red) are used. This should be the most compact translation from rotation to orientation. Internally, the ball-joint connection will require extra grooves in the axial direction to disable axial rotation of the joint. The PS-axis will require only one, 2D joint in the center of the ball. Two external ”finger” are required however.
The ball-socket joint and the internal PS joint will have to support the full ROM of the outputs. From the preliminary study we have a maximal ROM of 25[°], which is rather small. Future use of bigger ROMs might become problematic here.

4.4 Choosing concepts to pursuit

It can be stated here that the first three concepts have been included for the sake of completeness, but have been considered barely or not at all from here on in the development. By an appeal to the human sense these designs can simply be described as ungainly and awkward. More tangible aspects, such as the need for separate, repeated mechanism, consequently the large volume of space, and the necessity of many, co-operating parts inside moving frames makes these designs inferior to the more clear-cut concepts of the last two (Walled Gyro, and Ball in One) concepts. In these designs it is also unclear whether forces on the mechanism will rely on the structure or on the PS axis (which tends to move these structures) which is an inherent problem with moving frames. The set of joints required in these concepts also require to be 2-DOF, since they require rotation of the PS axis under a static angle. In contrast, the Walled Gyro avoids this problem by having the frame rotate with the axis, thereby only requiring a hinge joint.

The Walled Gyro and the Ball in One (from here on BiO) concepts were the result of a focus directed more towards compact design. The Walled Gyro was an attempt to reduce the effect of stacking duplicate mechanism which often resulted in voluminous designs. By having the second mechanism rely on the frame of the first, the result is a partially overlapping system. The BiO concept came from an attempt to get rid of the double system all-together, and have a single joint actuated twice (hence the name). Both rely on a more complex mechanic, but by doing so require fewer or less complex joints and certainly space as a whole. From here on, it is therefor these two concepts that will be pursued.

5. Concept development

5.1 Walled Gyro

As stated in the description of the Walled Gyro, the PS axis required a transition in its rotational speed to change its speed between the last two frames. As in figure 4.21, the cyan frame is able to orient relative to the base (white) frame by the rotation from the PS axis, which it uses to be guided via pins in the (white) groove. The dark blue frame is supposed to repeat this feat, but is rotated by the same PS axis, thereby lacking a speed relative to the cyan frame (its base frame). Unless the PS axis changes rotational velocity between the cyan and blue frame, this is a fatal flaw rendering the concept futile. The choice has however been made not to pursue this concept. A reduction within the mechanism would undoubtedly (further) increase complexity, and increase required space, damaging both the strength and the weakness of the design. The principal idea was also troubled by a parallel design choice as described in section **??**. Instead, a set of new versions, re-thinking the concept, have been conceived in an attempt to avoid the problem at all. For completion this section has been included to finalize the Walled Gyro concept, though with hindsight it can be stated here already that the concept lost its appeal compared to the BiO concept.

Version 2

Figure 5.1: Workout of the double base groove version of the Walled Gyro concept

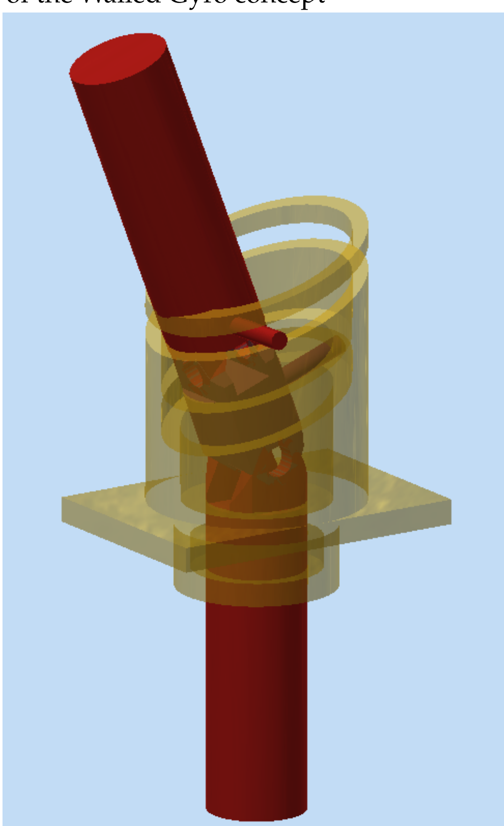


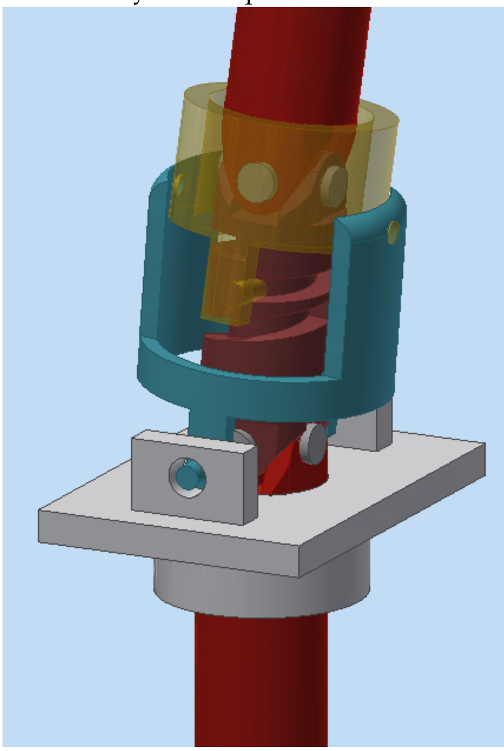
Figure 5.1 shows a worked-out concept of version two of the Walled Gyro, where the base plate holds both grooves for each DOF. It allows the PS-axis to orient itself relative to the base frame, which the figure shows done via two pins. The axis requires two 1-DOF joints to support this pin mechanism, since else the pins would axially rotate relative to the groove rather than orient the mechanism. Problem one here is that the PS-axis cannot be guided by anything more than the pin and its own mechanic strength, which makes the pin a serious weakpoint. Secondly, the PS-axis moves relative to the base frame, making it non-compliant with the axis. The figure shows already that the axis doesn't get enough space inside the second groove. Due the limits of the hand it is hard to extend the diameter of the groove, meaning the axis might become quite small. These two problems enlarge each other, where a bigger groove radius means longer pins and vice versa.

Last, the second groove, though not limiting, becomes troublesome. Aside from the task to lift the pin up and down according to the required orientation of the DOF as function of the PS, the groove also has to act as a proper guide to the pins.

This means that the second groove will have to deal with the movement of the PS-axis due the first groove. The axis orients itself tangent to the second contact pin, meaning it won't always have it's origin in the center of the circle, and won't always stand radially out relative to the base frame. The second groove becomes heavily convoluted with several functions which will decide it's height, turn and twist. Making these functions, let alone find a program capable of modeling them, will take a lot of effort.

Version 3

Figure 5.2: Workout of the double tilt frame version of the Walled Gyro concept



In figure 5.2 we see version 3 of the Walled Gyro, which focuses on the use of the two frames differently. In an attempt to have both frames move relative to the PS-axis the pin concept was extended to be moved by a groove inside the PS-axis itself. First comment on that is that the axis might become thinner as we can only rely on the core of the grooved shaft.
Both frames are able to tilt relative to their parent frame in one DOF. From there on they have a pin inside the groove of the PS-axis at either a higher or lower level. This is needed because the PS-axis cannot have a joint and a groove at the same height. It is greatly beneficial if the joints of the PS-axis are at the same height as the joints of the frames, and since the frames will move along with the PS-axis this is no problem. The axis requires two 2DOF joints for each orientation.

Main concern with this design is the pin-groove connection itself. Ideally, the pins are moved up and down, which causes the frames to tilt relative to their axis of rotation. Extending the pins on there lever-arms causes them to also move in and out radially to the PS-axis, and to twist up and down relative to the groove.

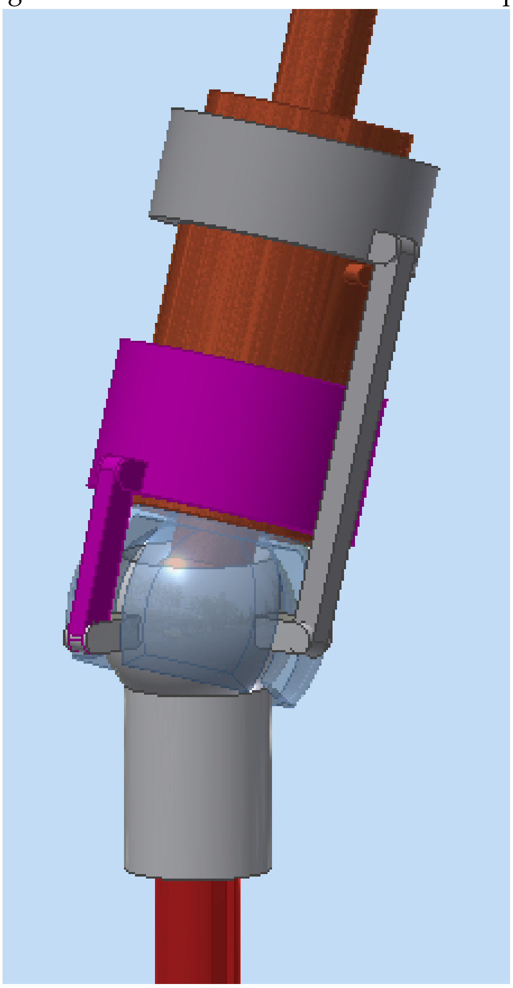
Making the arms longer gives us the ability to work with the in/out effect by focusing on pushing the pins in/out rather than up and down. This is less preferred however, since unlike the up/down the groove can push the pin only out, and has no counter part to move the pin back unless the groove-pin connection gets more complex (which will inevitably require more space).

focusing back on the up/down pin motion, the pins should stay relatively close (in longitudinal direction) to the axis or rotation for each frame to minimize the in/out and twist effects. The limiting factor in terms of this dimension is re-requirement of the height of the two grooves, in other words: how long the middle section of the PS-axis needs to be. Since the groove is on the inside of the mechanism it will have a smaller diameter, causing it to be shorter. It's probably possible to make this part of the axis slightly thicker, causing the groove to be an addition to axis rather than a subtraction, which would increase the diameter and width of the groove.
Here again we have the problem that the forces come down entirely on the pin-groove connection. Secondly, this design relies again on two 2-DOF joints, and starts to deviate back to a "double stacked" mechanism as regarded obsolete in section 4.4.

5.2 BiO concept work-out

In section 5.1 rules the Walled Gyro out as a viable concept, thereby shifting the design focus completely onto the Ball in One concept. This section will further work out the design to finalize all aspects of the concept. To start, a quick calculation has been made on the grooves, their required path and specifically their height. From here on a re-design can be made with more realistic dimensions. Knowing the total volume available from the project definition, the size of the remaining parts can be decided upon.

Figure 5.3: Workout of the Ball in One concept

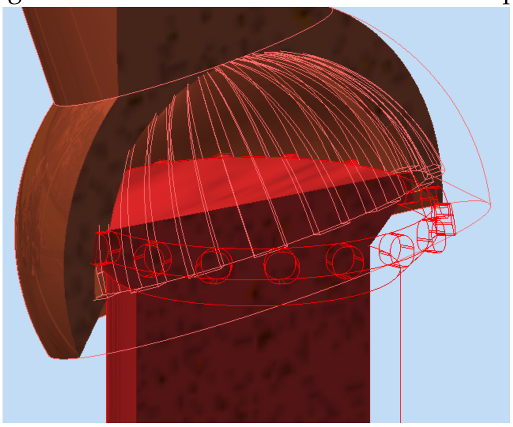


In figure 5.3 we see a better worked out version of the BiO concept. First notable difference is that the proportions of the ball and the slider are inverted, meaning that the sliders look significantly bigger than the actual ball. This is simply because the sliders are the actual mechanism while the ball acts merely as a joint. The sliders require a minimal length to house the required groove and need to give space to each other. The height of the grooves is directly proportional to the required angle of the ball-socket joint, and the length of the moment arms on the ball. Shorter moment arms require less pronounced (lower) grooves, and thus lower sliders.

The ball turns out relatively small due to two reasons. First of all, though the ball could be bigger in terms of diameter, the total length of the mechanism is already approaching the maximal length available. Secondly, the lever arms as part of the ball were calculated with a radius of 15[mm], which forms a limitation on the diameter of the ball. Extending the length of the lever arms would result in higher grooves as discussed before, and should be avoided. The grip of socket around the ball is also limited due the need to allow the full ROM, though this can be made a-symmetrical since the two DOFs don't use the same range.

A clear advantage of this system is that at least the direct linear loads form any external forces will be caught by the ball joint, rather than the pin-groove connection. Any torques (driving the mechanism inversely) will still get to the pins, but the overall bigger diameter of this design gives them a better resilience compared to the Walled Gyro concept.

Figure 5.4: Workout of the Ball in One concept



As part of the Ball in One concept a ”dome gear” was designed, which is probably a lot smaller than the average double linkage joint. It uses one radially toothed male gear and a dome-shaped female gear. If male teeth are rounded they are able to stay in the slot of the female tooth even if this rotates relatively to the radial orientation. This design should be able to transfer toque while allowing for a limited rotation in two DOF where at all times at least half of the teeth connect. The two parts do need to be kept together in their respective longitudinal position, which will require an external frame. In case of the BiO concept this gear drive might be perfect, though production will be cumbersome.

5.3 Groove calculations

The grooves used by the BiO concept, and in theory by the late Walled Gyro concept, require some basic calculations. Focus sing on the BiO concept, the ball and socket joint requires the ball to tilt in orientation. By fitting the ball with a moment-lever which can be pulled up and down the ball can be oriented to the right orientation in one DOF. The task of the sliders is to tilt the moment-levers to the right height, for which they will use the grooves. The higher the groove, the higher the slider will lift the moment-lever to orient the ball further out from its center. Ignoring the effect of radial movement of the moment-lever (at a maximum of 25° this would reduce the effect by 9.4%) a simple formula can be used.

$$\tan(\alpha) = \frac{H_{lever}}{L_{lever}} \rightarrow H_{lever} = \tan(\alpha) \cdot L_{lever} \quad (5.1)$$

where H is the height of the moment-lever, L is its length and α the orientation of the ball. This shows that keeping the length of the moment-levers short will require the levers to be pulled less high, thereby reducing the required length the sliders need to move. Keeping the levers short, however, also requires the diameter of the ball socket joint to be kept small.

Figure 5.5: RUD groove example at 103.5[°] for L = 10[mm]

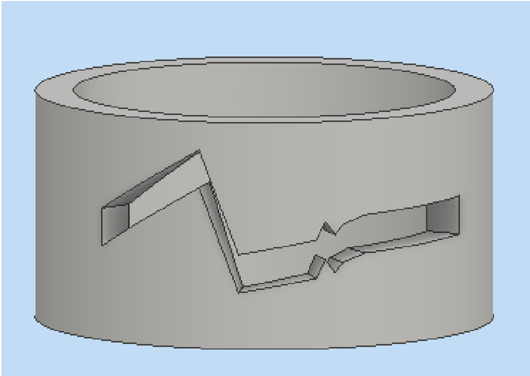
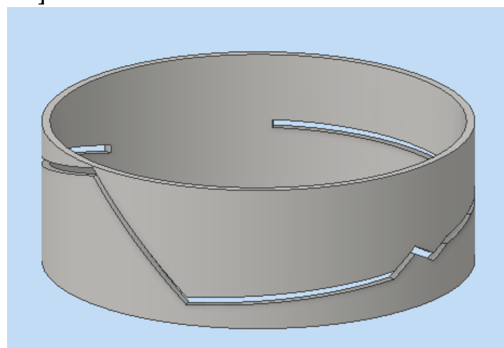


Figure 5.6: RUD groove example at 310.5[°] for L = 50[mm]



Aside from the height of the groove, a second dimension is available. The preliminary research found the ROM of the PS axis to be about 100°, which, as projected in figure 5.5 takes only a third of the total surface of the sliders. The slider in this figure is based on a moment-lever length of 10[mm], which is an extreme case, but it shows how the groove becomes ”spiky”. Though the groove would later be smoothed, it shows the required changes in height over a relatively short length (rotation of the pin). Particularly the ”steepness” of the groove hints to future problems with the pin-groove connection in terns of friction, required torque and precision. High steepness also tilts the connection in favor of external forces which now are able to drive the mechanisms backwards (torque on the ball causes the sliders to drive the pins). Increasing the length of the moment-lever would increase the diameter of the sliders (making the groove longer) yet require the groove to become higher (see function 5.1), which would ultimately conserve the problem.

