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Developing a robotic thumb with limited backdrivability

Utvikling av en tommel til robot med delvis
tilbakevirkende kraft

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Developing a robotic thumb with limited backdrivability

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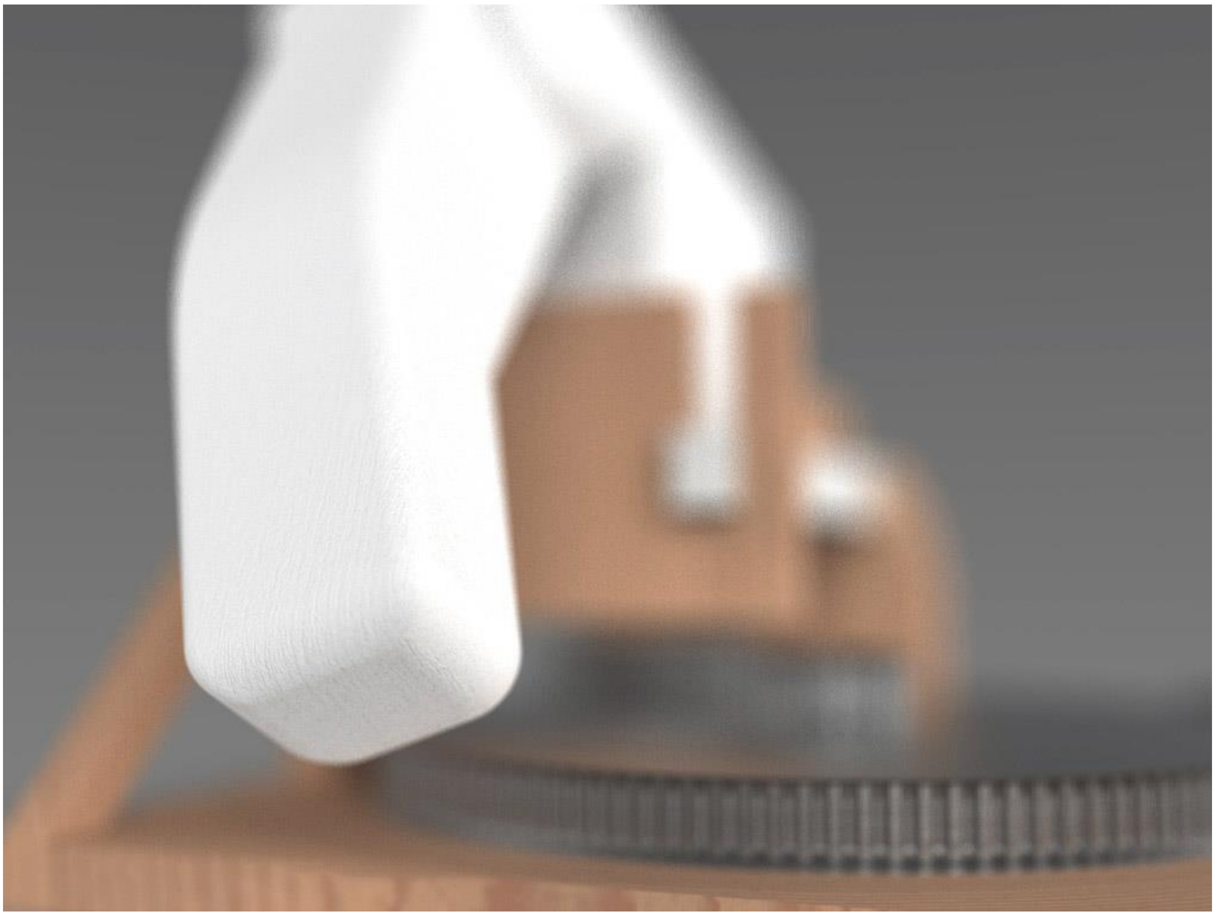

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PREFACE

Before you is the thesis “Developing a robotic thumb with partial backdrivability.” It explores how a backdrivable thumb could be developed to ensure a safer human-robot interaction. The thesis has been written between January and May 2018 as the concluding part of a Masters' degree in Mechanical engineering at the Norwegian University of Life Sciences.

From a previous subject, where it was attempted to make robotic fingers, sprung the idea of creating a backdrivable thumb so that the other fingers could be simplified. This idea was formulated along with Phong Nguyen at Halodi Robotics, and could pose a breakthrough in both controllability and safety for robotic hands. The problem statement forced me to use everything I've learned at the university, thinking systems through both forwards and backwards, including making several rapid prototyping tests.

Foremost I would like to extend my gratitude and thanks to Head Engineer Kristian Omberg and Assistant Professor Ola Omberg who threw me into several fun and challenging projects which taught me the basics of agile engineering, programming and rapid prototyping. Without them my education would be very different from what it is today.

Thanks to my supervisor Associate Professor Odd Ivar Lekang for his guidance. My co-supervisor and Assistant Professor Ola Omberg deserves some extra thanks, as his support, thesis guidance and reviews have proved very helpful. Thanks again to Head Engineer Kristian Omberg, CTO & founder of Disruptive Engineering Fredrik Kleven and co-student Markus Leonard Hansen for helping with ideas and debating solutions. Thanks to Writing Advisor Clayton Gouin for his great advice and insight into academic writing. Thanks to Industrial Mechanic Bjørn Tenge for help with assembly and prototypes. Thanks to Associate Professor Jan Kåre Bøe for preparing me as well as he did to write a masters' thesis.

Lastly, thanks to my domestic partner, Maria Linn Naphaug for her love and support during long working hours, and to my parents. Without them I wouldn't be where I am today.

I hope you enjoy reading!

Ås, 12. May 2018

ABSTRACT

The goal set in this thesis was to develop a robotic thumb with at least one backdrivable joint with a 15 N minimum grip strength, all within a human hands' size constraints. Backdrivability is the mechanical principle of being able to transfer force from input to output and vice versa. Using this principle lets the thumb to act as a force measurer for the fingers, allowing for precise grip strength measurement with a non-complex hand using few sensors. Backdrivability also makes it possible for the robot to safely interact with humans, since it will always be possible to escape the robots grip. No prosthetic or robotic hand on the market today can do this.

This project was started in a previous subject where research on creating a robotic hand was done. A possible solution for robotic fingers were found. The idea was to remove the outmost joint in the finger and control the two remaining joints directly. This resulted in many motors with little gain in controllability. An idea to create a backdrivable thumb came from these issues late in the development stage, and became the basis for this thesis.

Using the Integrated Product Development (IPD) method, the market was first found as mentioned above. The product requirements were worked out with the costumer, and by using Pughs matrix the optimal solutions for the design could be found.

The limiting factor was creating a backdrivable transmission system with little friction and backlash. To find the optimal solution, several transmission types were tested. Few transmissions worked well under heavy loads when used from output to input. A proof of concept prototype using timing belts and threaded screw-like gears was created to test the transmissions in a more real-life situation. This prototype uncovered a relation between geared backdrivable transmissions and friction that was unmentioned clearly in any sources, and an idea was stipulated on how backdrivability degrades with static friction in gear trains.

Recommended further work is figuring out how to compensate for static friction in geared backdrivable systems for robots. Work on minimizing friction in small gear trains will also significantly further the possibilities of creating a small and geared backdrivable thumb. In addition, it is important to continue to look for the correct simplifications, not only the most optimal solutions.

SAMMENDRAG

Målet med denne masteroppgaven var å utvikle en robottommel med minst ett ledd som kan tilbakevirkes med en gripestyrke på minimum 15 N. Tommelen skal være innenfor målene til en gjennomsnittlig menneskelig hånd. Tilbakevirkende kraft omfatter i denne masteroppgaven det mekaniske prinsippet om at giroverføringer tillater at kraft overføres fra start til slutt, og slutt til start i giroverføringen. Ved å benytte dette prinsippet kan robottommelen fungere som en kraftmåler for de øvrige fingrene, og tillate nøyaktig måling av gripestyrke med få sensorer. Hvis tommelen kan tilbakevirkes kan systemet bli mindre komplekst samtidig som interaksjon mellom robot og menneske blir sikrere. Grunnen til økt sikkerhet er at grepet til roboten vil være lett å unnslippe. Per dags dato tilbyr ikke eksisterende proteser eller robothender denne muligheten.

Undersøkelser rundt utvikling av en robothånd ble gjort i et forprosjekt høsten 2017. En mulig løsning ble funnet for fingrene. Ideen bak løsningen var å ha direkte kontroll av to ledd i fingeren. Dette resulterte i mange motorer med lavt utbytte sett i forhold til økt kontroll. Ideen bak en tommel med tilbakevirkende kraft kom sent i forprosjektet, og er videreført i denne masteroppgaven.

Ved å bruke integrert produktutvikling ble markedet funnet først, som nevnt ovenfor. Produktkravene ble funnet med kunden, og ved å bruke Pughs matrise kunne de optimale produktløsningene bli funnet.

Masteroppgavens begrensende faktor var utvikling av en robottommel med lite friksjon og lite tilbakeslag, samtidig som det skulle være mulig å stoppe robotens gripekrefter. For å finne den optimale løsningen ble flere typer kraftoverføringer vurdert. Få av de identifiserte overføringselementene var tilpasset tyngre belastninger i begge retninger, og for å teste et overføringskonsept ble en prototype laget. Prototypen bestod av tannreimer og gjengede skruer som ble benyttet til gir, og de utførte testene viste en relasjon mellom girede tilbakevirkende overføringssystemer og friksjon. Relasjonen er ikke tydelig beskrevet i de vitenskapelige studiene funnet i den tidlige fasen av prosjektet. På bakgrunn av resultatene fra prototypetestingen ble en antagelse formulert rundt hvordan statisk friksjon spres i et girsystem som må fungere tilbakevirkende.

Det anbefales å jobbe videre for å finne en løsning som kan kompensere for statisk friksjon i et girsystem med muligheter for tilbakevirkende kraft. Ved å finne en slik løsning økes mulighetene rundt utviklingen av en liten, sikker og giret robottommel med mulighet for virkende krefter i begge retninger. I tillegg er det viktig å fortsette og lete etter de beste forenklingene, ikke bare de mest optimale løsningene.

TERMS AND CONCEPTS

These chapters are to give the reader an insight into the explanation of terms, symbols, concepts and formulas used in the report.

Important terms

This is a list of the most important terms used in the thesis.

Table 0-1: Important terms used in the report.

Term	Definition
Exempli gratia (e.g.)	Latin for “for the sake of example.”
Id est (i.e.)	Latin for “in other words.”
Degrees of freedom (DOF)	Number of movable axes. E.g. one roller bearing joint has 1 DOF.
Degrees of control (DOC)	Number of actuated axes. E.g. a rotary motor creates 1 DOC.
Actuator	A component creating movement.
Underactuated	The number of actuated joints are lower than the degrees of freedom.
Humanoid	Resembling a humans’ shape
Computer aided design (CAD)	Modelling programs used to create 3D-models of parts and assembled product.
Finite element method (FEM)	Digital analysis of forces acting upon a 3D-model.
Payload	Term for the actual weight an apparatus is lifting or carrying.
Backdrivable	When displacement can be transmitted both from input to output and from output to input with the same relative force.
Rapid prototyping	Associated term for production methods that are quick and relatively easy to use, like 3D-printing and laser cutting.
Additive manufacturing	Creating a part by putting material together layer by layer, like a 3D-printer.
Uncanny valley	A hypothetical relation posed by Masahiro Mori stating that something that is very humanlike, but not quite right creates a deeply unsettling feeling or even revulsion in humans.
Ingress Protection (IP-rating)	Ingress protection rating is set from standard IED 60529, a standardized rating system handling protection from dust and water ingress.
Microcontroller	A small computer on an integrated circuit board. Used for simple operations and/or to control electrical components and systems.
Proof of concept	A prototype validating that a postulated design functions correctly.
Compliant	When a joint allows for movement without any interference from motors or transmission systems.
Backlash	Also called play. Motion loss due to gaps between parts.
Modular	Functions independently of other factors.

<table>
<tr><th>Term</th><th>Definition</th></tr>
<tr><td>Inertia</td><td>A physical objects resistance to any change in its state of motion.</td></tr>
<tr><td>Intrinsic</td><td>Originating inside an organ or part, used for muscles placed close to or on bones.</td></tr>
<tr><td>Extrinsic</td><td>Originating outside an organ or part, used for muscles placed close to the skin.</td></tr>
<tr><td>Plastic</td><td>An irreversible change in a materials structure due to a large load.</td></tr>
<tr><td>All terms are illustrated in Figure 0-1.

Thumb bones:
Distal
Proximal
Metacarpal

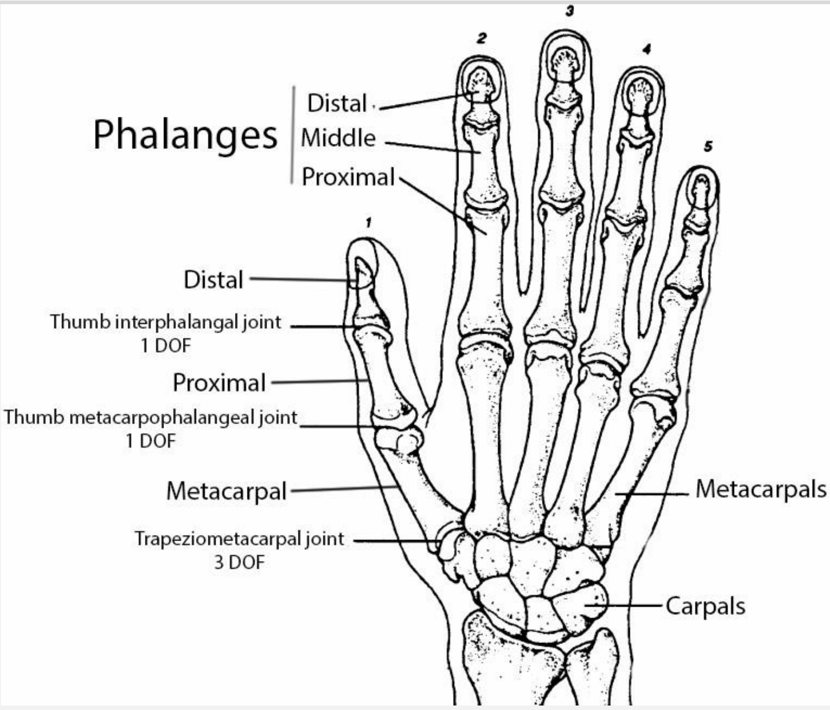
Thumb joints:
Interphalangeal
Metacarpophalangeal
Trapeziometacarpal</td><td>


Figure 0-1: Joints and bones in the human hand. Figure after D.J. Sturman [1].
</td></tr>
<tr><td>Thumb</td><td>Prototype part is defined as the distal and proximal phalange.</td></tr>
<tr><td>Prehensile</td><td>Movement where an object is seized and held partly or wholly inside the hands grasp.</td></tr>
<tr><td>Tactile</td><td>Relating to touch, something perceptible by touch. E.g. a tactile unit in the hand can sense touch.</td></tr>
<tr><td>Hysteresis</td><td>Retardation of an effect acting upon a system. I.e. friction causing an object to move slightly after an external force has been applied.</td></tr>
</table>

Symbols and units

List of mathematical and other symbols along with their SI-units.