Choosing to extend the groove over a broader range of the sliders would offer a longer groove while remaining the diameter of the system as a whole. Figure 5.6 shows a slider with a diameter for 50[mm] long levers, but with the groove extended 3 times its length. It can be seen in this figure that the steepness of the groove has declined, in favor of the design. This seems an advantageous choice to make. Earlier the design choice to make the moment-levers 15[mm] long was mentioned, resulting in the size as shown in figure 5.3. Finally, the length of the groove was extended to 3.5 times its original length, resulting in 362.25°. This results in a small overshoot (a circle only has 360°) but keeps the ratio a clear-cut number, which is needed when gear transitions are required, while maximizing the length of the groove.

Naturally, this decision has a consequence. The PS-axis inside the mechanism now has to rotate about 360 degrees, yet the output of the PS-axis is till just 103.5 degree. The mechanism will require a reduction of 3.5 between the mechanism's PS and the output PS. How this reduction is made will have to be discovered.

Figure 5.7: Final version of the RUD groove

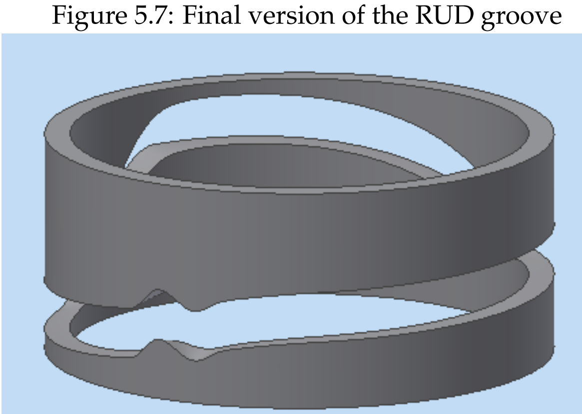


Figure 5.7 shows the final version of the RUD groove before modification into a slider. The groove was made in Autodesk Inventor using a surface between two circular splines of 360 points each. Once the surface was made a cylindrical solid could be cut to have the right top and duplicate bottom.

5.4 Design workout - first iteration

Figure 5.8: The BiO design - Version 1.2

With the eye on prototype production, the BiO concept has been developed further into a valid design. As seen before, the sliders are significantly bigger than the actual ball joint. Also the requirement of the RUD and FE "fingers" requires more space, due the use of printable plastics. In this design we start coming across some choices concerning the assembly of the device, since it is quite compact and many parts fit inside another. First notable is the ball inside the socket, which needs to be encapsulated by all directions, but also needs to be put inside at some point. Though with a strong metal frame the encapsulation might be put to a minimal (91°would theoretically be enough), for any FDM method the prototype will have to be manufactured differently. Splitting the socket in half and making one part a "hat" to be put on after the ball is placed seems the easiest solution at this stage. A second concern is the PS-axis inside the grooves, particularly the pins. Here, instead of the pins being part of the axis, the axis has a hole to house a pin which is inserted later. If the grooves have a hole on the outside, the pin could be placed through the groove in the axis, and will be kept there if only the axis sacrifices some degree of the full rotation. This probably is needed in all further designs, since the grooves cannot be assembled "around" the PS-axis. The connections of the fingers with the sliders and the ball need to be 2DOF. The connections at the ball are made of so-called keys, which allow motion in both directions of the ball. This horizontal bridge will not affect the required height of the fingers, so long at the connection is forced to be tangent. At the sliders the second rotation is minimal, and might be overcome by loosening the pin connection to allow some wiggling.

Figure 5.9: The BiO V 1.2 - finger-pins

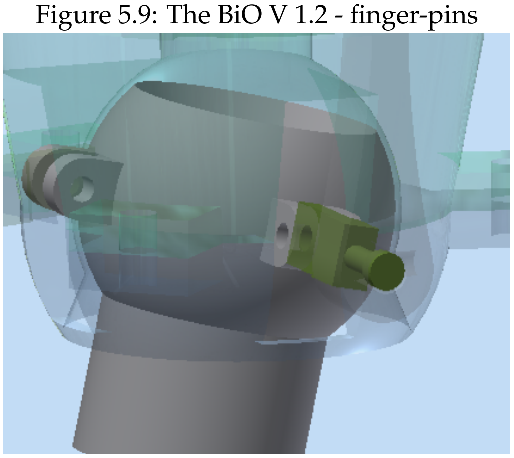


Figure 5.9 shows how the finger pins are made of a double pin joint. As the ball rotates in two orientations, the pins need to comply with the rotation caused by their own input, as well as by the other. Tilting the ball by one pin inherently makes the other pin move in a diagonal path. Though this effect is minimal (again, about 9% side-ways motion for every vertical motion as a worst-case scenario) it does affect the mechanism enough to require 2-DOF joints at both ends of the fingers.

Figure 5.10: Further workout of Version 1.4

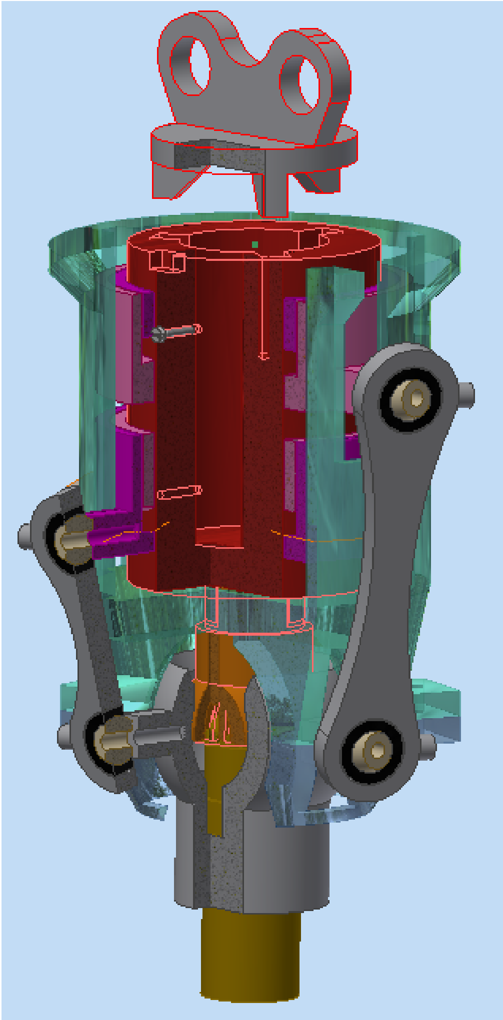


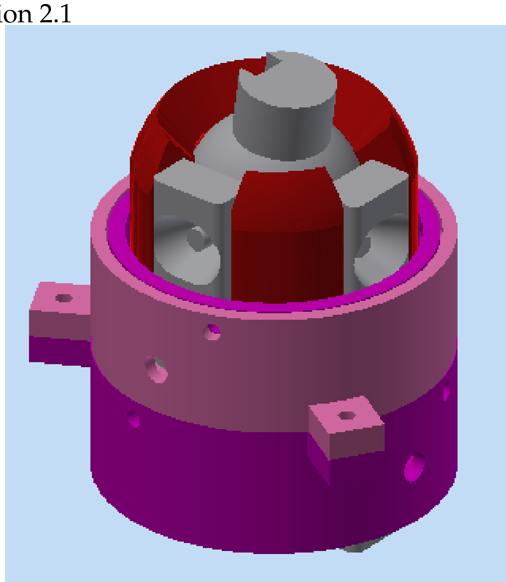
Figure 5.10 shows a more complete design in version 1.4 which was 3D-printed for prototype purposes. The small size increases the complexity of the design while assembly has to be kept in mind here. Note that the top part of the PS-axis joint (yellow-orange) has been split (orange from red) to fit through a hole in the frame (glass), only to be re-connected to the core (red) by a screw. This was done to use pre-existing parts to fix the mechanism in place rather than relying on extra parts or complexity.

The finger-keys that were before have have been replaced with spherical joints. This has the advantage that these are standard, small parts right for this task. The downside is that the lever-arm is effectively extended by half their length (an effect the keys did compensate for), meaning the grooves need to be re-calculated which has not been done here. A key (grey part on top) has been made to rotate the core manually, while the frame (glass) has been rimmed at the top to let the finger connectors pass through.

Here the dome-gear was first tested successfully. During all orientations the gear was able to transmit the torque through the ball-socket joint (orange to yellow). All parts were printed with a precision of about 0.05[mm], though small geometry was still a delicate matter. In the design, a bigger tolerance was used to ensure the fitting of all parts. Small rattling, backlash and space for movement was detected, particularly in the pin-groove connection. The output PS-shaft (yellow) also slid out of the dome engagement at times.

Though the prototype was a success in proving all major parts to work sufficiently, the design still had some downsides. As the development to a more realistic, complex design continued, the need for bigger fingers, more complex sliders (now two parts each), the required four 2-DOF joints, an unconventional custom gear, and an over-all still rather large body crept in the necessities.

Figure 5.11: Second concept of the BiO - Version 2.1



After considering the numerous disadvantages of the first BiO designs, a V2.1 concept was designed. Avoiding the necessity of the external linkages that lengthened the lever-arms, the design as in figure 5.14 was made. The "fingers" are brought to the inside and are now rotated along with the core (red) which rotates them relative to the grooves (purple) which are now the external, solid frame. By rotating the entire core, the ball will directly follow the PS-axis and other orientations all in one movement. The core needs a third, completely flat, groove to keep it in place in terms of the axial length, since otherwise it allows an extra DOF which ruins the output.
Since this mechanism does not need an inner axis, no third layer frame, and no external linkages, the total volume of this design is significantly smaller, both in diameter (5mm less) and especially in length, which is only half that of the v1.4 design.

Figure 5.12: Core with fingers and ball

Figure 5.12 shows the inside of the mechanism, where the two fingers are rotated by a slit inside the core (red). As the pins of the fingers slide through the frame which now houses the grooves, the fingers are moved up and down. This will in turn orient the ball inside the socket of the core, which will rotate along with the core as dragged by the fingers.

To allow the motion of the two fingers the pins of the ball again need 2-DOF joints. In this case no special connection is needed as the pins have a direct connection with the fingers through simple geometry. The fingers do however need to allow the motion of the pins required by the spherical motions. Here, again, the pins will have some horizontal motion with the vertical motion, at times where the other pin is at a high or low. This requires the holes in the fingers to become broad slots, to allow the diagonal motion of the pins. In certain cases that means the pins have the extra freedom to rotate axially around the PS-axis. Though this effect is minimal, this does cause rattling and backlash. However, since the design is much more compact the lever-arms (pins of the ball) are much shorter, minimizing this effect. In the future, the use of dampers can be used to further minimize this effect while still allowing the required extra motion.

Figure 5.13: Close up of ball-pin and finger

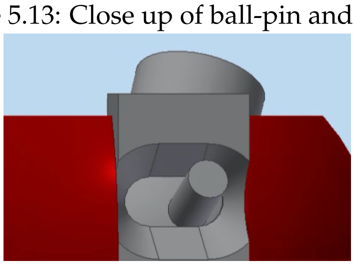
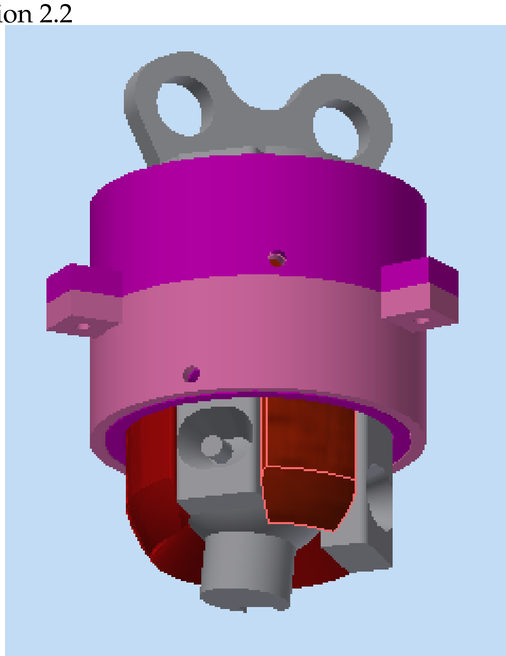


Figure 5.14: Second concept of the BiO - Version 2.2



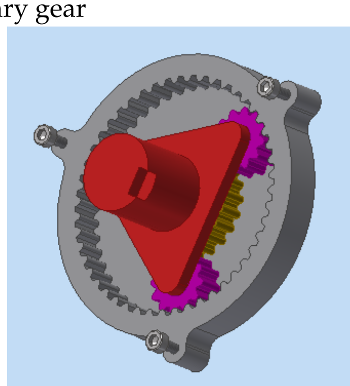
Version V2.2 was developed to be 3D printed in plastic. It was manually actuated and tested, which showed a successful orientation of the ball while the core rotated through the frame. The small rattle and backlash was encountered as expected. To assemble the ball inside the socket, one quarter of the core had to become an independent part, later connected through two sunken screws in the core. The socket also required a slight cylindrical space from the outside to the center in the direction of the secondary core part, radial to the PS-axis.

Overall it seemed that this design was far superior to the first version of the BiO concept. Though a solution had yet to be found for the backlash, the V2 design was smaller, used fewer parts, and was overall more robust. From here on the attempt was made to continue with this design.

5.5 Reduction mechanism - second iteration

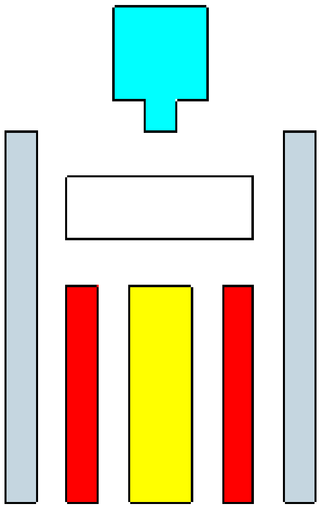
Now that two viable versions of the design were present, a step-back had to be taken. In section 5.3 the decision was made to extend the groove to 360°, which meant the final PS-axis had to be reduced by a factor of 3.5. So far, both design have not yet incorporated this necessity, and will have to be extended. Both designs end in a rotating shaft, supposedly the PS-axis, which has to be reduced in velocity. Version 1 has this shaft protrude through the ball (yellow through gray in figure 5.10) while version 2 has the ball rotate directly. Version 1 therefor has a non-rotating frame that does move along with the orientation of the axis, making it the perfect basis for a reduction mechanism. Version 2 lacks such base, and will require a reduction mechanism somehow orienting along with the ball. This gets complicated since the orientation has its origin in the center of the ball, meaning the reduction mechanism will have to sway around the ball to connect to the ball's output shaft. This is a serious downside to version 2, which otherwise was superior in almost every way.

Figure 5.15: Example of a 1:3.5 planetary gear



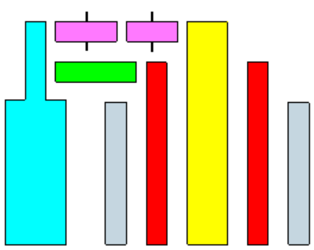
One of the most compact reduction mechanism for low rates is a planetary gear. Using a set of gears, the rotational input of one axis can be transmitted reduced or increased to the other axis. A reduction of 1:3.5 is relatively easy with this technique, yet requires some space yet again. In terms of reduction, it would be easiest to attach the planetary gear at the end of both designs, where version 1 can rely on the output shaft of the non-rotating ball to support the housing of the transmission. In theory, the planetary gear can be rather small too. However, if the transmission was added at the end of the mechanism, it would become responsible for the forces expected on the mechanism as well. Both the required output torque, the weight of the mechanism and hand, and the moments tangent to the PS-axis would all have to be supported by this transmission, which made the option easily too fragile. In general, this was deemed a poor choice.

Figure 5.16: Schematic overview of the planetary gear inclusion



Since the reduction mechanism could not be added at the end of the design, it had to be at the top. So far, PS-Axis in version 1 is a direct extension of the rotating core, however, there was space to extend the PS-axis as a secondary, independent axis within the core. Since the core was largely hollow, a mechanism could have perhaps fitted inside. Returning back to the planetary gear mechanism however, a second problem was encountered. For clarity: the core of the mechanism has to rotate 360°, while the PS-axis (inside the core) should rotate only $\frac{1}{3.5}$ of that. The frame, outside the core, has to stay stationary. The reduction therefor has to be from middle to inside, with a connection to outside. Figure 5.16 shows a schematic overview of the parts involved. Adding a planetary gear (white) at this point would require input from the engine (blue) and its output to connect to the independent PS-axis (yellow). The frame of the transmission would also have to connect to the frame of the mechanism (gray). Secondly, the engine's output would also have to connect to the core (red), in 360°, thereby having to pass the transmission somehow. This was problematic, and no solutions have been found to overcome this (simply geometric) problem.

Figure 5.17: Schematic overview of a gearbox



An external gear-set was required, and has been decided upon. The engine would connect to a set of gears together resulting in the transition required for the independent PS-Axis, while the engine also connects directly to the core, thereby controlling both with each their respective speed. In figure 5.17 such connection is presented schematically, where two gears (purple) connect to the PS-axis (yellow), and a direct connection (i.g. a pulley) (green) connects to the core. How to span the distance with a direct connection is not yet specified here (a pulley system would add a whole level of complexity). It is, however, clear that this is the best means of compensating for the extended groove consequence on the PS-axis.

The addition of an engine is likely to significantly increase the size of the total design. The size of the engine and the engine's gearbox will depend on the required torque on the PS-axis and mostly the core. In general, a lower requirement in torque allows for a smaller engine. In this aspect we can make use of the added gear-set. By expanding the gear-set to reduce the required torque of the mechanism as a whole a smaller engine can be chosen, thereby trading-in extra volume of the already existing gear-set for a reduced volume of the required engine.

5.6 Design finalization - third iteration

Figure 5.18: Third iteration of the combined designs

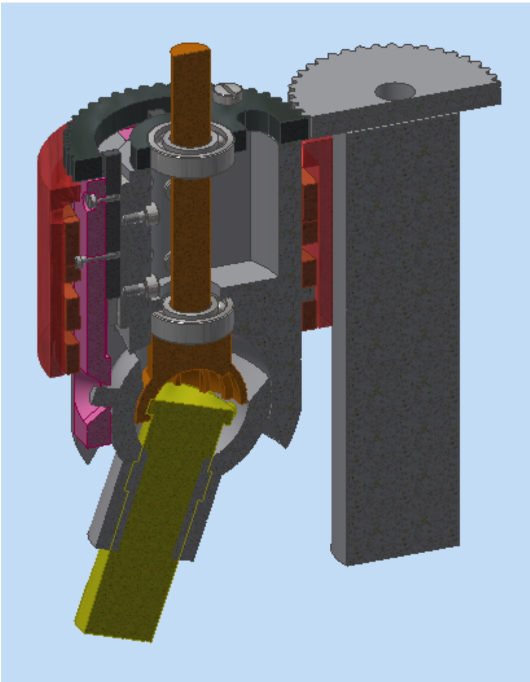


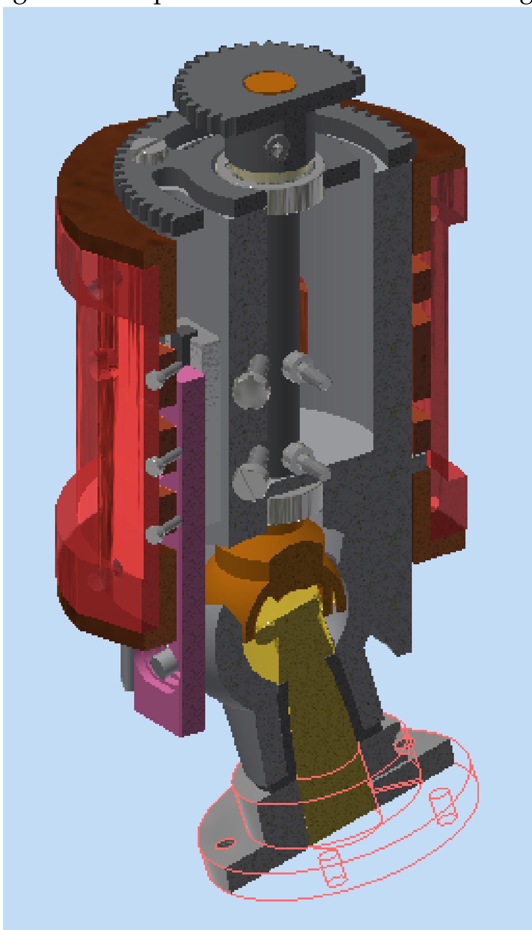
Figure 5.18 shows a fusion of version 1 and 2. After it became clear that the transmission between the core and the PS-axis could not be build at the axis of the ball, version 2 was no-longer an option. Version 1 however, seemed bulky compared to the more compact and efficient version 2. By combining the best of both, a new version of the design has been made. Using the orientation mechanics of the version 2 core and fingers, yet with an independent PS-axis as in version 1, this new model is able to orient the ball efficiently and rotate the PS-axis at a different speed while remaining compact and efficient.

This new design is largely based on version 2. The ball is still kept in place by the socket, which is split in two to fit the ball in during assembly. The ball has been enlarged to fit the dome-gear inside, and allow the both parts inside during assembly. The fingers have been fitted with linear-sliders to ensure proper guidance, and the upper PS-axis (the dome in the dome-gear) has been fitted with two bearings. From here on the parts of the PS-axis will be referred to as the mortar (up) and pestle (down).

On the top, the core is fitted with a large gear. Ideally, the engine (added with a representative) drives this gear directly. By using gears the most direct connection is ensured without the need of extra mechanics such as pulleys of cables. The mortar has been elongated to allow connection to a future gear-set also connected to the engine. Having the engine parallel to the mechanism was found to be the most compact solution to the limited space as defined by in the Project Definition. This assembly uses almost all available space in terms of height and thickness (mainly of the hand), and therefor has to concentrate on volume in the width.

6. Final design

Figure 6.1: Improved version of the final design



6.1 Final mechanism

Figure 5.18 shows the final version of the mechanism. Several bushings, or sleeves, are added to guide the moving parts, particularly between the frame and core, and between the ball-shaft and final PS-axis (pestle). These bushings play a crucial role in the smooth rotation of all parts, while also keeping the core and bottom part of the PS-axis in their respective longitudinal place. The main-frame and ball have been designed to press-fit the bushings in place, requiring tight tolerances. The core, containing the lower bearing of the PS-axis will require a similar tolerance, though a pipe has been added around the mortar to ensure the right longitudinal placement of the parts connected. Last, a flange has been added with a similar shape and size to the Steeper EQD wrist connector (see section 2.2.5). The flange will rotate along with the PS orientation of the pestle and is clamped with a radial screw, ensuring full connection to any external hardware.

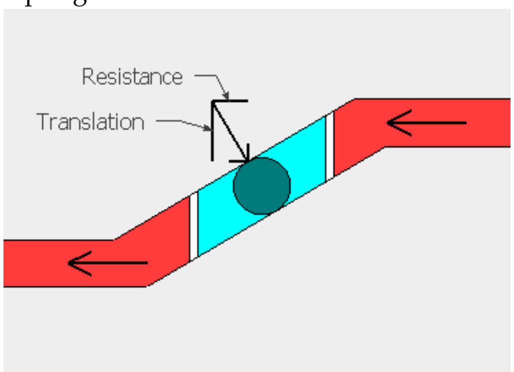
The main-frame (red) has had its two flanges cut flat in a tri-symmetrical fashion, in accordance with the tri-axial screw-sets of the grooves embedded inside. These flat, outer sides of the frame allow extra holes for external screws, which are the first connection to a frame beyond the mechanism self. A frame to hold the yet required engine, gear-set, and the frame of the surrounding hand can be connected here.

Several complex parts have been designed so far, and matters of production start playing a role. Due the relatively high loads the mechanism will have to take, a metal fabrication is sought after. Using conventional production methods some parts designed thus far are nearly impossible to make. A discussion was led on whether the parts had to be changed to be designed by these conventional methods, or whether other methods existed after-all. Metallic 3D printing has evolved exponentially in the last few years, and many companies exploring this technique could be found. Seen the complex shape of the parts and their relatively small size (A mostly hollow cylinder of 55[mm] long and 3[mm] thick was the largest part), some parts have been selected to be printed through this technique. Also the grooves with their complex guiding surface (radii of 1.33[mm]) had to be printed. The core (both parts), ball, mortar, and pestle have been selected for this technique. To save costs and time, most custom parts have been altered to be made by conventional methods. The remaining parts (bearings, bushings, screws, engine, and gear-set) have been ordered from from independent companies, though some parts required post-modifications after received. Particularly the big gear in figure 6.1 has been given extra slots and threaded holes to fit on the core, as well as a precise hole to press-fit the upper bearing. Also 3D-printed parts require post-modifications on precision holes and threaded holes. After conversation with the 3D-printing companies, stainless steel was found to be easiest, and cheapest to produce. Due weight reasons, lighter metals such as aluminium and copper were considered, but would cost significantly more, while making up only 36% of the complete volume.

6.2 Force calculation and engine selection

Section 2.3 presents an overview of speed and torque specifications of other wrist mechanisms. To end in the high range of such list, the ambitious goal has been set to create an output torque of 2[Nm]. The asterisk here, however, is that the list as in section 2.3 shows the output of the mechanisms per DOF, while most of the devices mentioned use independent engines to drive these. In the case of this design, only the PS-axis is driven directly by the engine, while the other two DOFs are driven indirectly through the mechanism.

Figure 6.2: Schematic overview of the reaction forces in the pin-groove connection



Due the nature of the pin-groove connection, some force losses will be encountered. The groove will have a diagonal transfer of power with the pin, causing forces to disperse due simple trigonometry. While the pin moves through the groove, it will meet more resistance and come in less favorable configurations the "steeper" the groove is relative to the pin's straight path. The "pitch" of the groove determines the efficiency with which the pin can cause the fingers to slide up and down, thereby orienting the ball in the remaining, dependent DOFs. Though the grooves are dynamic and different at each point, the steepest point (with some addition) comes to about 30°. This converts to a efficiency in force transference of about 87%.

To orient the ball, and thereby the hand, the mechanisms will have to overcome this loss of force. Secondly, at an unfavorable orientation of the hand, the mechanism might also have intentions to be back-driven. Were the ball to push the fingers upwards due the weight of the hand, the mechanism would have to lift this weight first. Orienting the ball at this point would require at least an equal force by the engine.

Two calculations for the required torque of the engines can therefor be made: the torque required by the PS-axis, and the torque required by the mechanism. The calculation for the PS-axis is rather simple since the engine will output a torque by some possible transmission directly to the PS-axis, resulting in the formula

$$T_{Motor}[Nm] = \frac{T_{PS}[Nm]}{K_{gs}[-]} \tag{6.2}$$

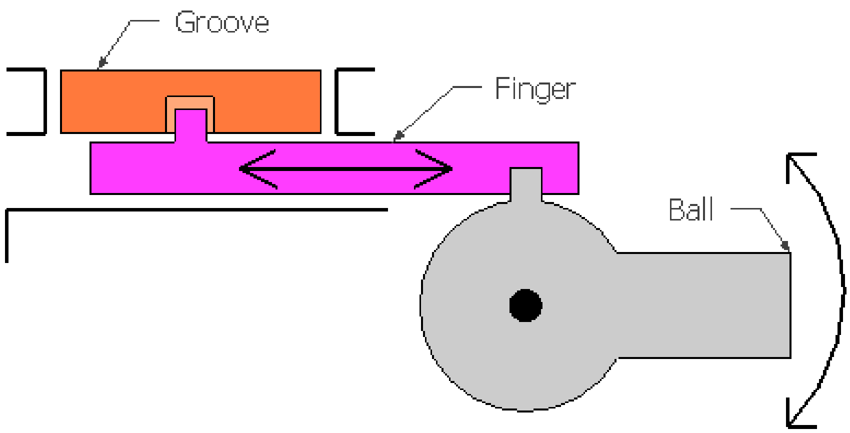
where K_{gs} is the order of the transmission of the gear-set. Friction of the parts has not been taken in account here due the use of sliders, bearings, and bushings along the axis. The efficiency of the gears, both in the gear-set and the dome-gear, has also not been taken in account.

For the remaining, dependent DOFs the calculation gets a bit more complex. Starting with the weight of the hand, expected at about 0.7[kg] (rounded off to 7[N]), the mechanism might receive push-back by the mass back-driving the mechanism at an unfavorable position in the pin-groove connection. Figure 6.3 shows a schematic overview of the rotation of the ball pulling the pin to drive the groove. At a worst-case scenario, this force needs to be overcome. Stating that the center of mass of the hand lies around 100[mm] away from the wrist joint (see figure 2.1) a moment arm is created on the ball-joint which is transferred to the finger by the ball's pin of about 11[mm]. The finger, pushed by the ball, then connects to groove via the pin connection, at a worst-case angle of 30°, allowing it to spend 50% of its force on rotating the mechanism through the groove. Using a function to describe this allows to find the required torque on the PS-axis to overcome this effect.

$$
\begin{aligned}
T_D[Nm] &= \frac{W_{hand}[N] \cdot M_w[-] \cdot r_{hand}[m]}{r_{ball}[m]} \cdot E_{PG}[-] \cdot M_\mu[N] \cdot r_{pin}[m] \\
&= \frac{7[N] \cdot 1.5[-] \cdot 0.1[m]}{0.011[m]} \cdot 0.5[-] \cdot 1.35[-] \cdot 0.016[m] \\
&= 1.031[Nm]
\end{aligned}
\tag{6.3}
$$

where M_w is a 1.5 multiplier for the weight of the hand, E_{PG} is the efficiency of the reversed pin-groove connection, and M_μ is the friction coefficient of the pin-groove connection which is roughly double of the expected friction according to $\cos(30°) \cdot 0.2$. This means that at a worst-case scenario the mechanism requires a torque of about 1[Nm] to be driven, concerning the dependent DOFs.

Figure 6.3: Schematic overview of the external moments back-driving the mechanism.



As stated in section 2.2.6, Maxon's Motors will be used as the supplier of the electrical engine used in the design. The engines are particularly small, but supply an output torque within the milli-Newtons-meters, meaning a reduction is required. The engines come with a fitted gearbox to increase the output torque of the engine to a limit set by the strength of said gearbox. Most such gearboxes have an intermittent load capacity between the 0.5 and 0.8 [Nm]. To select the right set 104 gearboxes have been reviewed and filtered from smallest to largest. A strong focus has been put on the size of the engine-gearbox combination to keep the over-all size of the wrist mechanism minimal and within proportions.

The choice has been made to also extend a custom gear-set, reducing the requirements of the engine further by a factor 3. The gear-set required to adapt the PS-axis to its right speed would require a set of gears which could easily include a secondary reduction. Both the PS-axis and the dependent DOFs mechanism would thereby require only a third of their original input from the gearbox. This opened the door for many of the smaller gearboxes, where finally GPX 16 Planetary Gearhead was chosen, with a diameter of 16[mm] and a total length of 27[mm] was chosen. Using the single lowest reduction available for this type, the DCX 14L DC motor was chosen including a standard decoder for a total length of 70.2[mm]. These choices have been made based on the required torque, total size, and the rotational velocity which, unfortunately, had to be reduced to 34[rpm], or 1.75[sec] for a full rotation.

6.2.1 The gear-set

Figure 6.4: Final design including engine and gear-set

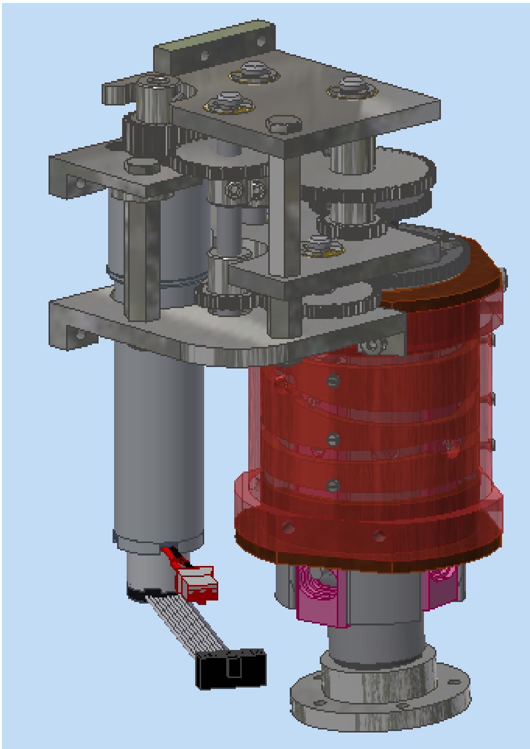
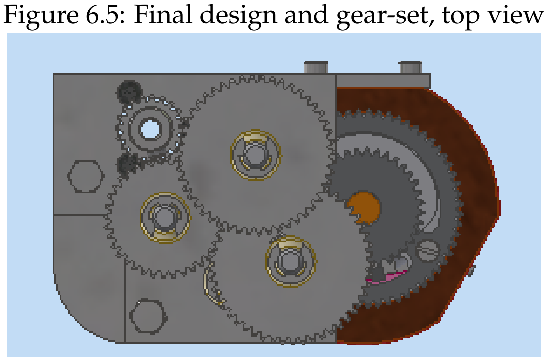


Figure 6.5: Final design and gear-set, top view



The gear-set has been designed to accommodate both the general reduction between the engine and the mechanism as a whole, and the relative reduction between the mechanism's core and PS-axis. The engine therefore drives, in fact, two gear-sets. One reduction of 3:1 to the core, and another of 1:10.5 to the PS-axis. The gears have been selected from Misumi, a supplier of ready-made parts. The gears have been arranged as compact as possible, while working in the width of the design and refraining from making the design "thicker". Figure 6.5 shows how the gear-set works in parallel with the mechanism and constraints the gears to the size of the mechanism itself.