Table 0-2: Table showing symbols with explanations and SI-units.

Symbols	Meaning	SI-unit
A	Area	mm^2
E, E-modulus	Elasticity-modulus	MPa or N/mm^2
F	Force	N
g	Gravity constant	(9.81) N/kg
l	Length	mm

Symbols	Meaning	SI-unit
w	Width	mm
m	Mass	kg
M	Momentum	Nmm
τ	Torque	Nmm
r	Radius	mm
d	Diameter	mm
σ	Stress	MPa
W	Section modulus	mm^3
i	Gearing ratio	-

Formulas

List of mathematical formulas used in the thesis.

Table 0-3: A list of formulas used in the thesis.

#	Formula	Meaning
1	$A_{circle} = \frac{\pi * d^2}{4}$	**Area of a circle** mm^2
2	$\sigma = \frac{F}{A}$	**Tension** MPa
3	$M = F * l$	**Momentum** Nm (Nmm)
4	$W = \frac{\pi * d^3}{32}$	**Second moment of inertia (e.g. circle)** mm^3
5	$\tau = \frac{M}{W}$	**Shear tension** MPa
6	$F = \frac{M}{r}$	**Force** N
7	$i = \frac{d_{gear\ B}}{d_{gear\ A}} = \frac{\tau_B}{\tau_A} = \frac{M_b}{M_a}$	**Gearing ratio** For gear trains, product of all gear ratios are calculated.
8	$Safety\ factor = \frac{yield\ stress}{working\ stress}$	**Safety factor** Relation between working load and breaking load
9	$d = \sqrt{\frac{4 * F}{\pi * \sigma}}$	Diameter mm, a cables diameter from applied loads and ultimate tensile strength.
10	$\tau_{output}^{backdriveable} > \left(\prod_{i=1}^{n} K_i\right) * \tau_{input}^{min}$	Torque Minimal torque needed at input to be backdrivable at output.
11	$F = m * g$	Force N

#	Formula	Meaning
12	$M = F * r$	Momentum Nmm
13	$m = \frac{f}{g}$	Mass kg
14	$\%surge = \frac{Max\ load - resistance}{\max load}$	Percentage How much an applied load can increase before its higher than the max load.

TABLE OF ELEMENTS

1 INTRODUCTION

This chapter will give a brief overview about this project. It will clarify why designing a partially backdrivable thumb is interesting, some background to why this is desired and the limitations set in the design.

1.1 Background

One major conundrum within robotics during the last years has been recreating the human hand. This thesis aims specifically at solving the problem "how to create a robust mechanical hand." The thesis statement is therefore as follows:

Helping solve the issue of creating a humanoid robotic hand.

The human hand is a complex system with many degrees of freedom (DOFs), muscles and sensing receptors. Recreating these requires simplifications and sacrifices to strength and manoeuvrability. The thumb is an especial challenge, which is why the thumb is this thesis' focus. How to create a mechanical thumb that can directly measure grip strength without needing external sensors is probably through backdrivability.

Backdrivability is the most desired solution for allowing robot and human interaction. The term backdrivability is defined as allowing movement from input to output and vice versa using the relative same force, and it requires a direct drive motor. In a direct drive motor there is no gearing, and current is linearly correlated with outputted force. By using this fact, the force exerted on the thumb can easily be found. By using a backdrivable system, a user can move the robot freely around without any resistance. This makes the thumb safe for use with humans since they can always escape the robots grasp by pushing against the thumb.

Safety has always been a large concern for allowing human-robot interaction. Robotic design must be inherently safe. Users must have the possibility to stop the robot with ease using their own hands in case an error happens, and this failsafe must be on the mechanical level and not software level.

This research is being conducted to improve the humanoid robot Eve being made by the company Halodi Robotics, which is nearing its finishing stages. Eve has two fully backdrivable arms, and the legs are being designed now. The next step is to allow for interaction with the world, and for that Eve needs hands. That is why this thesis aims to solve the issue of creating a backdrivable robotic thumb that will be safe for human interaction.

1.2 Idea, problem statement and process goal

Problem statement:

Creating a modular, two degrees of control robotic thumb where one joint is backdrivable.

To solve this problem, the thumb will use a direct drive motor with a geared transmission which allows for backdrivability. The transmission intends to keep friction and inertia to a minimum, with little to no backlash. These are the most important aspects in ensuring a secure and robust grasp with the correct grip strength.

The idea is to use the correlation between current and force in a direct drive motor to make a backdrivable thumb that can act as a "spring" counterweight against the other fingers. By positioning the thumb perpendicularly on the fingers pushing axis, it allows the fingers to push directly on the thumb. This setup makes it possible to measure grip force accurately. A limit can be set at e.g. 10 N. When the thumb registers that it has a 10 N force pushing onto itself the motors in the fingers are stalled with a 10 N achieved grip strength, using nothing but the direct correlation between voltage and power exerted by the motor. This may be how to create a “smart” hand using underactuated fingers and little to no sensors other than a motor encoder.

Process goal:

Finding the optimal backdrivable transmission for a backdrivable thumb.

How to transfer the force from the motor to the thumb, and then from the thumb back to the motor will be the most important problem to solve. This is what will allow for backdrivability and a robust operation. When designing the thumb both research and testing on several transmission systems will be essential.

1.3 Relevancy and purpose

It has been stated that the thumb differentiates humans from apes and other primates. The thumb allows for precise and varied hand movements [2]. Recreating the thumb mechanically in a form factor as small as the human hand is challenging, and finding the correct simplifications has proven just as challenging.

Solving what the optimal simplifications in a robotic hand is, can lead to cheaper prosthetics. Current prosthetics are very expensive. Between 10.000 and 20.000 dollars [3]. Most previous robotic hands have also been created with humans in mind. Few hands have been created solely focused on robotics, and have therefore been optimized with very different goals. Finding the optimal number of axes to control is vital. Too many and the hand will be too complex for grasping software and unruly to use, too few and the hand will be very limited in its usage. Creating a thumb with at least one backdrivable joint in cooperation with a good solution for the other fingers might be the optimal solution for creating an underactuated robotic hand.

1.4 Limitations

These are the limitations set for this project. They stem from various reasons, either from time constraints or because they stray too far from the problem statement of creating a backdrivable robotic thumb.

Physiology:

- Most important design element is the thumb.
- Focus on prehensile movement, i.e., grasping movement.
- Focus on functioning movement, this means that the degrees of control will be reduced.
- Degrees of freedom will be reduced in comparison to a human hand.
- Palm will be simplified to one single stiff plane.
- Wrist joint design will be omitted, including a connector to the wrist.
- No focus on achieving dextrous in-hand manipulation.

Control:

- No programming.
- The hand will get power from the main unit/robot.
- Theoretical motor values will be used as a basis for selection.

CAD/FEM:

- Simple FEM analysis on Von-Mises stress and deformation.
- No cable simulations.
- No mathematical modelling.

Production:

- The thumb designed will be a proof of concept.
- Design will be aimed at quick prototypes, with a mass producible design being made later when the prototype has been validated.

Other:

- No explanation of theory behind the calculations done (Von-Mises, etc.)
- No patent checks.
- No life cycle analysis since the design disregards mass production.
- Modular, there is no space for motors inside the forearm on the robot.
- No deep dive in the prosthetics market since prosthetic hands are created with a completely different market and user in mind.