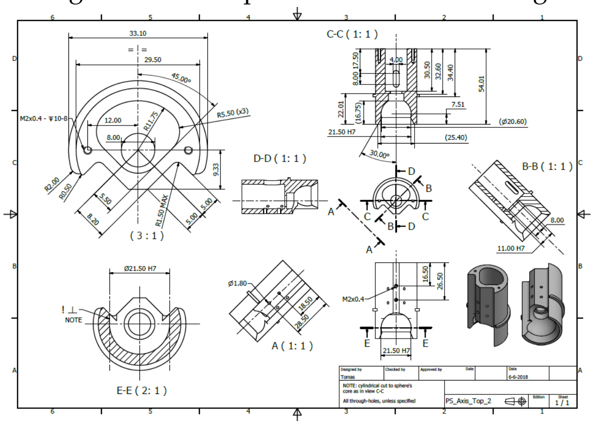
A total of 10 gears have been used, including the gear of the motor and the two gears of the mechanism. Five layers of gears have been arranged using four plateaus of frame-plates. The gears are suspended by axes, each fitted with a bearing at each end for maximal guidance and minimal friction. The frame-plates also have support columns between them, and have been designed as shelves on a common board. The plates are therefor part of the frame of the mechanism, which is designed to connect to the same structure at each third of the exterior. In the design of the CECA2020 hand-project the mechanism was involved with, this final design has been kept in close consideration.

The engine has been designed as part of the gear-set. Involving the motor as part of the volume greatly reduces the total space required and allows to move the parts in the width rather than the thickness. The motor has been connected to one of the frame-plates by counter-sunk screws as part of the gearbox. The engine's orientation has been chosen to face the empty space underneath the gear-set, which is likely to house any future electronics required. The frame has also been adapted to support extra geometry such as electronic-boards.

6.3 Production

The final design has been worked out sufficiently to have production started. Contact with multiple suppliers has given the opportunity to buy several off-the-shelve items such as bearings, bushings, and gears. Of the custom parts, most have been developed to be producible according to conventional machining, as was possible at the Bio-Robotics lab. A sub-set of the custom parts required more advanced, 3D-printing techniques, for which a set of suppliers have been found and discussed with.

Figure 6.6: Example of a technical drawing



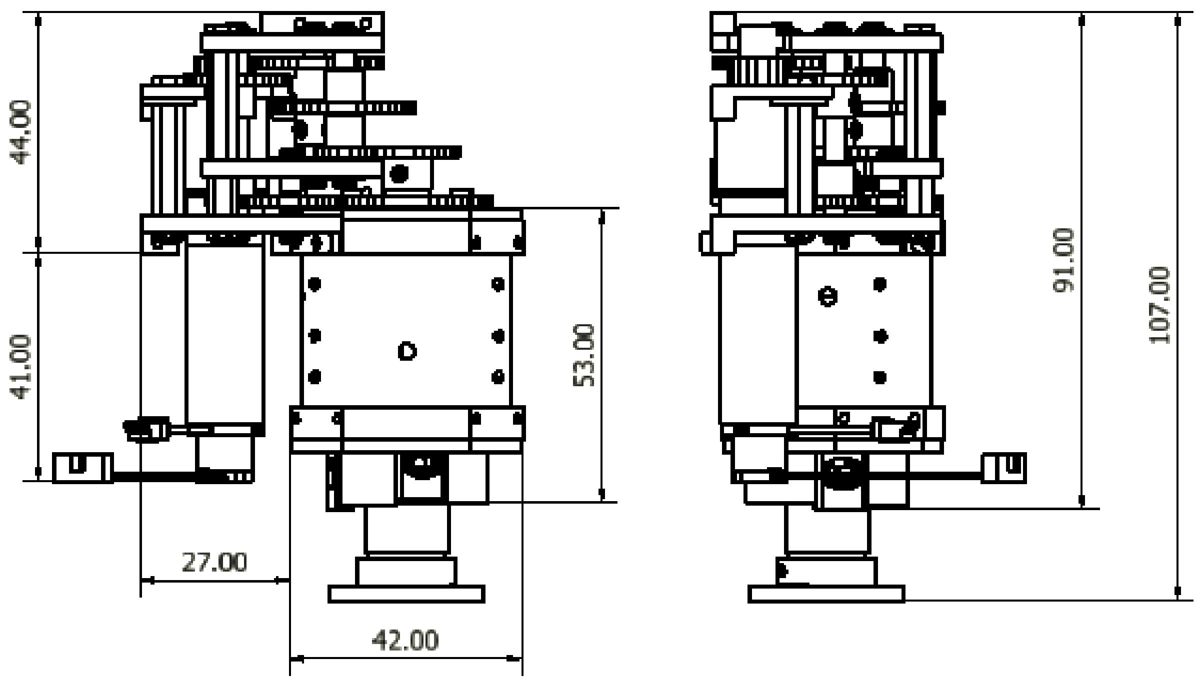
All non-custom parts have been ordered at Misumi, Igus, and Maxon Motors. They have been delivered within the time appropriated to the project, after which some parts have been send to the lab's workshop for post-processing. For this work, technical drawings have been made to indicate the necessary changes. Such drawings have been made for all custom parts as well, some of which have been send to the lab's workshop. These parts have been produced as well. Remaining were the custom, non-conventional parts which have been ordered for 3D-printing for which 2D and 3D specifications of the parts were available. The parts have been modified to so-called "phantom" parts of the original, to ensure post-production was able to fix required threading and tolerances. As of this version of the report, the parts have however failed to be produced and delivered.

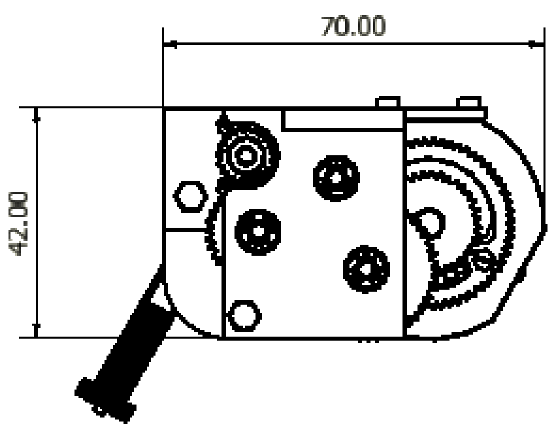
The lab's intentions are to have the parts produced in the near future after which the mechanism can be assembled and tested. So far, the mechanism has not been tested beyond digital versions and earlier prove-of-concept prototypes. Particularly rattling, noise-levels, and lashback can be tested relatively easy once the assembly is done. A more complex method is required to understand if the mechanism indeed produces the path as found in the preliminary study.

6. Conclusion

6.1 The final design

Figure 6.1: Overview of sizes of the final design





Using the digital model of the mechanism, and with knowledge of the material types, some estimations can be made. First of all, the size of the mechanism, motor, and gear-set are all known. The mechanism has a modest diameter of 42[mm] around the broadest base, with a length of 53[mm] including the core. Where exactly the mechanism exits the hand or forearm to become the wrist is not specifically defined, though the length of the motor does make limitations. If only the neck of the ball and all parts following are outside the total frame, a length of only 16[mm] of the mechanism is exposed.

Unfortunately, the engine and gear-set add a significant volume to the total design. Mainly due the gear-set, the mechanism is extended with an extra 44[mm] in height, causing a total length of 91[mm] of inner structures. The engine, with a total length of 83[mm], runs parallel to the mechanism for almost the entire length, in spite of attempts to keep it small.
To calculate the expected weight of the mechanism, all metallic parts have been given properties of stainless-steel, and the bushings those of ABS plastic. Volume calculations indicate a total weight of about 710[g], where the mechanism makes up for about 485[g], and 650[g] with the gear-set included. The engine, though considerable in size, weights a total of only 60[g], making up less than 9% of the total weight.

6.2 Specifications

Figure 6.2: Overlap of the final design with the specified volume

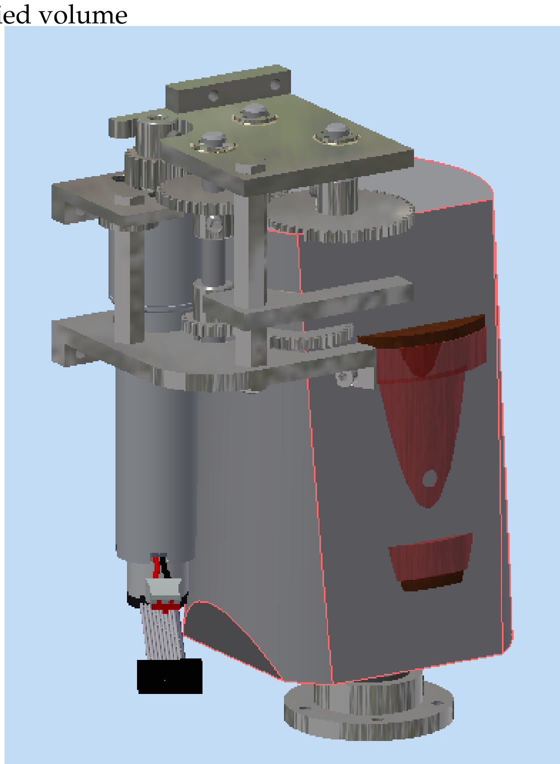


Figure 6.2 shows the final design overlapped by the specified volume as defined by the intersection of the hand and wrist volume (see section 2.2.1). It is obvious by this example that the total size of the design does not meet the design-goals of the project. Though the thickness of the design is too large as well, mainly the length and width overpass the specifications by about 17[mm] and 18[mm] respectively. The expected total weight of 710[g] also trumps the CECA2020 hand project's goal of a total weight of 700[g]. Obviously the wrist mechanism is not the only component inside the hand. Though the velocity of the DOFs in terms of rotation was not specified, a total rotation time of 1.75[sec] is also significantly higher than other, comparable mechanics (see section 2.3). A mechanism with high rpm will always be able to lower its velocity, in this, the design is constrained. Whether the velocity is too low, however, remains to be determined during final prototype testing. Part of the reasons for the gear-set came from the demands on torque and load on the mechanism. Both these specifications have been met abundantly, according to design and calculations. After calculations, the pestle (which will carry the entire weight of the hand) has been increased 1[mm] in diameter to support a total weight of 5.7[kg] with a 25% added margin.

According to the design, the full path as found in the preliminary study has been reproduced successfully through the means of an integral mechanism. By the influence of a single electro-motor, the mechanism is able to orient a prosthetic hand in three orientations while maintaining load and velocity.

In spite of the voluminous result, the mechanism does include a proper frame to connect to surrounding hardware. It has been designed to connect to a single "back-plate" which should form the frame of either the hand of fore-arm. The mechanism also includes several other attachment points in two other, tri-symmetric directions. The mechanism also remains open space for other hardware such an electronic card, and has utilities to connect these close to the mechanism's body. After consultation with the CECA2020 project, the hand design has undergone slight changes and was able to fit the mechanism after-all.

6.3 Summary

The mechanism does not meet all requirements set by this project. The total weight and size are considerably too high for both projects involved. The emphasis of this work has firmly been put on the mechanics of the design. First priority of this work was to prove the theory of the preliminary study, which was based on the hypothesis that wrist mechanisms would benefit from a synergetic approach to their design. The mechanism is (theoretically) able to mechanically re-create the synergetic relation of the two dependent DOFs from the input of a single engine which gets perpetuated as the third DOF. As such, the mechanism proves that this synergetic approach is physically possible, within reasonable complexity (i.e. number of parts, transmissions or shape of parts). The mechanism is also successful in baring the expected forces according to the design goals while remaining relatively small in size. Though the total volume and mass of the design is too big, the combination of a complex mechanism able to bare significant loads while reconstructing a new synergetic theory has been accomplished.

7. Discussion

During the design a heavy focus was put on the mechanics. Main priority was to get the mechanism to work, and be able to follow the path specified by the preliminary study. This path, along with the desire for an under-actuated mechanism, were the main challenges as any accomplishment would have been unique. Proving the synergetic approach of this project, and the subsequent theory found by the preliminary study, was the main goal of this work. The achievement of this goal has come with sacrifices on size and weight, but should be considered a success nevertheless. A first prototype to a unique approach in bio-robotic prostheses has been designed which from here-on can only be improved.

The issue concerning the weight of the mechanism has an obvious start at the gear-set, but an undeniable end at the mechanism's core. Though the gear-set contains a bulk of gears, plates and axes, it makes up for only 23% of the estimated weight. The core mechanism will require improvements to battle the total weight fully. Some basic strength calculations have been completed on the most high preforming parts, but these were admittedly rudimental. More complex finite element methods (FEM) could be used to further calculate the parts of the design, and skim them of material un-required for their specifications. This same process could shine light on which parts allow different materials, particularly plastics or carbon/glass fiber. Parts such as the mechanism's frame, the gear-set frame, and the mortar are not expected to carry high loads and would make suitable subjects for such investment.

In terms of size, it seems unlikely that this design could become significantly smaller. Perhaps that through a meticulous work of FEM and more custom parts the overall shape and size could be altered favorably, but the global issues would not be addressed. It can be said here that the gear-set was an unwanted, and somewhat unexpected, consequence by the choice to lengthen the groove to 360°. Though the choice was well funded, its requirement for a reduction was a backlash to the design not entirely foreseen.
Were a future party willing, they would be well advised to explore a construction parallel, and alternative, to the choices of this design. Going back to the choice on the length of the groove, keeping it at the original length would give access to several design choices. Though the pin-groove connection would become more strenuous, the following concept phase could copy the version two concept almost identically. Needing no internal axis and no reduction, the design could perhaps be half the length of this work's final mechanism. Leaving more space for a stronger engine, meaning a gear-set might not be needed at all.
This new mechanism would require a stronger motor, and is likely to find higher forces requiring it to grow bigger than this work's version two. A stronger engine is likely to become thicker, and not necessarily shorter. So-called flat engines have been considered in this work before, compensating low speeds with high torques. Whether this trade-off results in a over-all benefit remains to be seen.

Because this work's yet proven nor un-proven parallel design, as well as the lack of any physical tests, the question remains whether prosthetic wrist mechanisms benefit from a synergetic approach. If a smaller, lighter design is feasible and successful, most requirements of this work would be met. Able to fit in the partner projects, with a general small size and low weight, while still able to create the full orientation output under stress of a full load, the mechanism would be outstanding in a mechanical aspect. Whether the mechanism (and its approach) is desired in a functional sense remains to be tested. Adequacy of the range of motion, the speed to reach each position, and the alignment of the positions and the resulting coupling between the DOFs are examples of features that need to be tested with a physical prototype.

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DELFT UNIVERSITY OF TECHNOLOGY

MECHANICAL, MARITIME AND MATERIALS ENGINEERING (3ME)
BIOMEDICAL ENGINEERING DEPARTMENT

LITERATURE STUDY

18 September 2018

A literature study on the requirements in the design of an active prosthetic wrist mechanism

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supervised by
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Abstract

This literature review focuses on the importance and use of prosthetic wrist mechanisms. After a study on the varying usage of wrists in human interaction for un-impaired and amputees it becomes clear that the function of the wrist is widely used and important. In the prosthetic sense, wrist mechanism are also shown to have significant impact in the total functionality of the prosthetic. Last, through surveys prosthetic users indicate a limited range of motion concerning the wrist to be among the top 10 reasons for abandonment. From these surveys, as well as general sources, a list of requirements for wrist mechanisms has been formulated. Consulting a state of the art review on wrist mechanisms shows a great lack of wrist mechanisms in general, and a low appeal to the requirements as defined in this work. It is shown that prosthetic wrists are mostly under-developed, and lack the functionality and requirements needed to make a useful system.

After observing how most designs focus on only few of the important aspects of prostheses the conclusion is made that the requirements for such wrist mechanisms are perhaps too high, and that designing such mechanisms is not trivial. As a solution, the use of ”Synergetic relations” is suggested, effectively coupling the required output of wrist mechanisms. Synergies are theorized to help lower the requirements, by reducing the number of required engines, thereby helping size, weight and complexity. Research in the use of synergies in wrist mechanisms shows however that this approach is used almost not at all.

From here, a review on synergies is done. After reviewing a case in which a principal component analysis is used to find a synergetic relation the conclusion is made that such synergies need to be rather dynamic to fit the use of wrist properly. An attempt to find synergies among literature on the range of motion of the wrist during activities of daily living proves that finding such synergies is not a trivial task. Finally, a new research describing the use of a new method to define a synergetic path through all degrees of freedom, driven by a single actuator is reviewed. It is this new method that seems to achieve the required functionality of a complex wrist mechanism while balancing other required traits of a prosthetic as found in this study. Through a synergetic approach to the use of the wrist, the method seems to allow the design of a new mechanism able to exploit the use of synergies to reduce the remaining requirements.

This report therefor advocates the design of a new prosthetic wrist mechanism using an extrapolation of these findings. The design of such mechanisms could prove the mechanical validity and feasibility of such syergetic approach, and could be used to prove if such mechanisms indeed do benefit from the approach in terms of size, mass and complexity. Whether the synergies are also desired in a functional and practical sense can also be answered only through a physical prototype.

Contents

List of abbreviations

ADL	Activities of Daily Living
(2)DOF	(two) Degree of Freedom
FE	Felxion/Extension
IMU	Inertial Measurement Unit
PS	Pronation/Supination
ROM	Range of Motion
RUD	Radial/Ulnar Deviation
SD	Standard Deviation

1. Introduction

This literature report is part of a set also containing an internship report and a thesis report. The literature reviewed in this report will serve to support both other works in terms of comparison, inspiration and as a foundation to working theories. Part of this literature will be used to support the internship report, which in turn functions as a preliminary study to the thesis report, which will be supported greatly by this report as well.

Work done in this report is therefor part of a greater project executed at the BioRobotics lab of the Scuola Superiore Sant'Anna university in Pontedera, Italy. After work done by Casini et al. (2017), who found a great significance in the role of a multi-articulated wrist for the functionality of the hand, a new focus was put on a small, lightweight prosthetic wrist mechanism. A new program was set-up to develop and design such mechanism. Exactly how the mechanism should have multiple outputs while remaining small and light-weight was to be found in this work. This research was done to understand the requirements of the mechanism, comparable products and their importance, before the new mechanism would be developed. Though the review of literature was not expected to give answers as to how to design the device mechanically, a general direction and design goals were to be extracted from this research on wrists and wrist mechanisms in general.

2. Methods

The methods of this work will be kept purely theoretical. Through the review of existing literature, attempts will be made to make several conclusions form a general collection of data and opinions. The goal of this work is not to prove preceding thoughts or opinion, but to pursuit and make clear the needs in prosthetic wrist mechanisms for future work.

To support the design of a new wrist mechanism, as was the goal of the global project by the Biorobotics lab of the Sant'Anna University, a set of topics have been set to further inspect and discuss. With hindsight, these topics are the chapters of this report. A first topic of the project was to further investigate (after work done by Montagnani et al. (2015)) the importance of wrist joints. Since use and abandonment of prostheses was a topic on its own, particularly the use of the wrist in general was to be investigated. Abandonment of prostheses was known beforehand, so research was done to find a relation between upper-limb prosthetic use and abandonment and the function of wrist mechanisms. From these sources a list of requirements for wrist mechanisms could also be formulated through a "demands and wishes" summary from questionnaires.

A state-of-the-art review was found by searching for exactly those words. Most reviews had embedded their own opinion and conclusion. After finding such sources, each mentioned and cited work opened doors to the specific literature of that design. Using the original literature of each design directly led to an array of information forming a more intrinsic overview of excising mechanisms and designs.

Later, when research around synergies became relevant, specific key-words have been used to relate, for example, synergy, collaboration, coupling and adaptive mechanisms with prostheteses, mechanics, kinematics and anthropometry. Results have been filtered and selected to, at first, be relevant to the use of synergies in a theoretical sense, and later specifically to the wrist or other upper-limb joints/mechanisms. When syenergies showed to have limited literature in light of wrist mechanisms, an attempt was made to prove the use of synergies. Sources for this work were sought in other literature which was popular around literature on the human wrist, particularly (functional) range of motion, kinematics and motion during use.

Maily websites, such as sciencedirect.com, reseachgate.net, and ieeexplore.org were used to find relevant literature on hand and wrist importance, prosthetic usage and abandonment, state-of-the-art reviews, specific prosthetic mechanisms and general anatomy specifications. Since this work is mainly interested in general statistics, the attempt will be made to find similar information from several sources. Seen how these sources often mention each other, more follow-up data can be found through references in each paper. Naturally, authors on interesting literature will be scanned for more of their work as well. Through the BioRobotics Lab a set of books and papers is also available from earlier research and interests. The Lab also has published several articles itself, and holds knowledge of these subjects ready for consideration.

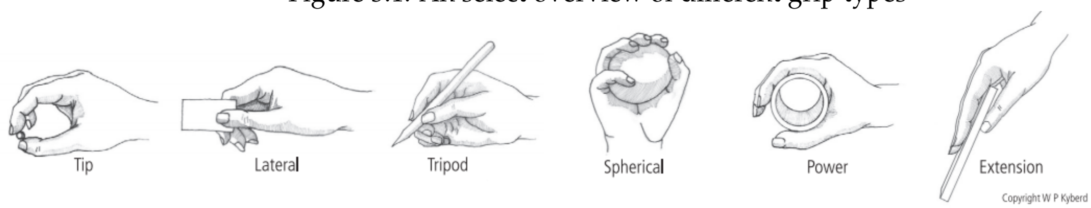
For completion, a list of commonly used key-words (excluding their combinations and alternatives) for search engines has been established. Each search result could be further filtered by searching for other key-words also mentioned in this list. For example, the results for searching for "grasp types"; "kinematics", could be further filtered by looking for key-words such as "wrist"; "hand", of "upper limb".

activities of daily living
adaptive synergies
anthropometry
artificial hand
biomechanics
functional wrist motion
grasp taxonomy
grasp type
hand synergies
hand, wrist, motion, coupling
kinematic, wrist
prosthesis rejection
prosthesis, use, abandonment
soft synergies
state of the art, prosthetic wrists
under-actuated
upper extremity joints

3. The importance of wrist joints in prostheses

3.1 Grip types

Figure 3.1: An select overview of different grip types



The human hand is used mainly to hold objects to either displace or interact with (moving while holding). Grasping a wide variety of objects is therefor important, as it is the first step to interaction. Feix et al. (2009) found 33 different grasp types on the basis of a literature survey, though they were able to bring this down to 17 as some types were grouped. Zheng et al. (2011) used 30 different grasp types by observing the actions of a maid and a mechanic. They found that both used only six and nine types respectively 80% of the time, and switched between types about 2000 to 2500 times in four hours.

Though all these types specify how the fingers are used, the wrist has not been observed here. It seems a small step to understand however, that with such variety of the hand usage comes a high variety of wrist usage as well. Since the wrist needs to accommodate the orientation of the hand, and thus the fingers, and thus the object held, the grasp types rely on the different degree of freedom (DOF) the wrist is able to provide. Each grasp type is defined by the orientation of the wrist as much as by the fingers, and will rely on its own range of motion (ROM) accordingly. A lateral pinch, for example, is typically used to rotate a key. Tripod grips are used for writing, where sphere, and disk grasps are typically used for viewing an object. Tip grips are used when sowing, and power grips are used on door handles.

The Southhampton Hand Assessment Procedure (SHAP) is a designed set of objects and interactions to assess the usage of the hand, wrist and arm of the subject. In short, the subject is asked to perform a series of replacement task on a variety of objects, and to interact with a set of objects chosen to simulate activities of daily living (ADL) (Kyberd et al., 2009). The SHAP test is widely accepted as a proper assessment of hand and arm functionality, and features its own set of ADL which incite the subject to use a set of grasp types. The assessment works through a timer which keeps track of the required time to perform a task. The test is often used to find the efficiency and recovery of impaired patients, including prosthetic users. Problematic about this assessment however, is that there's no measure of compensatory movements done by the patients to overcome loss of function. In compensation, the patient uses DOF other than the ones missing to achieve their goals. For example, large shoulder abduction to compensate for a static wrist. This is a phenomenon often seen during these types of tests, as described by Kyberd as well. These tests make it clear that though the patients are able to perform the tasks in the end, the loss of function of the wrist causes a significant need for adjustment, which often comes paired with strain.

3.2 Complexity of the wrist

To accommodate the rotation and orientation of the hand, the wrist has developed to quite a complex structure. Consisting of eight tightly wound short bones the wrist is capable of two DOF on top of the radial-ulnar freedom of movement (Marieb and Noehn, 2013). There is a standing discussion whether these carpals function as a row of column of bones, as well as the exact location of center of rotation and that the bones move during overall movement of the joint (Youm et al. (1978), Ferris et al. (2000)). Some even propose that there are two different types of wrists between people (Ferris et al., 2000), and it is commonly accepted that there is coupling between the two DOFs (Li et al., 2005). From an evolutionary standpoint, the complexity of this joint can be a direct argument for its necessity.

3.3 Prosthetic use and abandonment

Prostheses are used for the obvious reason of regaining functionality of a limb lost or missing, but also help with other causes such as therapeutic phantom limb pain treatment and personal aesthetics of the body. Many prostheses might therefor hardly be functional while others focus on easy-to-use functionality while reducing strain. Thus a wide range of prosthetic types have emerged, yet their abandonment is surprisingly high. Though several surveys have been conducted on this matter, here is presented a selection of these reports.

Raichle et al. (2008) completed a survey with 107 upper limb amputees, 56% of whom reported using their prosthetic at all, for 10.67 ± 5 hours per day and 24.45 ± 8.5 days per month (mean $\pm$ SD). This shows that though the prosthetic is used often, the duration of use is often limited. Interestingly, they also found a correlation between use in hours per day and the proximity (elbow or shoulder) of the loss of function.

Pylatiuk and Schulz (2005) completed an anonymous online survey and got answers from 35 persons. They found that only 33% used their prosthetic for 4 or more hours at work, while 66% used their prosthesis for 8 or more hours in recreation and 26% reported ”occasional” use.

Last, Biddiss and Chau (2007) show the results of a 25 year survey on upper limb prosthetic use and abandonment in which 40 out of $\sim$200 articles provided rejection rates. They report an average of 26% of adults rejecting body-powered prosthetic with a range up to 66% and 23% rejecting electrically driven prosthetic with a range up to 75%. Rejection rates of body-powered hands were significantly higher for hand-like devices vs. hook-like devices.

In a survey of 1575 prosthetic users Atkins et al. (1996) asked users of both body-powered and electrically driven their opinion on the importance of prosthetic elements and which should deserve priority. Among the long-term goals, both sides specified the need for additional wrist mobility which reached first, third, and fourth rank of priority (PS, RUD, and FE respectively) in transradial amputees and second, fourth, and sixth rank (PS, RUD, and FE) for transhumeral amputees. Atkins states clearly that improvements of wrist motion are a strongly asked-for quality in future prostheses.

3.4 Wrist contribution to arm functionality

Thinking that the wrist plays an important role in the total usage of the arm makes one surprised how little attention this joint gets in the overall conversation about prostheses. Chapter 4 will show that most devices tend to increase complexity by increasing the number of DOFs of the hand (multiplying hand articulation), but often ignore its means to orient. Believing in the importance of the wrist, Montagnani et al. (2015) set out to prove that a simple hand device with an adequate wrist would perform similarly to a modern multi-articulated hand.

By using splints on ten healthy subject's hand a set of four different configurations was made, each with their unique set of DOFs on the hand and wrist. Specifically the comparison between the 3-DOF configuration B (PS & FE, open/close) and the 23-DOF configuration C (PS, natural hand) was made. During experiments involving the SHAP test and a motion analysis test (a 6-camera motion recording) the subjects were tested on speed and the use of compensatory motion during execution of the tasks.

The SHAP test revealed results of both configurations to be significantly similar, and could not state one better than the other. The motion analysis judging the compensatory movement needed showed that both configurations had their own downsides, though none worse over the other. Last, when asking the subjects which of the two they preferred, they were unable to make a choice. Montagnani concluded that a 2-DOF wrist accommodating a simple gripper had about the same practical performance as a wrist-splinted natural hand.

3.5 Wrists in prostheses

So far this chapter has shown that wrists in daily interactions are of great importance for the functionality of the hand. A missing or limited wrist shows significant impairment in the use of the hand. Surveys on the use of prostheses shows a serious abandonment and limitation in prosthetic use however. When asked what is missing many report wrist functionalities first, showing a clear demand from the market. Montagnani et al. (2015) also showed in his research that a higher developed wrist mechanism would be beneficial in a functional vs. complexity sense. Chapter 4 will explore how many prosthetic wrists are on the market so far.

4. Necessities in artificial wrists

Review on the abandonment of prostheses shows that a prosthetic is useless if it is rejected by the supposed user due reasons such as aesthetics. Strangely, Pons Rovira et al. (2004) showed in a survey that the goals of the makers and users of prostheses are not entirely aligned. It seems logical that demands such as a reduced weight, good-looking outside, and quick respond time interfere with the most direct path towards a functional tool. Yet, these features are a high need among amputees. It is important therefor to define a list of design goals for prostheses which includes the needs of the wearer, and go beyond the simple mechanical features. With some foresight from the state-of-the-art, many focus on the functionality of their designs, expecting that more DOFs is better. Ultimately, the artificial hand is often expected to be successful when it can do the same as a real hand. However, there are numerous other factors that need to be considered beyond mere mechanics.

Comfort
Comfort is made up of several features including weight, socket fit, and sweating. For wrist-diarticulated amputees it is common to wear a socket over the forearm to which the artificial wrist mechanism is attached. Weight is a common issue here, especially the more distal the center of mass. This is a great argument as to why the focus should lie on the more proximal wrist mechanism rather than a complex hand mechanism. In either case, the total weight of the prosthetic should be kept low, as it is one of the top complains from prosthetic users (Østlie et al., 2012). Another part of comfort is the potential wires required to interact with the mechanism in the case of a body powered prosthetic, and the harness they come with. Many electrical prostheses make use of EMG sensors which often need skin-contact and possibly conducting gel.

Appearance
Though most wrist mechanisms have a relatively modest look, appearances of the prosthetic do matter. Many different prostheses have been made with different aesthetic emphases, though mostly a anthropomorphic, skin-toned look is pursued (Zuo and Olson, 2014). Noise levels and the fluidity of the animations are also important, though this is valued on a far lower level.

Size
Size is important in general, for various reasons, but with wrist mechanism another level is added. Writs mechanisms determine the space between the forearm and the hand, and therefor need to be kept small. Some mechanism also try to fit inside the prosthetic hand when the amputee still has the full arm enabled. In these cases especially, the mechanism as a whole needs to be small enough to fit other, neighboring components.

Control
With functionality in a prosthetic comes the need for input, i.e. a means of controlling the DOF. Prostheses are often limited not so much by the mechanical possibilities to make a multi-DOF design, as much as by the means to derive individual input signals from the user. Many of the multi-DOF prostheses therefor rely on far fewer independent input signals than the number of freedoms available, and have to sacrifice dexterity for functionality. A correct term for these devices would therefor be "multi-articulated" as their functional DOFs are fewer than their mechanical. A 3-DOF wrist mechanism would ideally have three individual inputs from the amputee, though this would be difficult to cultivate and would yet need more inputs to activate any hand mechanism.
Many mechanisms rely on workarounds to this problem, where, for example, a continuous signal makes the mechanism pass by different settings, or one signal is used for settings while another is used for activation.

Multi-DOF
Last, an importance should be put on the multiplicity of the DOF of the wrist mechanism. Wrist mechanisms are not uncommon in prostheses, yet their demand is still high. Atkins et al. (1996) showed that wrist mobility was a greatly asked-for feature in prostheses, in all DOFs of the natural wrist. Montagnani et al. (2015) also showed that the wrist can have an significant functional level, but was able to reach this with at least a 2-DOF joint. Last, most wrist mechanisms are 1-DOF (see chapter 4) yet do not seem sufficient to have a general content with prostheses. The requirement can therefor be made that the wrist should at least have two DOFs. The parallel hand projects, as well as the following wrist project, at the Sant'Anna University also demand the development of a new wrist mechanism which uses all three DOF, to set a new standard in wrist mechanisms.