1.5 Eve: A humanoid robot prototype being designed by Halodi Robotics

Eve is the brainchild of every employee at Halodi robotics. They are designing a humanoid robot for the human workspace, the housekeeping robot that has been prominent in science fiction literature since the 40’s. A fully backdrivable arm has been created for the robot to make it safe. Backdrivability makes it possible to naturally interact with the robot since it allows the user to simply push and guide the robots’ movements, and thus incorporating safety by being able to easily stop any movement the robot makes.

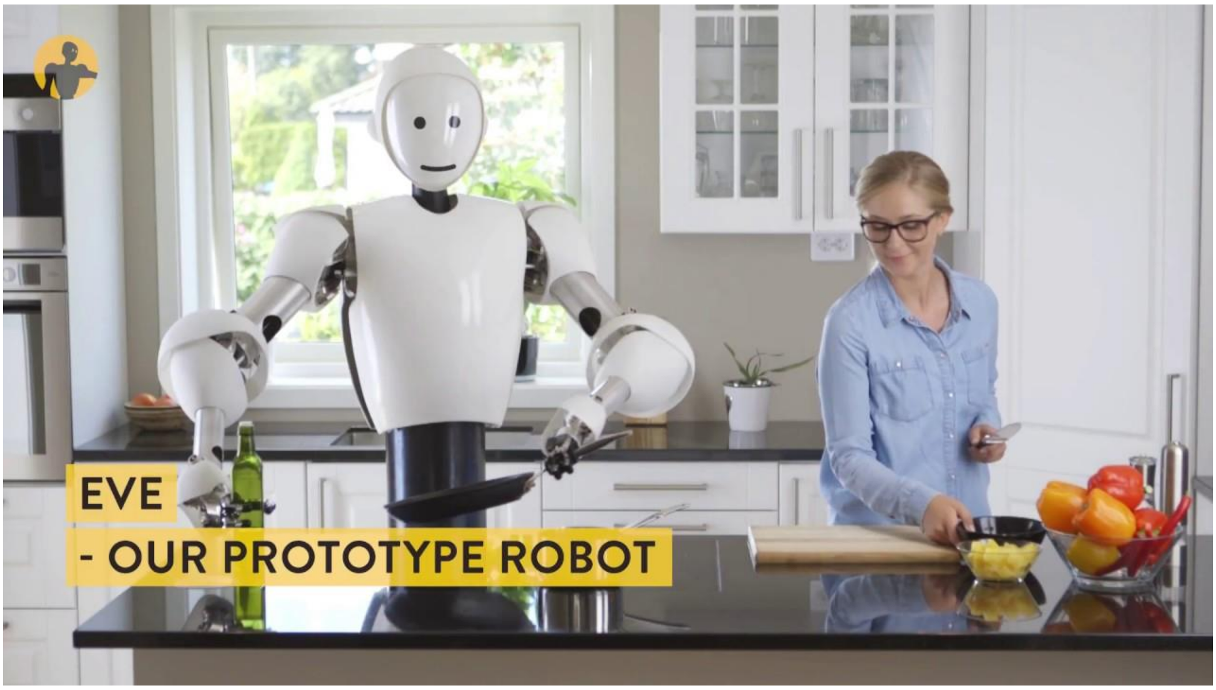


Figure 1-1: Eves completed parts from a promotional video. Here shown with passive pre-mounted three-point claw grippers. [4].

By allowing safe human-robot interaction, Eve can become a household robot. For that reason, Eve is created with mass production in mind. The price range they are aiming for is about 20.000 NOK. A price they mean is reasonable for the product they are delivering, and this relatively low price is what they believe will cause mass adoption for robotics in the home. Creating the legs and a wrist joint is the next step for the Halodi team, with the hand being the last thing to design.

2 THEORY

A human hand analysis is the baseline for creating any artificial hand. It is important to take inspiration from nature, since nature has used a long time to develop the hand mankind has today. Using this intrinsic knowledge of man's own limbs, design choices becomes more transparent.

2.1 Empirical or analytical approach to movement

The two main approaches to recreating human movement are the empirical and the analytical approaches. An empirical approach tries to recreate grasp from studying many samples, meaning recreating human movement by mimicking it. This can be problematic due to a limited DOF robot hand having problems with recreating the more complex human hand motions, and a grip mimicked directly after a human grip usually functions unacceptably [5]. An intricate hand motion analysis may be needed to recreate the movements properly, especially since certain movements happen quickly [6]. To avoid using direct hand motion analysis, an analytical approach can be used instead.

The analytical approach uses mathematical algorithms for finding the best approach to grasp an object with the specific hand being used. Grasping software is in constant development, and according to Balasubramanian et al. combining both may yield the best results. His team let humans guide grasping software and place the grip for the software, which yielded better results than the program alone. Just letting the humans decide the grip still yielded the best results [7].

2.2 Human hand movement

Human hand movement can be divided into two main categories:

1. Prehensile movement
2. Non-prehensile movement

Prehensile movement is movement where an object is seized and held partly or wholly inside the hands grasp. Non-prehensile movement is movement where no grasping is involved, but encompasses object manipulation using pushing or lifting motions with either the hand or the fingers [8]. Due to the flexibility and possibilities prehensile movements offer, it will be this chapters' main subject. Two main features makes prehensile movements possible: grasp robustness and manipulative dexterity:

Grasp robustness is defined as how well an object can be held onto in relation to the grasp strength, number of contact points, slippage, and how well the grasp can be achieved with external forces influencing the object. I.e., grasp robustness is associated with preventing a grasped objects motion in relation to the hands movement. Object manipulation using the whole hand is vital to grasp robustness because it ensures a good grip [9].

Manipulative dexterity encompasses advanced in-hand manipulation, such as rotation, translation and re-grasping. Manipulative dexterity is defined as the capability of changing position and orientation of a manipulated object inside the hand workspace. This requires a hand capable of low fingertip forces, as well as continuously sensing variable forces accurately in the whole hand [10].

2.3 How to achieve movement

In the previous chapter, different types of movement were outlined. How to duplicate human hand movement is difficult since the hand is an integrated system with many components and actuators that work harmoniously together.

2.3.1 Muscle

As defined by Napier, hand grips can be divided into two main categories; power grips and precision grips. Power grips are grips where an object is held tightly within the palm. A precision grip is when an object is pinched or held between the thumb and fingers flexor element, meaning between the fingers outer joints, commonly called a pinch grip [8]. Both grip types are illustrated in Figure 2-1. These grips are controlled by two different muscle groups, those that cross the wrist, and those that reside within the hand. These are respectively called the extrinsic and the intrinsic muscles [11].