These requirements are set for prostheses in general, but wrist mechanisms specifically and are gathered from questionnaires as the demands and wishes of prosthetic users. Without meeting all these requirements to some degree, any mechanism is likely to end up abandoned and receiving a poor review. It is important, therefor, to state the need for prosthetic wrist mechanisms to adhere to these demands fully. In chapter 5 a closer look will be taken to the state-of-the-art. Several examples will be shown and reviewed as to whether they meet these needs.

5. State of the art

Bajaj et al. (2015) made an overview on the state of the art of 62 different prosthetic wrist mechanisms. An extensive overview of different types of wrist mechanisms is made after introducing a general lack of such systems compared to the hand mechanisms.

A variety of passive mechanisms is introduced, relying mainly on principles of friction or clipping to maintain orientation and manual intervention to unlock. Most of these joints are 1-DOF, predominately PS. Some joints are 2-DOF, often PS and one other DOF chosen depending on the orientation of assembly. It is also common for companies to ”stack” systems to reach higher DOFs. Body-powered joints often use manual orientation setting from which it can be reset by unlocking to a return position using cables and a harness. For wrists, such passive but body-powered mechanisms can be set by, for example, pushing the hand in radial deviation on a table surface. These mechanisms are likely only 1-DOF as a second DOF would require its own cable and unique input motion.

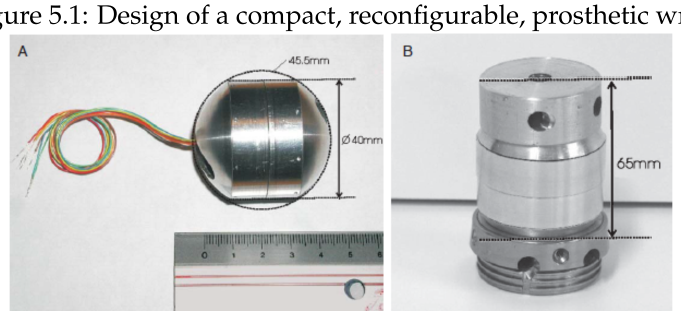
Active wrist mechanisms are mostly controlled using myoelectric signals which require sensor-skin contact and are often convoluted. Again, most of these joints are rotators only in PS, some of which are housed inside the prosthetic hand, and some connected to the forearm socket. So far, few 2-DOF active mechanisms have been designed, some again by simply stacking two 1-DOF systems. This region within the field is however among the latest in development, and many focus on compact, light weight, and efficient designs. Bajaj found 6 of these devices all of which are placed on the forearm. Another three mechanisms for transhumeral disarticulation enjoy more space. Two 3-DOF wrist mechanisms are found, both using three individual motors in the space of nearly an entire artificial forearm.
In general most multi-DOF systems are serial mechanism of individual mechanics stacked on top each other, using multiple engines.

Some designs from the list are shown below as case-studies. Each case will be held in the light of the requirements of chapter 4 and consequently reviewed to either have a sufficient design or not.

5.1 A compact, reconfigurable, prosthetic wrist (Zinck et al., 2012)

As discussed, many prosthetic wrist actuators focus only on PS. Zinck relies on previous research looking into the perfect 1-DOF axis, as most prostheses have, which ended in a suggested orientation. This orientation was sought after in the first place because the predominant PS axis was usually chosen somewhat arbitrarily. An argument for 1-DOF wrist was also made due the need to add exclusive inputs to control the mechanism.
To test a multitude of possible single axis orientations for a rotator, Zinck designed an engine inside a spherical body which can be assembled in a range of orientations. Here they focused on practicality by keeping weight and volume to a minimal. The result became a rotator within a spherical body of 45.5mm diameter able to house the output shaft in a range of oblique settings. The design had not yet been implemented. Though the motor is comparable to the average 1-DOF wrist it is actually slightly bigger and heavier due the special body while gaining only little extra in terms of functionality.

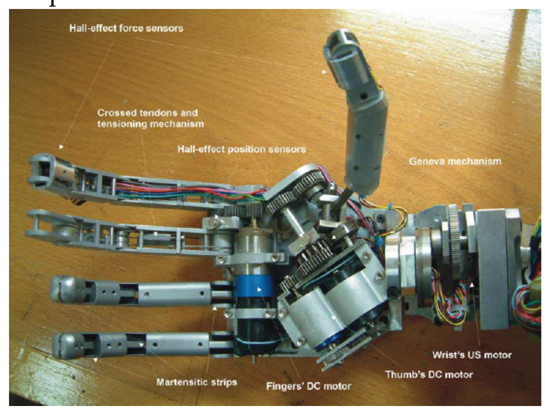
Figure 5.1: Design of a compact, reconfigurable, prosthetic wrist



5.2 The MANUS-HAND Dextrous Robotics Upper Limb prostheses: Mechanical and Manipulation Aspects (Pons Rovira et al., 2004)

The MANUS hand is one of the more advanced hands as part of a long-standing project. Based to perform a set of four basic grips the hand was designed with functionality in mind for a wide range of different amputees. After a survey of 200 amputees and 150 rehabilitation professionals, of which about 60% replied, they found that the amputees focused more on aesthetics, weight and discomfort than functionality, while the professionals focused on functionality, specifically on grasp types. Pons decided to focus on the latter, and designed a rather complex, and sturdy hand, though the total came to about 1.2 kg. The single DOF wrist consists of a single ultrasonic motor, which was chosen mainly for its size in thickness in case of a wrist diarticulated amputee. The wrist was designed hollow to allow wiring to pass through.

Figure 5.2: The MANUS-HAND Dextrous Robotics Upper Limb prostheses: Mechanical and Manipulation Aspects

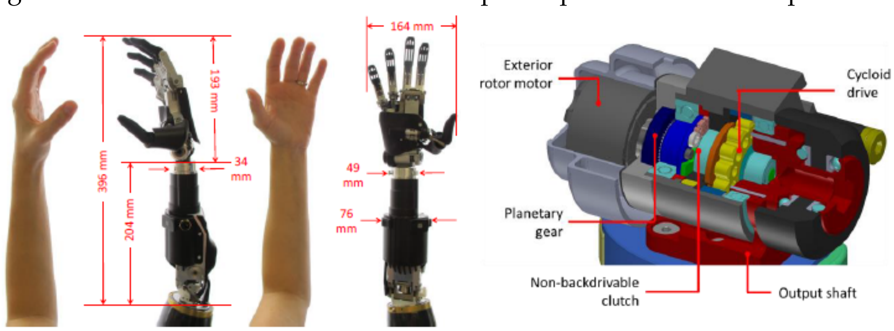


The mechanism was then connected to the motor via a flexible joint to account for slight misalignment. The wrist can perform PS only. The MANUS-hand is a typical example of a complex, multi-DOF hand mechanism based on only a very simple wrist joint.

5.3 The RIC arm - a small, anthropomorphic transhumeral prostheses (Lenzi et al., 2016)

As part of an entire prosthetic arm, Lenzi also focused on the wrist mechanism. For a compact and effective design, they incorporated a custom cycloid drive, a high efficiency planetary gear transmission, and a non-backdrivable clutch in the motors. Inspired by the findings of Montagnani et al. (2015) they decided to make a 2-DOF wrist supporting a 1-DOF hand. Two identical motor are used for PS and FE of the hand, respectively placed in the forearm and inside the hand. Here, the wrist joint is certainly more complex with double the DOFs, but it is clear that the mechanism takes up a lot of space. Though in this case that space is available, more distal diarticulations will not be able to enjoy this design.

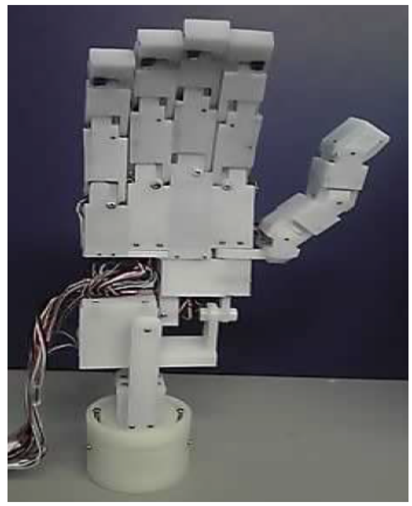
Figure 5.3: The RIC Arm - A Small Anthropomorphic Transhumeral prostheses



5.4 Dexterous Mechanism Design for an Anthropomorphic Artificial Hand: Osaka City University Hand I (Mahmoud et al., 2010)

Mahmoud designed a 19 DOF hand on top of a 3 DOF wrist made mainly from plates of Polypropylene Copolymer (PP). They focus on functionality of the hand which has about the same size as a human hand while maintaining a light weight. Through a cable-tendon system all actuators of the hand are inside the palm. The wrist is made up of three servo engines, two of which rotate a double axis (one directly and one via a belt), while the third rotates this frame in PS. This way, a simulation is made of the human wrist, which is said to have all rotations in one point. The motors of the wrist are placed inside the wrist mechanism, giving it a considerable size relative to the hand. This design is one of the few reaching a 3-DOF wrist mechanism, but does so by using three individual engines. The relatively small engines are also relatively weak compared to other designs, which is the only reason the design remains as compact as it is. The three idividual engines of the wrist will also require three individual inputs, increasing complexity of the wrist ontop of the complexity the hand already creates.

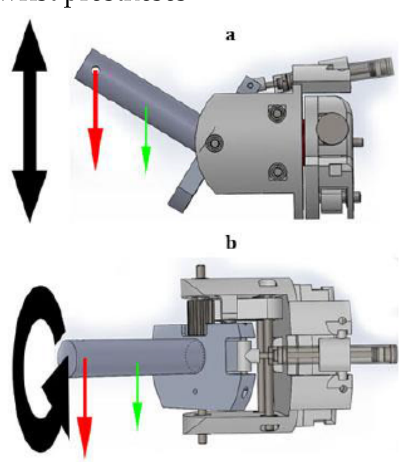
Figure 5.4: Dexterous mechanism design for an anthropomorphic artificial hand: Osaka City University Hand I



5.5 Two-degree-of-freedom pneumatically powered wrist prostheses (Roose and Plettenburg, 2014)

Roose designed a 2-DOF wrist mechanism based on pneumatic pistons. These would offer a lightweight alternative to electrical engines while maintaining strength and dexterity. Making use of two pistons the mechanism can achieve PS and FE, the first by a compact lateral piston and the second by a in-series piston. The wrist also makes use of two locking mechanisms, each a set of pawls locking a gear, released by their own piston. In the end, the FE mechanism is build on top the rotation mechanism, causing the FE piston to rotate along with PS. This mechanism is able to output a 2-DOF orientation on the wrist, but again does so using two individual actuators. The complexity of the mechanism also requires a second set of pistons for locking done by a separate mechanism.

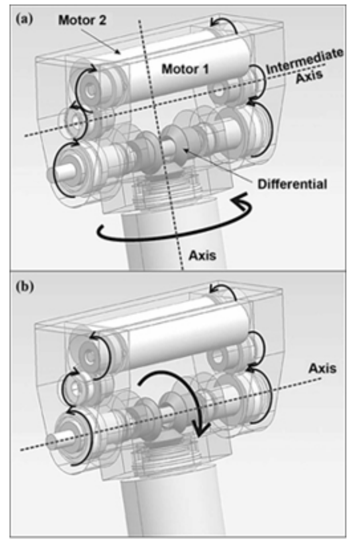
Figure 5.5: Two-degree-of-freedom pneumatically powered wrist prostheses



5.6 Two-degree-of-freedom powered prosthetic wrist (Kyberd et al., 2007)

Kyberd sought after a 2-DOF wrist mechanism that would take as little forearm space as possible, while increasing the common ROM of prostheses. He used a differential gear system to link the output of two electrical engines to two common shafts, one for PS and the other for FE. By spinning the engines either along, or against each other the mechanism would turn over one or the other axis. One of the engines is placed in-line with the stump, while the other is placed tangent on the far distal point of the mechanism. Using this method the mechanism is able to reach exceptional orientations, but sacrifices strength and cannot be locked. The device is also specifically small.
This is a nice example of the advantages possible when thinking outside the box. While still making use of two electrical engines, by applying the mechanism different some unprecedented advantages have been made.

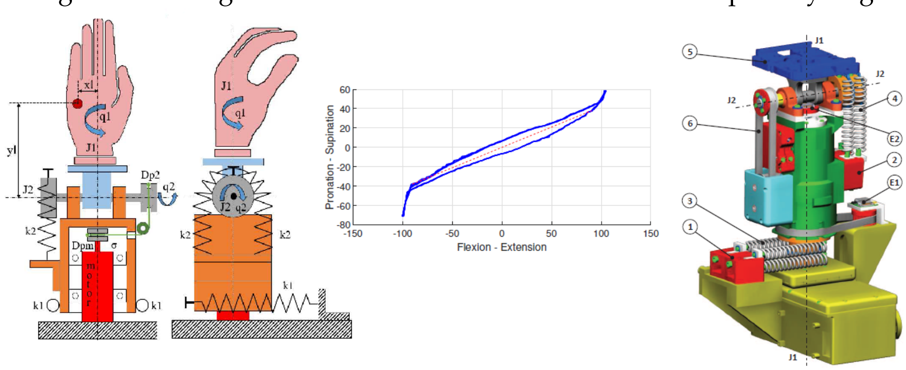
Figure 5.6: Two-degree-of-freedom pneumatically powered wrist prostheses



5.7 An under-actuated wrist based on adaptive synergies (Casini et al., 2017)

Casini focused on a 2-DOF wrist actuated by a single engine. The mechanism comprises of a single degree joint on top of an engine. Through a transfer system, the torque of the engine is applied on the joint as well, so that the engine can rotate the mechanism as a whole (PS) and the joint simultaneously. Depending on the orientation of the hand the joint functions as a FE, RUD, or some diagonal axis. Both the engine's output as PS and the orientation of the joint are restricted by a set of springs. By varying the elastic constant of the two spring-sets, the engine's output force will result in different equilibria concerning the orientation of the wrist. This way, one engine can have an oblique output of the wrist between PS and the second axis.
Casini's work continues with subject experiments to find the ideal single axis, and chooses a set of spring constants to approximate their result.

Figure 5.7: Design of an under-actuated wrist based on adaptive synergies



5.8 Overview of wrist mechanisms

As Bajaj et al. (2015) pointed out, there is a general lack in prosthetic wrist mechanisms. Of the most advanced only a few have more than one DOF, and those that do often use separate engines for each. Only Casini et al. (2017) was able to use a single engine for more than one DOF output, but did so while relying on passive elements which are limited in configuration. Mahmoud et al. (2010) managed to have a 3-DOF wrist by using three independent engines. This, so far, does however not seem a sustainable strategy, specifically for more distal dis-articulations.

Though these different researches are trying to reach common goals, they seem to achieve them only separately, and at the cost of other goals they have deemed less important. *Which* goals are important does not seem to be agreed upon however, and most projects focus on their own ideals. Compared to the development of artificial hands, which has been documented as far back as 200 BCE (Zuo and Olson, 2014), artificial wrists have been lacking behind, and have not had nearly the same level of interest from the scientific and engineering community.

From chapter 4 we have an overview of general requirements for prosthetic wrist mechanisms. Judging the prostheses as found by Bajaj non of them seem to fit all demands. A spectrum where either 1-DOF mechanisms are small and light or multi-DOF mechanisms are large and complex seems to leave no single design adhering to all requirements. Mahmoud creates a 3-DOF wrist only to use weak plastics to compensate for the small and weak engines. Lenzi creates a sturdy 2-DOF wrist only to take the space of half the hand and fore-arm. Choices between the requirements seem to be necessary. This indicates, if anything, the difficulty of designing a multi-DOF wrist mechanism while also satisfying other requirements. It seems appropriate therefor, that a new method to designing these mechanisms is found. If at the current state the requirements are too high, some of them need to be simplified.

6. Research in synergies

6.1 Use of synergies

The previous section points to a number of issues that seemingly have something in common. Multiple engines are used to create higher DOF mechanisms, only to inclease in size and weight. How these mechanisms are to be controlled is often not discussed. High functionality requires a higher level of control, meaning more individual inputs the user has to be able to generate. A high number of cables, and each their required harnesses, becomes uncomfortable and difficult to control, similar to requiring many EMG sensors. Since each signal has to be independent, not only does each system need its own part of body motion, but the user needs to have the capacity to control these inputs separately as well. In control, a common solution is to reduce the number of features of the mechanism, or create combinations of the inputs. This way, fewer independent inputs are needed, which should reduce complexity for the wearer, and increase comfort. When functionality is reduced, it takes only a small step to start reducing the number of DOFs. If a hand will open and close with four phalanges having the same output, the number of *articulations* is effectively reduced greatly. Fewer articulations means a need for fewer independent engines, which often reduces size and weight. It seems then, that by combing features, many of the common issues around prostheses can be helped.

”Synergy” is a concept used often in the world of robotics, where the use of elements to create a number of functions greater than the number of those elements is used to increase functionality while keeping weight, parts and complexity costs low. More specifically defined, a synergy is “a functional property of a multi-element system performing an action, whereby many elements of the system are or can be constrained to act as a unit through a few coordination patterns to execute a task” (Santello et al., 2013). This concept might prove to be of great help in the world of prostheses as well.

In chapter 5 we see this principal applied already. Kyberd et al. (2007) used two engines to create a new pattern of outputs. Though technically no real functional benefit was made (two engines were used to create a 2-DOF output) the use of synergies did allow the design to be extremely compact. Casini et al. (2017) did apply a design capable of functionality increase, where a single engine created a ”path” in two dimensions simultaneously. This path was also modifiable, and provided an output adapted to research on the most commonly used path by human subjects.

In general, the benefits of synergies seem real. Though Casini in the end could provide only a single path (which might be considered a single articulation), the ability to rotate and flex the wrist joint with a single engine proved to be functional enough (according to Casini), while it also reduced the number of required engines, thus the complexity of control and likely the weight and size of the final design. A broader pursuit of the use of synergies between the DOFs of the wrist would therefor be a good advice. The method of using smart mechanisms to reduce the number of inputs required to make a higher number of outputs seems to help reduce the requirements of wrist mechanisms, thereby making it easier to design a mechanism conform all requirements.

6.2 Principal component analysis

After their design, Casini et al. (2017) performed an experiment to find the best shared orientation for their mechanism to operate in. With a set of ten subjects, nine tasks were performed to simulate the usage of the wrist under activities of daily living. Using a set of markers on the subject's arms and hands, data on the usage of the wrist specifically could be gathered through an optical motion capture system. Though they recorded the full arm during the total performance, they were specifically interested in the pre-grasp orientation of the wrist. From this experiment three-dimensional data (the three DOFs of the wrist) was found for all subjects performing all tasks. Using principal component analysis, they found two strong components relating PS and FE. By the relative strength of the components they were able to set the relative spring constant of their mechanism to have one input simulate the same orientation output as found by the analysis.

Principal component analysis (PCA) can be used as a good way to find a common axis among data, where a single line is defined as the closest approximation to all points (Abdi and Williams, 2010). Using this technique, more can be said about the general "orientation" of the data and its inclination towards axis used to define the data. In Casini's case, the data was defined by the three DOFs of the wrist, but was found to have an inclination towards two axis diagonal in the DOF space, thereby relating the DOFs with each other. Since the components found by the analysis is always one dimensional (a straight line) it offers a good way to relate a 1-DOF input to a multi-DOF output (where the output is the orientation in the previously defined DOFs of the wrist). This strength is also a weakness however, since the components are always straight (and following components are always tangent) the method is limited in defining new "paths". For example, it might have been a better approximation for the FE to orient after the PS had rotated for a certain amount, making the synergetic relation more dynamic. Principal component analysis is not able to define a path in this way, since the components only represent directions. Though PCA offers a comprehensive method to find the general inclination of data, it's lack in dynamics makes it a tool perhaps too simple to use on a joint as complex as the wrist. Though more complete data on the orientations used during ADL was available, this method is not able to fully describe wrist usage, even by average.

6.3 Dynamic synergies

Data on maximal and functional wrist orientation is available from multiple sources (see also the appendix). Commonly, this data is found after recording a set of subjects performing a number of tasks chosen to represent ADL. The recordings include motion of the wrist, which is often averaged until a conclusion can be made on the (range of) orientations the wrist required to perform the set of actions. Particularly the works from Aizawa et al. (2010), Ryu et al. (1991), and Nelson et al. (1994) are interesting, since they show their findings averaged between subjects and repetitions, but per task. This allows to make an overview of the orientations used by their subjects during their performance for each task.

Table 6.1 shows the ADLs used by the different sources. The names of the tasks have been greatly simplified for the sake of clarification and overlap between the different works. Furthermore, the tasks have been split in *self contact* and *interaction* tasks, though not all sources make this difference. Palmer, clearly with the widest range of tasks, also includes tasks from carpenters, housekeeping, mechanics, secretaries, and surgeons, though he hardly shares these tasks with the other works done.

Nelson criticizes Palmer's inclusion of tasks to represent ADL, such as "throwing a ball, loading a typewriter, turning a steering wheel, and turning a screwdriver", yet included them in his study. Understandably, some of Palmer's tasks are neither daily nor up-to-date. Nelson states that no set of tasks has been proven to truly represent ADL and that "a study would need to determine which subset of ADL, if able to be performed, would imply that a person could perform the entire set of ADL necessary to be functional.". He continues his discussion by stating that performing the ADL therefor does not prove functionality, and consequently states that his, nor any earlier, findings indicate *functional* ROM, but merely the ROM used for those tasks. What ROM is *needed* for each task, in his opinion, remains undetermined.

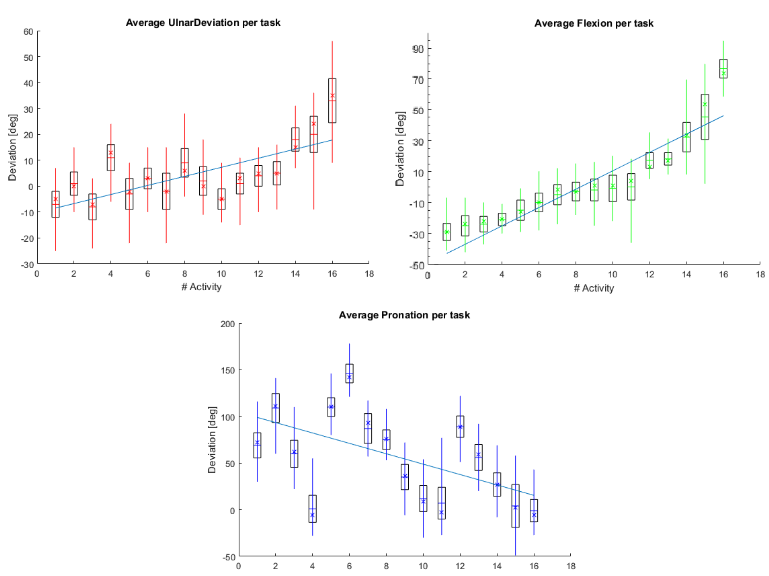
Self contact	Palmer	Brumfield	Ryu	Nelson	Aizawa
Head (top)		*	*		*
Mouth					*
Neck		*	*		
Chest		*	*		
Axilla					*
Back					*
Waist		*	*		
Hip					
Sacrum	*	*	*		
Foot		*	*		
Peroneal care			*	*	*
Dental care			*		
Comb hair	*		*	*	*
Wash face					*
Necklace					*
shirt buttons	*		*	*	*
tie a tie			*		
tie laces	*		*	*	
Interaction					
Drink from cup	*	*	*	*	*
Pour	*	*	*	*	*
Cut with knife	*	*	*	*	
Fork to mouth	*	*		*	
Spoon to mouth					*
telephone	*	*		*	
Newspaper		*			
Stand up chair		*	*		
Faucet	*		*	*	
Jar lid	*		*	*	
Spatula	*		*	*	
Hammer	*		*		
Screwdriver	*		*	*	
Door nob	*		*	*	
Key	*		*	*	
Steering wheel	*		*	*	
Writing	*		*		
Wring washcloth	*			*	
Turn can opener	*			*	
Stir in bowl	*			*	
Flip page book	*			*	
Print name	*			*	
Dial 0	*			*	
Load typewriter	*			*	
Throw ball	*			*	

As stated before, Nelson, Ryu and Aizawa report their findings of the orientation used per task, and thus allow for a deeper insight. Aizawa shows the most complete data with a mean, median, standard deviation (SD), 5^{th}, and 95^{th} percentile over 16 tasks. He is also the only one to report PS. Furthermore, Nelson shows data with the average, median, and maximal orientation for 24 tasks. Last, Ryu offers the median, minimal and maximal values of 14 tasks.
This level of detail allows us to plot the orientations for each task for each DOF, and re-order them to our interest. One such interest might be what happens when we re-order the tasks such that for one DOF the values increase monotonically. Linearizing one of the DOF could show dependencies of the remaining DOF.

	Palmer	Brumfield	Ryu	Nelson	Aizawa
Handsaw	*				
Power saw	*				
Power drill	*				
Ruler	*				
Pull out nail	*				
Broom	*				
Dustpan	*				
Sponge	*				
Wastebasket	*				
Vacuum	*				
Socket wrench	*				
Wing nut	*				
Cotter pin	*				
Mallet	*				
Sharpen Pencil	*				
Fold letter	*				
Suture	*				
Square not	*				
Scissors	*				

Table 6.1: Overview of all ADL used

Figure 6.1: Data by Aizawa et al. (2010) on the angles of the wrist per task ordered by ascending flexion. The graph shows the mean (-), median (x), SD (box) and 5^{th} to 95^{th} percentile.



Re-arranging Aizawa's data by increasing flexion shows an interesting, similar trend in RUD, where PS seems to be unaffected. This would indicate a relation between FE and RUD where if one DOF was moved trough its ROM, the other would have a direct "positional" relation within its ROM, with a relatively linear trend. Li et al. (2005) also showed a linear coupling between these DOFs during motion of the wrist, indicating as well that a commonality between them is prevalent.

Data from Nelson and Ryu however does not support this theory. After ordering the tasks for ascending flexion the remaining RUD does not seem to correlate. In fact, the flat trend-line in RUD in both data-sets would suggest that RUD is used completely independent from FE during these tasks. From this comparison therefor, no conclusion can be made.

Figure 6.2: Data by Nelson et al. (1994) on the angles of the wrist per ADL ordered by ascending flexion. Separate data on the four angles (FE and RAD) was combined to show the average of each angle (box), the maximal angle found for both orientations and the median (x), where the opposing orientation was translated to the negative.

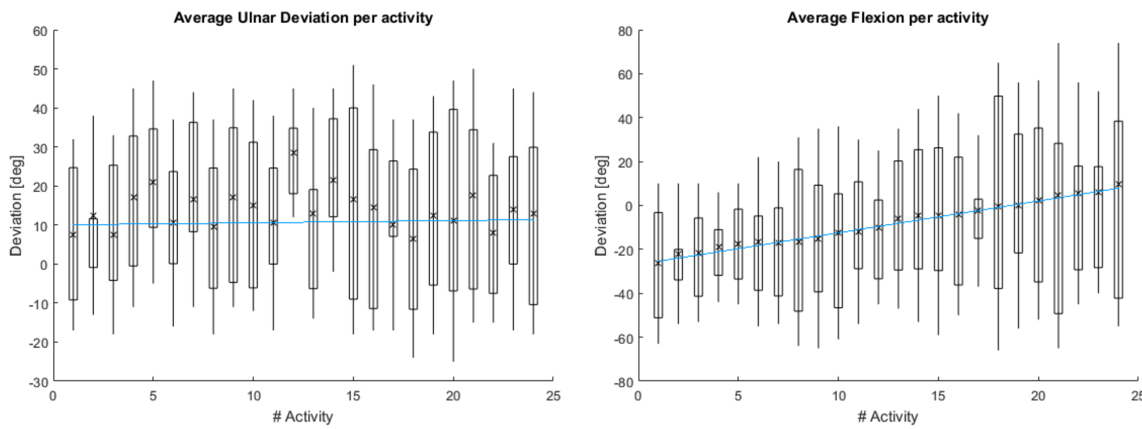
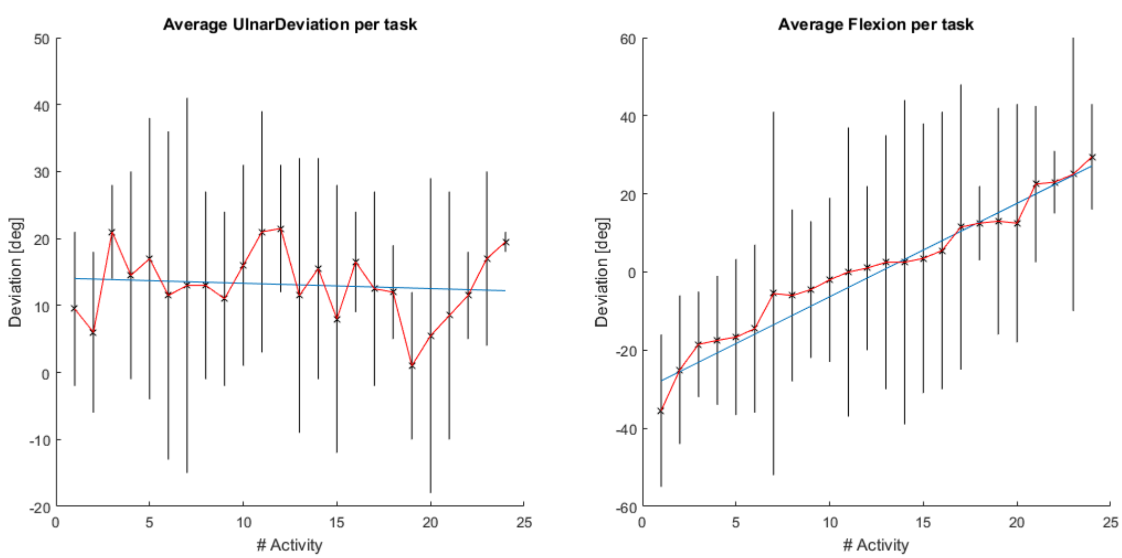


Figure 6.3: Data by Ryu et al. (1991) on the angles of the wrist per ADL ordered by ascending flexion. Minimum an maximum was extracted for the data, mediam (x) was added.



6.4 Synergy by polynomial approximation

Based on the work as reviewed in the previous section, Lenssen et al. (2018) set out to find a new synergistic relation between the three DOFs of the wrist, which was to be actuated by a single input. Ten subjects were asked to complete a set of tasks chosen to represent ADL, which were chosen specifically to correspond to prosthetic-user level of complexity. Secondly, because it is likely for prostheses to be used second to the remaining, healthy hand, some tasks were repeated where the dominant hand was used for so-called ”support tasks”. During these tasks IMU sensors were placed on the hand, elbow, shoulder, and back of the subject. From this data the relative orientation of the wrist, elbow and shoulder could be extracted.

Figure 6.4: A: Polynomial fit per DOF. B: Total 3D fit of the data

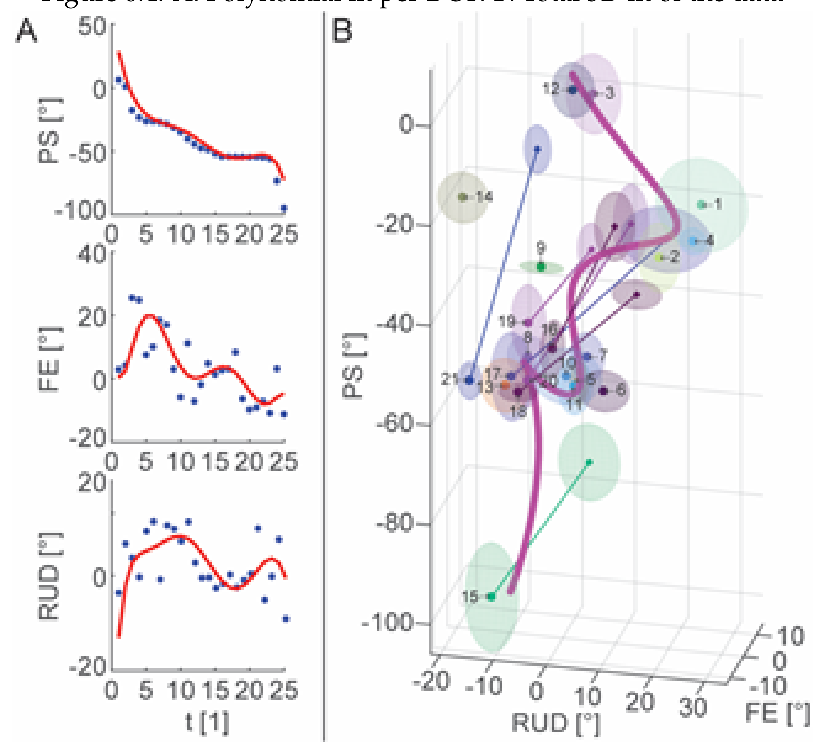


Figure 6.4 shows the data as found by averaging between subjects for each task (see B). Using three polynomials, each fitted in one DOF (see A), a total ”path” through the data has been made to fit the data as close as possible, while keeping the lines smooth. As a result, the path relates all DOFs in a single, continuous set of orientations that best fit the usage of the wrist as found by the experiments. Lenssen suggested that creating some mechanism able to reproduce this path could be the basis for a synergetic wrist. Since it could use a single input (PS was suggested because it had the largest ROM) to determine the required orientation of the remaining, dependent DOFs. This way, a full three-dimensional output could be achieved along a single line of actuation.