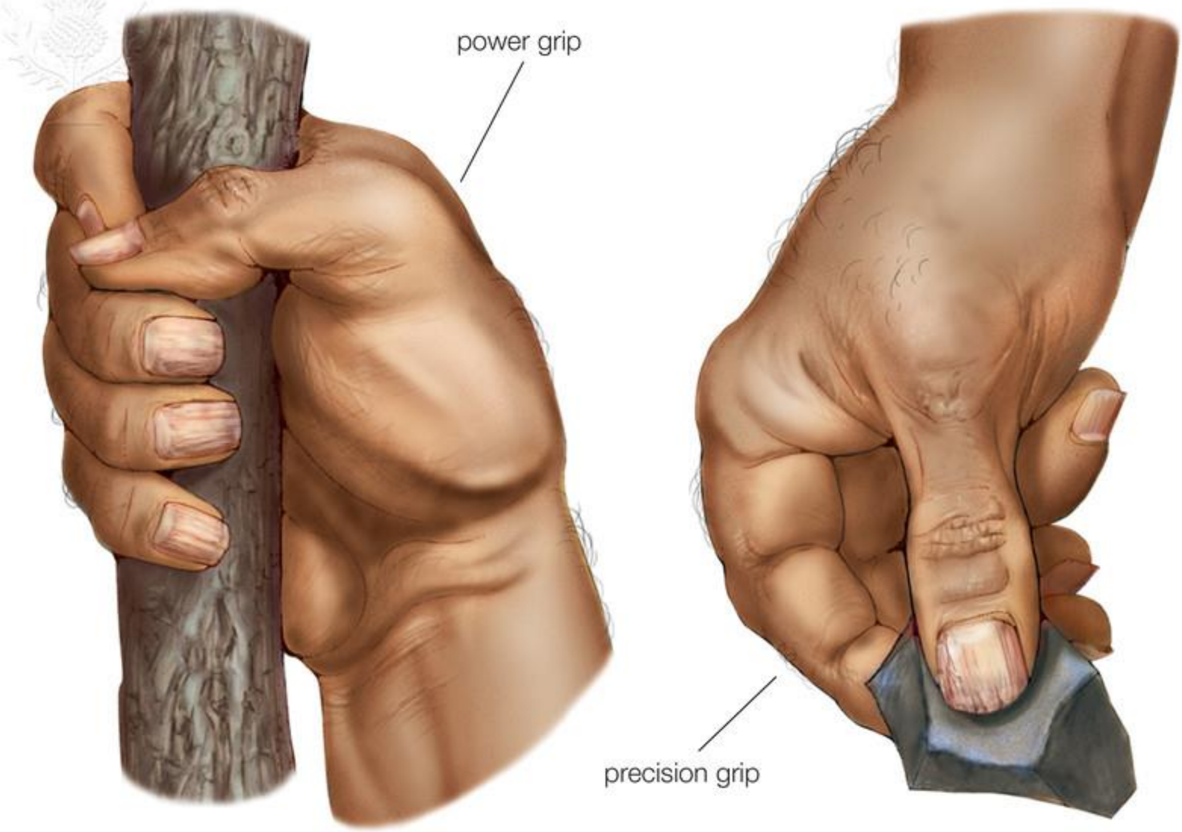


Figure 2-1: Illustration showing the difference between power grips and precision grips. From Encyclopaedia Britannica [12].

As found by several studies, the extrinsic muscles are the main providers for strength in power grips. In precision grips, some specific extrinsic muscles are used. The intrinsic muscles are used mainly for finely balancing an object within the fingers grip [11, 13, 14]. These different muscles create hand movement, but they can only pull. Muscles cannot push the fingers back out, and to create a push movement another muscle set using tendons is needed.

2.3.2 Tendons and joints

Tendons create the possibility of remote movement. E.g. a muscle in the forearm can move a finger. Tendons are primarily concerned with transmitting tensile forces, but can also be subject to compression and shear depending on whether they must pass through bony pulleys or not. Tendons can function between muscles as well, but mostly a tendon is a link between muscle and bone directly [15].

Joints are structures that separate two or more adjacent skeletal system elements. Depending on the joint, separated elements may or may not move on one another. Different joints allow for different motions; rotation, angular movement, or translation of bones. Gliding and rolling motions only occur in synovial joints. There are seven synovial joint types; plane, hinge, pivot, sellar (saddle), ellipsoid, bicondylar and ball-and-socket joints, five are illustrated in Figure 2-2. The ball-and-socket joint is the only joint allowing for all movement types [16].

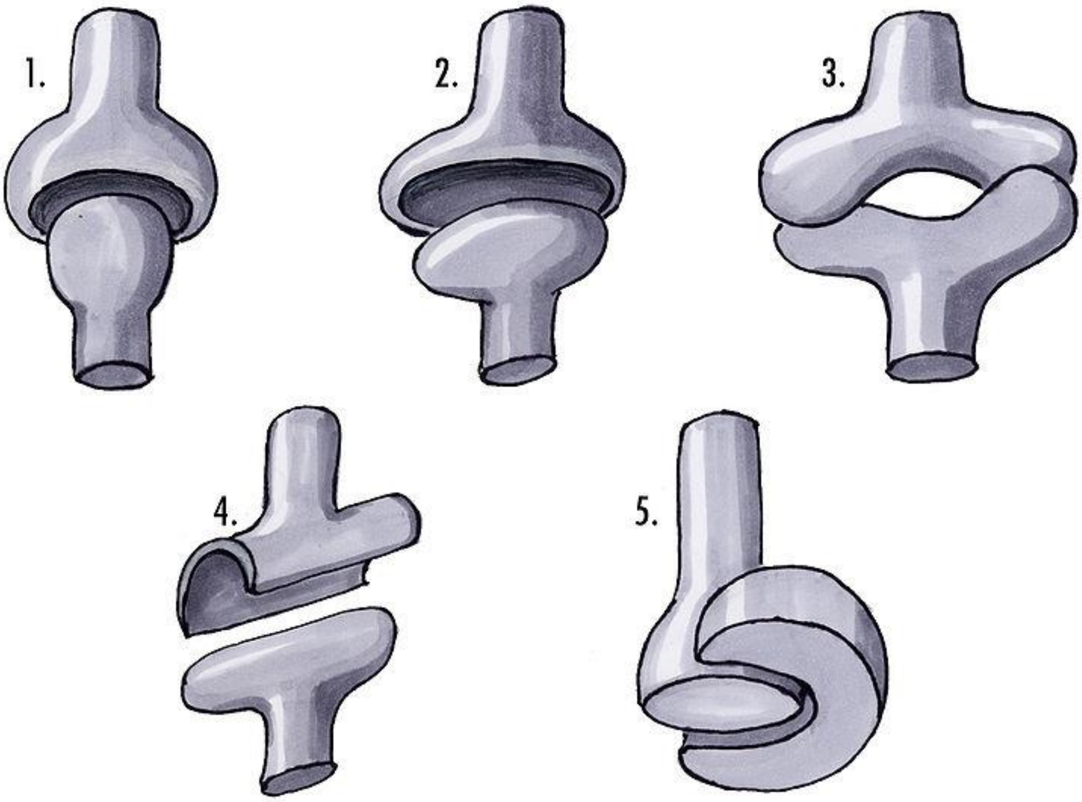


Figure 2-2: Drawing of different joints. 1. Ball-and-socket, 2. Ellipsoid, 3. Saddle, 4. Hinge, 5. Plane [17].

The most common joint in the fingers are ellipsoid joints. They allow the fingers to flex and extend, to move sideways toward the other fingers, and to swing forward with some rotation [16]. To use these joints effectively, the hand must know where an object is located inside the palm.

2.3.3 Feeling

There are 17.000 tactile units in the human hands skin area, and these are divided into four different types. Two are fast adapting, and two are slow adapting types [18]. These react to different stimuli types. In a static situation where an external agent is pushing onto a stationary hand; at first the fast adapting types activate. The slow adapting types activate when contact is started, and continue to function throughout the contact period. In situations where an object is moved over a stationary hand, the slow adapting receptors are activated even more vigorously [19].

2.4 Hand design key features

The peculiar requirements and applications for a specific artificial hand must be considered when designing it. For a humanoid hand, that may be looking at what human counterparts that should be exchanged. The brain, muscles, tendons, joints and sensory capability translate to kinematics, actuators, actuation transmissions and sensors. Materials and manufacturability will also be fundamental for creating an optimal design.

2.4.1 Kinematics

The human hand contains approximately 20 DOFs, excluding the wrist. This leads into how to contain all the mechanical human counterparts within a constrained volume composed by the biological model. Twenty DOFs can equate to 20 motors, or even more if the motors are only able to pull and not push. This leads to simplifying DOFs and Degrees of Control (DOC). In prosthetics, the DOFs and DOCs are reduced significantly, though they can still provide useful for the wearer [20].

Finding the correct DOFs and DOCs in robotics while still providing versatile grips is a different issue altogether. A human is not controlling the hand, and software has taken over the control process. As Balasubramanian found out, humans are presently better at kinematics than grasping software [7]. A decrease in DOF and DOC makes grasping less certain. Therefore, the degrees of freedom and control must be decreased where there is redundancy in the biological model so that near-equal performance can be acquired. Salisbury proposed in 1985 that a minimum of 9 DOCs were required to achieve dextrous manipulation [21]. For basic prehension, only 3 DOFs are required, assuming a rigid finger in addition to non-rolling and non-sliding contacts [22]. For the kinematics to make sense, a logical way to make the fingers move is needed.

2.4.2 Actuation

An actuator is needed to create movement in the thumb. One main bottleneck in creating an artificial hand comparable to a human hands performance and size is that current actuation technologies fail to provide high power to density actuators with an equally high efficiency [23, 24]. As can be gathered from the previous chapters, many muscles and joints are needed to generate a single movement. In the hands, a muscle transmits displacement to the jointed bony segments through the tendons, and then produces a force at e.g. a fingertip.

Several motors can achieve this, and below a few are listed:

- Direct Current (DC) motors (Brushed or brushless)
- Hydraulics
- Pneumatics
- Shape memory alloys (SMA)
- Piezoelectric
- Ultrasonic
- Solenoids

Finding the appropriate motor for a specific use means uncovering the application requirements. This can be force, efficiency, displacement, specific power to mass or volume, noise, size, mass, response time, robustness or gearing needs. Some of the differences between selected motors is shown in Table 2-1.

Table 2-1: Comparison of relevant actuators after Huber et al.[25]. Values are averaged.

Actuators	Power-to-weight ρ[W/Kg]	σ_{max} [MPa]	E_{max}[MPa]	E [GPa]	Efficiency
DC motors	100	0.1	0.4	*	0.6 - 0.8
Pneumatic	400	0.5 - 0.9	1	$\sim 6.5 \times 10^{-4}$	0.4 - 0.5
Hydraulic	2.000	20 - 70	1	~2.5	0.9 - 0.98
SMA	1.000	100 - 700	0.07	30 - 90	0.01 - 0.02
Solenoids	10	0.04 - 0.1	0.1 - 0.4	$\sim 0.7 \times 10^{-3}$	0.5 - 0.8
Piezo polymer	800 [26]	0.5 - 5	$\sim 6 \times 10^{-3}$	2 - 10	0.9 - 0.99
Human muscle	500	0.1 - 0.4	0.3 - 0.7	0.005 - 0.09	0.2 - 0.25

DC motors:

Direct Current brushed or brushless motors have permanent magnets that require an alternating stator current to produce constant torque. Brushless motors give better robustness, higher torque and speed bandwidth with lower maintenance needs than a brushed motor [27]. This at the cost of brushless motors needing a more complex motor control system. All DC motors produce excessive speeds and insufficient torque for the needs in a robotic or prosthetic hand and therefore they need drive reductions to increase torque and decrease speed [28].
DC motors are the most commonly used motors in prosthetics and robotics, examples are Smarthand [29], Speed Hand [30], Michelangelo by Ottobock [31], Stanford JpL [32], Okada [33], Belgrade [34], Barret [35] and many others.

Pneumatics and hydraulics:

A different approach is using pneumatic actuators, where the outputs mechanical energy is realised by the potential and kinetic energy of a fluid working under pressure. The systems usually consist of a force element (cylinder), a command device (valve), connecting tubes and position, pressure and force sensors. A pneumatic transmission is linear, fast and accurate while providing low friction and a compliant system. Problem areas are that it requires a separate pressure/pump unit, and the wear and tear on parts are high due to the system working under constant pressure, usually about 30MPa [36]. Another problem is the compliance in pneumatic transmissions making them unruly for precise control, especially with external forces acting upon the output [37].

Shape memory alloys:

An alternative actuator like a Shape Memory Alloy (SMA) is interesting due to their high power to density ratio. They are usually compromised of nickel and titanium [38], and work by inducing a phase-change by either heating or cooling the material. This change appears plastic, but the large shear stresses induced in the material can be fully recovered upon raising the temperature [39]. This means its application is limited from how well the material can be heated and cooled, including a low efficiency around 10-15% [40].

Solenoid actuators:

Solenoid actuators are electromagnetic actuators which convert electrical energy to mechanical energy in the form of linear movement. These actuators are small, have a simple structure and are reliable as well as cheap. Electromagnetic actuators usually do not have linear static characteristics and may therefore require extra sensors or a microcomputer for accurate control. [41]

Ultrasonic and piezoelectric actuators:

Ultrasonic and piezoelectric motors both work using the same principle. A piezoelectric element is a material that either vibrates or creates mechanical stress when exposed to electricity. An ultrasonic motor uses a special piezo element that can vibrate, and uses this vibration to create rotary or linear motion. A piezoelectric motor uses the mechanical stress induced in the element as displacement to create either linear or rotating movement [42].
These motors' advantages are their compact structure, large torque density, small inertia, fast response time and self-locking abilities. Including precise controllability with no electromagnetic interference while capable of working under difficult environmental conditions. The disadvantages are their low power output and low efficiency (about 30%, depending on design), short operational life and unsuitability for continuous operations. Piezo elements have high requirements for drive signals due to the excitation signals needing a change in frequency when the elements temperature fluctuates [43, 44].

2.4.3 Actuation transmissions

A transmission system is needed to translate the actuators' displacement to movement in the fingers. There are many solutions to this problem, including tendons with sheaths or pulleys, gear trains, belts, linkages, flexible shafts and more. Such a wide variety of solutions means that mapping hand constraints and wanted use is important.
Major design goals are to minimize friction, backlash and inertia, while still maintaining a low weight and small size. Non-linear effects induced by too high friction or backlash makes controlling the movements accurately difficult or even impossible in variance with severity [45].

Table 2-2: A brief comparison of transmissions after [22]. The table is based on conclusions made in literature and what previous makers of robotic hands have discovered. Higher score is always better.

Transmissions	Low Weight	Small dimension	High stiffness	Little backlash	Low inertia	Low Friction	Little Noise	Reliability	PAP*
Tendons w/idle pulleys	●●●●○	●●●●○	●○○○○	●●●●○	●●●●○	●●●●●	●●●●●	●○○○○	No
Tendons w/sheaths	●●●●●	●●●●●	●○○○○	●●●●○	●●●●●	●○○○○	●●●●○	●○○○○	No
Linkages and cams	●●○○○	●○○○○	●●●●●	●○○○○	●●○○○	●●○○○	●●●○○	●●●●○	Yes
Cylindrical gears	●○○○○	●●○○○	●●●●○	●●○○○	●○○○○	●●●●○	●○○○○	●●●●●	Yes
Bevel gears	●○○○○	●●○○○	●●●●●	●●●○○	●○○○○	●●●●○	●●●○○	●●●●●	Yes
Flat bends and belts	●●●●○	●●●○○	●●●○○	●●●●●	●●●●○	●●●○○	●●●●○	●●○○○	No
Flexible shafts	●●●○○	●●●●○	●●○○○	●○○○○	●●●○○	●●○○○	●●○○○	●●●○○	Yes

*PAP = Push and pull

The table above gives a rough outline as to what transmission system allows for creating a backdrivable system with as little friction and backlash as possible. Tendon-driven mechanisms are the most direct link to the human hand. Complexity is an omitted element in Table 2-2; but it plays a large role in bio-inspired mechanical hands where their human counterpart is both non-uniform in tendon distribution, and uses redundant muscles as well as tendons. However, bio-inspired tendon driven limbs have shown engineering advantages such as low weight, low inertia, small size, backdrivability, low friction and design flexibility [46].