It seems that this approach to synergetic relations between the DOFs is more successful, and should be considered. Not only does this method reduce the required engines to one single engine, but it also seems the first in combining all three output DOFs to a single input. Based on the most commonly used orientations of the hand, this ”path” should provide the most used orientations of the wrist for prosthetic users. Lenssen did report that the ROM of the found path was smaller than the ROM of the data itself, an inherent problem in using best-approximation techniques. Because the theoretic mechanism relies on a single engine, the orientation is also non-holonomic, though this seems acceptable if the rotation is fast enough. All-together, this mechanism would likely correspond to many of the requirements mentioned in section 3.5, due the benefits of synergetic relations as explained in section 6.1.

7. Conclusion

Through reasoning from a biological perspective, as well as demands from the prosthetic community, the importance of wrist joints has been made clear. The range of motion of the wrist is a daily need, the lack of which is easily noticed in compensatory motion and lower functionality of the hand. A multi-DOF wrist orienting a simple gripper has also been shown to equate functionality levels of a complex, mutli-DOF hand mechanism while requiring less articulation. This indicates a general importance of wrist functionality in prostheses.

Though the world of prosthetic wrist mechanisms is considerably smaller than that of the hand, a variety of mechanism have been developed to battle the need for multiple DOF actuated wrists. State of the art review and surveys in prosthetic use show however that the current development of wrist mechanism is lacking in many aspects. A review with the focus on existing concepts and mechanisms along with answers from questionnaires by prosthetic users reveal important features for prosthetic mechanism in general, and wrist mechanism specifically. A general list such as in chapter 4 can be made from these requirements, which most wrist mechanisms only partially meet. In all cases, a required decision-making seems to lead designs to focus on some of the aspects while ignoring others, rendering the total design undesired.

A common (partial) solution to many of these requirements seems to come from the robotics field where the use of synergies is more prevalent. Synergies are suggested to benefit the design of wrist mechanisms by reducing their requirements, such as complexity and weight, while remaining the functionality of the final output. A further review shows that not many wrist mechanism make use of this concept however, and that research in this direction is still narrow. Finding synergies in human wrist usage is not trivial, as the often used general PCA are limited in their conclusions.

Finally, however, a promising study concluded a single input, multi-DOF output relation using synergies between the DOFs of the human wrist. Based on the documented usage of the human hand a single path was found which could form the basis of a mechanism relating one DOF to two remaining, dependent DOFs, thereby using a single actuator to re-create a realistic three-dimensional output of wrist orientation. This unique use of a synergetic approach to define wrist usage and orientation lays the foundation to a new type of wrist mechanism.

It is this principle of synergies in the design of wrist mechanisms, along with the other requirements as found in earlier chapters, which should be pursued in future designs to create a next set of lighter, more compact, and functional prostheses. Designing a mechanism able to mechanically reproduce the theoretical path as found by the synergetic approach would prove that synergetic relations in wrist orientation is physically and mechanically possible and feasible. Second, only through a physical prototype of such mechanism can the use of synergies be testes in a functional sense. Though this work concludes that synergies should be beneficial, it does so based on literature surrounding the topic, as the actual realization of such mechanisms has not yet been done. Whether a mechanism based on such synergies truly would reach a lower mass and smaller size, and if it is useful and functional enough for satisfying use deserves to be tested. If indeed beneficial, a new design method in wrist prostheses might well improve the creation, use and satisfaction around prostheses as a whole.

Appendix. Research in wrist motion

Before designing a prosthetic wrist, it is useful to know more about the healthy, human wrist. Particularly the preliminary study focuses on wrist motion to define a synergetic path for the mechanism to take, but even after this definition, the design of the mechanism itself will have to compare to a human wrist. In this section, research on wrist motion is presented and discussed among the different sources.

1.1 Maximal range of motion

The total, or maximal, range of motion (ROM) of the wrist has been studied be several sources using different techniques. In table 1.2 we see an overview of such sources ranging from 1985 to 2010.

	Flexion [°]	Extension [°]	Ulnar dev. [°]	Radial dev. [°]
Sarrafian et al. (1977)⋆	60	55		
Boone and Azen (1979)⋆	76	75	36	22
Brumfield et al. (1966)⋆	73/82 (M/V)	64/65 (M/V)		
The AAOS (1965)⋆	73	71	33	19
Li et al. (circ. mot.) (2005)⋄	35	64.5	21.5	19.5
Li et al. (pure mot.) (2005)⋄	41	64	32	20
Li et al (2002)⋄	75	64	51	24
Silva et at. (2000)⋄	56	48	35	19
Marshall et al. (1999)⋄	67	73	68	21
Ryu et al. (1991)⋄	79	59	59	21
Boone and Azen (1979)⋄	75	74	35	21
Heck et al. (1965)⋄	73	71	52	19
Mean	73	64.5	35.5	20.5
Spread	44	27	46.5	5

Table 1.2: Literature data on maximal RoM in degree, where ⋆ are reported by Nelson et al. (1994) and ⋄ are reported by Li et al. (2005).

From the table it is clear that the sources have difficulty to agree with one another. The spread of the results, particularly in flexion and ulnar deviation, are quite significant. These differences among the results can be linked to the differences among the research, a theme that will extend into the other reviews on the wrist dynamic. Primarily, sources often use different techniques and definitions. Such definitions include what the ”middle” for each DOF and how the axis relate to the hand, which is somewhat arbitrary, and are often chosen as a result of the technique used (Li et al., 2005). Concerning the techniques, there seems to be a division between overhead or brace systems which either use a global (defined by the environment) or local (defined by the joint) coordinate system respectively.

1.2 Functional range of motion

More useful to than the total ROM is the functional ROM, which is defined as the ROM used during the execution of tasks (Nelson et al., 1994) which often does not use the extremes of the ranges. Functional ROM is more relevant to synergies since these should be based on usage of the wrist during activities of daily living (ADL). When a synergy has been found, it is also useful to compare it's total ROM to the functional ROM of healthy wrist. In table 1.3 the sources for functional ROMs have been gathered.

	Flexion [°]	Extension [°]	Ulnar dev. [°]	Radial dev. [°]
Porter and Stockley (1984)⋆	45	30	15	15
Brumfield and Champoux (1987)⋆	10	35		
Palmer et al. (1985)	5	30	15	10
Nelson et al. (1994)	50	50	40	12
Aizawa et al. (2010)	76	29	33	8
Ryu et al. (1991)	78	60	38	21
Mean	45	35	33	12
Spread	68	55	25	13

Table 1.3: Literature data on functional RoM in degree, where ⋆ are reported by Nelson et al. (1994).

Here, again, it is clear that the literature done in the past finds it hard to agree with one another. The spread, particularly for flexion and extension (FE), seems significantly large.

As to why these numbers differ so much, both for the maximal, and functional ROM, a deeper analysis of the sources is required. Most sources differ not only in definitions but also in methods, and seem to criticize each other. The works of Ryu et al. (1991) and Nelson et al. (1994) are a follow-up on Palmer et al. (1985), and criticize Palmer for using mean values of all ADL. The second generations (Nelson, Aizawa et al. (2010), Ryu) report orientations of the wrist used per ADL, though which ones they use varies still (see table 6.1). Where Palmer, Nelson, and Ryu use local braces, Aizawa uses an overhead system resulting in global orientations of the limbs rather than local orientations where each limb is defined relative to their respective proximal limb. How the other studies define orientations is also not specified, since, though they use local sensors, orientations of the limbs can stack. Aizawa, for example, reports a pronation of 146 [deg] (not shown in table 1.3) though 0 [deg] has been defined as the neutral position for both pronation/supination (PS) and the wrist. Though the hand is able to point the thumb down, it cannot do so by pronation alone, meaning shoulder movement was involved. Whether the other sources are free of this is unclear.

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Principal orientations of the wrist during ADLs: towards the design of a synergetic wrist prosthesis

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Abstract—**To design an underactuated wrist prosthesis, a preliminary study has been conducted to identify the relationship between the Degrees of Freedom (DoFs) of the wrist during the execution of tasks of daily living. After the identification of the principal orientations of the wrist describing the tasks, polynomial functions were used to define a synergetic relationship between the DoFs. The latter can be implemented in a prosthetic wrist featuring one actuator to obtain motion along three DoFs, with the purpose of reducing compensatory movements.**

I. Introduction

PROSTHESES are designed to replace lost body parts, however, the rate of their abandonment is considerable among amputees due to the lack of sufficient function [1]. Recent advances in upper limb prostheses are characterized by a strong focus on highly dexterous, multi-fingered prosthetic hands, whereas only few powered wrists have been proposed [2]. However, it was suggested that it is the wrist dexterity that is missing and necessary in current upper limb prostheses, rather than hand dexterity [3]. This is especially true when considering the *compensatory movements* of the proximal joints, required to compensate for the lack of DoFs, which can be strongly reduced when using multi-articulated prosthetic wrists [3]. The need of compact and lightweight powered wrists is thus evident, however, developing it proved not a trivial task, mostly because of the large size and weight of the electric motors required for its actuation.

The neuroscientific concept of synergies offers a powerful tool to minimize the size, weight, and power consumption of active prosthetic wrists. Broadly defined, a synergy is “a functional property of a multi-element system performing an action, whereby many elements of the system are or can be constrained to act as a unit through a few coordination patterns to execute a task” [4]. To apply this concept, it is necessary to identify a relationship between the DoFs of the wrist such that meaningful coordinated motions result from one single controlled DoF. Studies conducted on healthy participants showed that it is possible to identify synergies between the DoFs of the wrist [5], [6]. However, an analytical relation between the functional orientations of the wrist, during activities of daily living (ADLs), has not yet been found.

The goal of this work is to lay the foundation for the design of a prosthetic wrist mechanism able to produce synergetic motions along three DoFs, i.e. flexion/extension (FE), radial/ulnar deviation (RUD), and pronation/supination (PS), with one single actuator. The target for such mechanism is to feature one DoF directly driven by an actuator, while the remaining, dependent DoFs are kinematically constrained to the first one. To design this mechanism, it is necessary to investigate i) the wrist orientations that are fundamental for the execution of ADLs, in order to identify the kinematic relation between them, and ii) whether such relation can be reproduced by a physical mechanism.

II. Materials and Methods

To address the aforementioned issues, a study (approved by the ethical committee of the Scuola Superiore Sant’Anna, Pisa) was conducted with 10 unimpaired participants (4 males, 20-35 years old, all right handed) which wore a set of 4 Inertial Measuring Units –IMUs– (PIVOT, Turing Sense, USA) on their dominant hand, elbow, shoulder and back in order to measure the orientation of their body segments. The participants were asked to sit at a table and to perform two repetitions of a set of 21 tasks representatives of ADLs (cf. Table I).

TABLE I: ADL Tasks

#	Self-contact tasks	#	Interaction tasks
1	Touch contralateral armpit	11	Pick coin (dominant)
2	Touch chest	12	Pick coin (non-dominant)
3	Touch contralateral temple	13	Cut with knife
4	Touch contralateral hip	14	Lift tray
#	**Abstract tasks**	15	Stir in cup*
5	Replace triangle	16	Pour in glass*
6	Replace small plate	17	Drink from glass*
7	Replace large plate	18	Open jar* (dominant)
8	Replace cup	19	Open jar* (non-dominant)
9	Replace cylinder	20	Turn door handle*
10	Replace ball	21	Turn key*

*dynamic tasks

The tasks were subdivided into *self-contact* (#1-4) and *interaction* tasks (#11-21), adapted from [7], [8], and *abstract* tasks (#5-10) chosen from the SHAP test [9]. Notably, some tasks were *dynamic*, i.e. they required a change in wrist orientation during their execution. Bimanual tasks (#11-12 and #18-19) were performed with both hands to capture

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This work was partially funded by the European Commission under the DeTOP project (EIT-ICT-24-2015, GA #687905) and partially by INAIL (the Italian national workers’ compensation) under the CECA2020 project. The work of C.C. was partially funded by the European Research Council under the MYKI project (ERC-2015-StG, Grant no. 679820).

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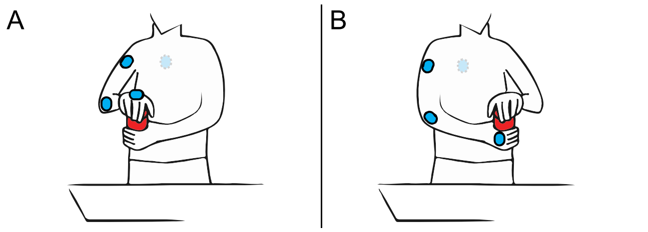

Fig. 1: Experimental setup. Dominant hand used as primary (A), or secondary hand (B) during representative tasks (#18 and #19). Blue circles indicate the placement of the IMUs.

differences when using a hand to support or to manipulate an object (notably, prosthetic hand users usually use the prosthesis in support to the contralateral unimpaired hand, less frequently the other way around) (cf. Fig. 1). For each data segment, the *Principal Orientation* (PO) was defined as the wrist orientation that the participants stably kept for the longest period of time during the execution of the ADL, whilst for the dynamic tasks two of such orientations were defined. The kinematic relation between the three DoFs was obtained as the best fit among the different POs and it was described by a system of three least-square polynomial functions $f_{PS}(p)$, $f_{FE}(p)$, $f_{RUD}(p)$.

III. Results

In particular, a set of 28 POs was obtained and three 7th order least-square polynomial functions were fitted to the data as a function of the POs numbered by descending degree of PS, indicated with p, where $1 \leq p \leq 25$ since POs of tasks #14 and #21 were considered outliers and ignored in the fitting (Fig. 2A). The kinematic relation produces a functional Range of Motion (RoM) of 103° for PS, 14° for FE and 28° for RUD. The 7th order was chosen since it minimized the partial derivative of the fitting curve with respect to PS angle (Fig. 2B). The mean error of the fitting, defined as the mean distance between the curve and the points representing the tasks, proved 5.0°. The R^2 values equaled to 0.99, 0.48, 0.66 for PS, FE and RUD respectively.

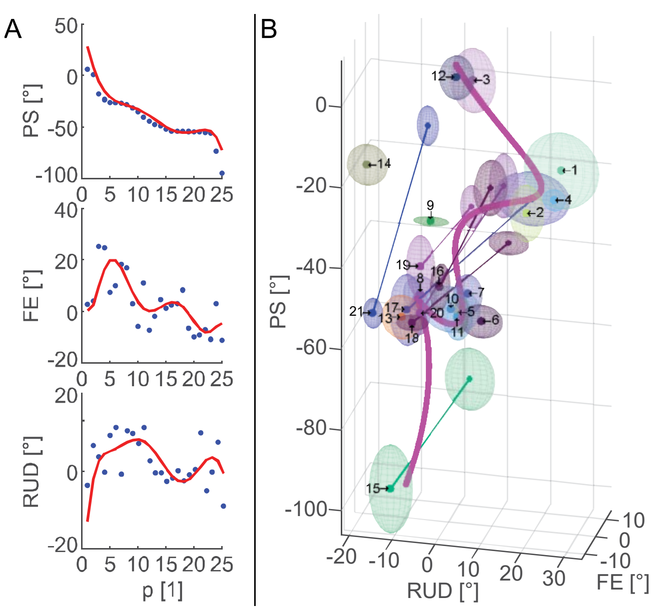

Fig. 2: (A) The three functions fitting the POs arranged by descending degree of PS (wrist prono-supination). (B) 3D representation of the mean (points) and standard deviation (colored bubbles) orientations of the wrist for each task tested (#). Dynamic tasks are represented with two points connected by a line. The synergetic relation is represented by the polynomial fit (thick solid line).

IV. Discussion

A system of parametric polynomial functions describing the synergetic relation between the 3-DoFs of the wrist during ADLs was obtained for the first time. With this system the motion of FE and RUD can be described as a function of the PS. This is necessary to implement a wrist featuring one single actuator that drives PS and a mechanism to obtain the orientations of FE and RUD with respect to PS. Hence, future work will be needed to devise a physical mechanism that reproduces this analytical relationship, towards a compact and functional device. The functional RoM obtained here is considerably smaller than the data reported in [7] and [8] and tests will be performed to assess whether the wrist mechanism that reproduces this synergetic relation is effective to preserve the ability of amputees to perform common tasks with minimal occurrence of compensatory movements.

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