In artificial robotic hands, using tendons with sheaths seems to be the most commonly implemented solution. Tendons with sheaths is again a direct counterpart to the human solution. The JPL Hand [32], DIST hand [47], LMS hand [48], Smarthand [29] and several others use Teflon-coated cables in flexible conduits. These sheaths induce non-linear effects and reduce efficiency, but allow remote actuator placement from the joints, resulting in a small and lightweight design [49].

By using idle pulleys instead of sheaths, the friction effects can reach negligent levels. This at the expense of system and control complexity. Other issues that arise with idle pulleys are that they can only pull, and a second pulley and motor set is needed to achieve two-way joint control [50]. If high stiffness is required, the cable must be constantly preloaded, resulting in unwanted strain on the components [51]. Flat bends or belts can also be used to increase the stiffness, as well as increasing strength, but the system will still have many joints which are difficult to control [52].

Morecki et al. showed that a rigid body possessing *n* bidirectional joints can be completely controlled using *n*+1 tendons, using only pulling actions [53]. Using less than *n+1* tendons creates an underactuated system, and more than n+1 creates redundancy. This, and several other motor and joint systems are illustrated in the figure below.

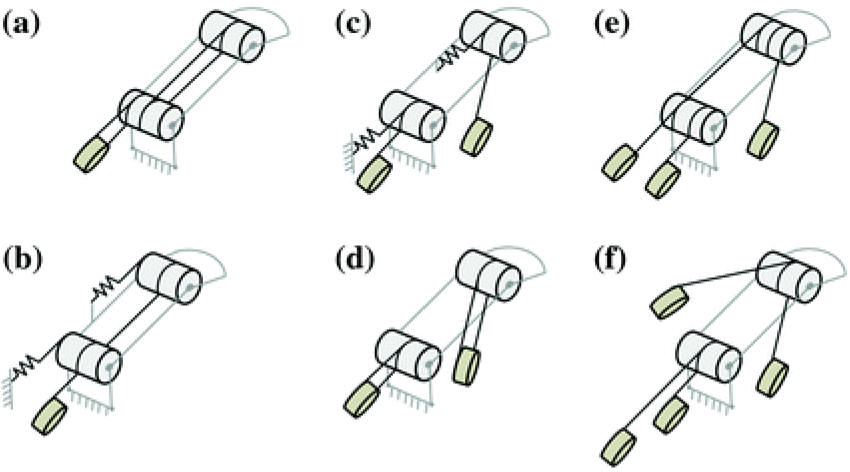


Figure 2-3: Schematic representation of possible kinematic architectures in robotic hands (green circles are motors, white are joints) after [22]: a) Motor (M) = Joints (N) coupled joints, b) M < N underactuated transmission, c) M = N fully actuated open chain, d) M = N fully actuated closed chain, e) M = N + 1 fully controllable, f) M = 2N agonist/antagonist transmission.

If a pull-only system is used, the amount of motors and control complexity quickly increases as the figure above illustrates. Using bidirectional joints with high stiffness properties makes for easier controllability.

Linkages or gear trains give the absolute best stiffness properties. They also need little maintenance, and allow for bidirectional joint control. On the other hand, linkages and gears substantially increase weight, the complexity and sometimes the hand dimensions as well [22, 54]. Setting up connected linkages in the fingers can give strong, self-adjusting grips, albeit a little unprecise [34, 55]. Gear trains have very little transparency, and has no way to sense what is happening at the systems end.

2.4.4 Sensors

Sensing and grasping a multitude of objects optimally is difficult for robots working in a human environment. To make this task easier, sensors are used. Sensors can be divided into two main categories: proprioceptive and exteroceptive sensors. Proprioceptive sensors measure information regarding the device itself, like motor rotation or tendon displacement. Exteroceptive sensors measure outside stimuli working upon the sensor, such as applied forces, friction, shape, temperature, etc. These can again be subdivided into for example tactile sensors, joint position and tendon tension sensors [56].

Extrinsic tactile sensors are able to derive shape, size, stiffness, weight and even texture on grasped objects [57]. Important factors for tactile sensing are: spatial resolution, sensitivity, frequency response, hysteresis and memory effect. They can have little wiring, high flexibility and different surface properties fit to diverse tasks [58].

A joint position sensor is typically a Hall-effect sensor [56]. A Hall-effect sensor is a thin conductive metal plate that can carry a current. A voltmeter is connected to opposite sides of the plate, showing a measured voltage of zero. When a magnetic field is applied to the plate, a small voltage appears across the plate and this is the Hall-effect [59].

Tendon tension sensors are used to compensate for the friction in transmission systems and for measuring external contact force [56]. A backdrivable system may be used to measure external forces without using sensors.

2.4.5 Backdrivability and its importance

A backdrivable system is defined as the easiness of movement transmission from the output axis to the input axis, due to an externally applied force [60]. I.e., when motion can be transmitted both from input to output and vice versa. A backdrivable system is easier to control, partly because tendon forces can be measured directly by measuring the resistive torque in the DC motor. This is doable since a backdrivable system usually requires a direct drive motor. Backdrivability is also advantageous related to safety and robustness, since backdrivability provides a natural protection against unknown external impacts. This is due to compliance, letting the system move if the motor current does not overpower the external impact [61].

Overpowering an external impact may not be an issue, since direct drive motors that are small, are also weak. Therefore, creating the necessary power for robust grasps with motors inside the hand can be problematic. Even though backdrivability makes the robot safer to use along with humans, since they can overpower the robots grasp, sudden power loss will mean that an object will be dropped. A non-backdrivable system will be able to hold onto an object with little to no power, and is therefore safer during an abrupt power loss [22, 60, 61].

2.4.6 Materials

A human hand is a stiff bony structure with dampening tissue to reduce possible damage on the bones as well as being responsible for dissipating strain. The nail protects the soft tissue from external forces, and hinders excessive soft tissue deformation at the fingertip. The skin works as a sensor and is essential for correct contact with the external world [22].

Using one single material to replicate all these properties is an impossible feat. Since a robotic hand must be robust, be able to handle high speeds, sudden impacts, large gripping forces and possibly corrosive environments, choosing the right material is vital. Often maximizing the specific stiffness (Young’s Modulus to density) is best. This will give a strong hand with low weight [62]. Other constraints such as minimizing wall thickness (aluminium alloys or composites), biocompatibility (titanium alloys) or corrosive environments (galvanized/inox steels) can also be considered.

2.4.7 Rapid manufacturing

Rapid prototyping (RP) encompasses a wide range of technologies used to quickly produce accurate parts directly from CAD files, with little to no human intervention [63]. 3D-printing will be the focus in this chapter. RP technologies may be broadly divided into two categories: methods that add material and methods that remove material. The material addition category can again be divided into what state the material used is in: liquid, particles or solid sheets. A RP technologies tree may look something like this figure below:

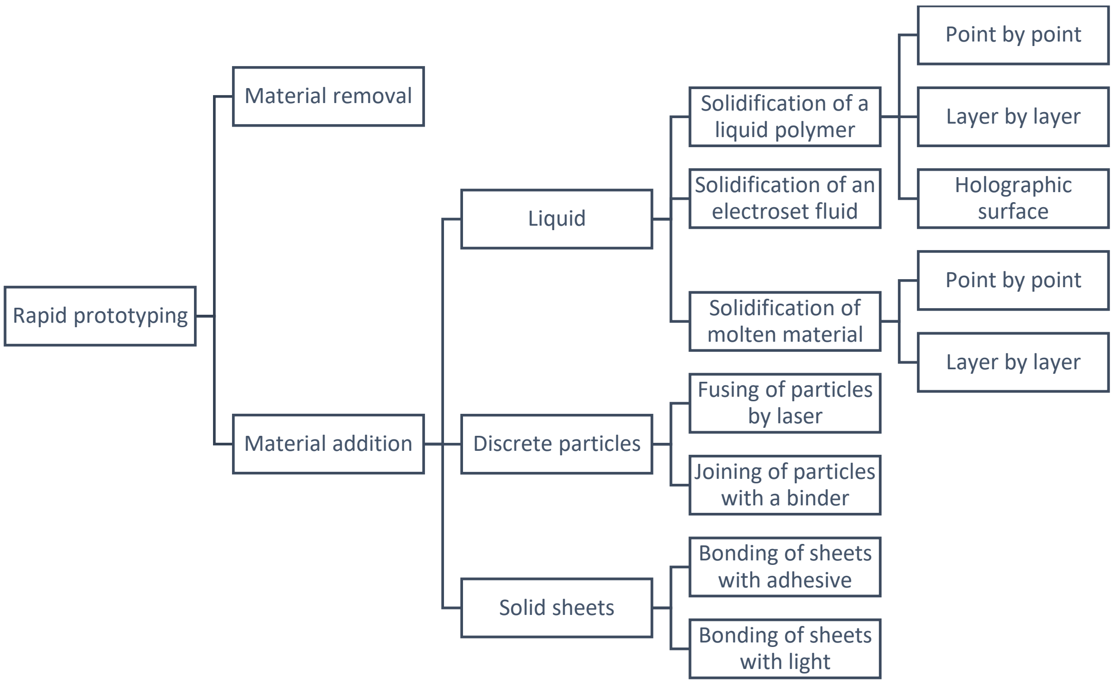


Figure 2-4: Hierarchical tree showing how different rapid prototyping methods function, state of material and how they create the desired part. Figure after [63].

Three different methods will be highlighted here:

- Fused Deposition Modelling (FDM): Point by point solidification of a molten material.
- Stereolithography (SL): Point by point solidification of a liquid polymer.
- Selective Laser Sintering (SLS): Fusing particles by laser using discrete particles.

These are chosen because FDM printers and SL printers are available at the workshop, and SLS printing is most commonly used by larger firms where 3D-prints can be ordered [64].

Fused deposition modelling:

FDM printing feeds a filament through a heated element and becomes molten or semi-molten. This liquified filament is then fed through a nozzle using a solid (usually metal) piston mechanism that deposits the material onto a surface or a partially constructed part. Through cold welding, the newly deposited material fuses with adjacent material [65]. Thermoplastic polymers are the most common materials to use with FDM 3D-printing. Examples are ABS, PLA and PC. These materials allows a 50-200 µm layer resolution and can be liquified and fed through a nozzle [66].

The nozzle head moves in the horizontal X- and Y-plane and deposits material according to the model geometry at a certain height. The nozzle head is commonly called an extruder and is shown in action in Figure 2-5. Height is set by the building plate which moves in the vertical Z-plane. Often the building plate is heated to avoid the materials buckling from large temperature deltas.

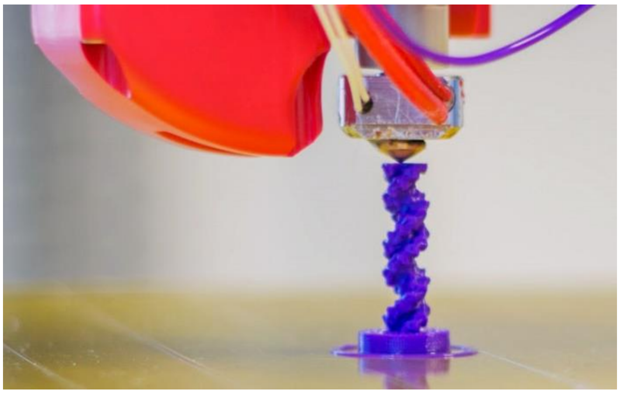


Figure 2-5: Extruder on an FDM printer during distribution of materials [67].

Stereolithography:

Manufacturing using stereolithography is based on controlled liquid resin solidification by photo-polymerisation in a pre-defined space. I.e. using light to make liquified plastic (resin) react to create a hardened plastic inside the building vat containing the resin. There are mainly two ways to accomplish this, by using a laser-based stereolithography printer (SLA) or through digital light processing (DLP). This process is executed layer by layer. When one layer is cured, the building plate is lowered deeper into the building vat, allowing for curing the next layer on top [68, 69].

There are differences when using SLA and DLP printing. DLP can print large objects quicker since it can cure the entire layer at the same time, while the laser must travel the entire layer size [70]. The trade-off is that SLA usually gives greater precision with a 10 µm possible layer height [66]. Workings of both types is illustrated below.

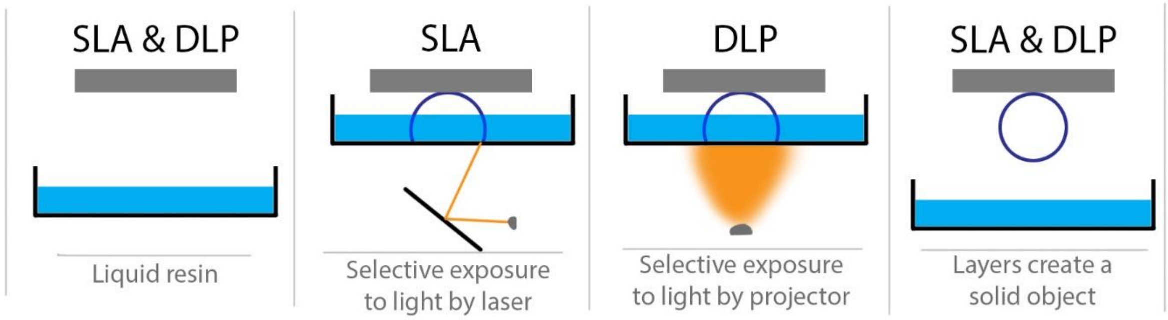


Figure 2-6: Explanation of the different adhesion methods used by SLA and DLP 3D-printers.

Selective laser sintering:

SLS printing works by sintering fine powdered particles selectively using a carbon dioxide laser beam. On some printers the chamber is heated close to the particles melting point. A roller spreads a fresh powder-layer on the building-plate after each layer is sintered, and this continues until the process finishes. The SLS process allows for using a large material variety, including plastics, metals and composites. Available commercial systems have a limited laser focus diameter of about 50-300µm and is therefore unable to produce components smaller than 500µm. Since SLS is a layered process using powder, thinner layers and smaller particle sizes are needed to increase the resolution and print accuracy [68, 71].

2.5 Market research

According to Statista the leading companies, based on revenue, within industrial robotics today is in order: ABB, b+m, Fanuc, Yaskawa and KUKA. ABB had a revenue of 6943.9 million euros in 2016 from their industrial robot sales [72].

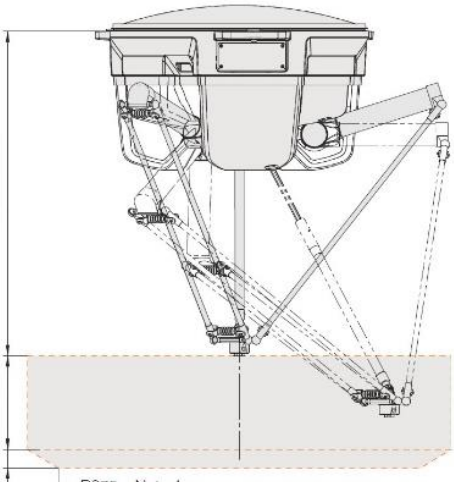


Figure 2-7: Delta robot IRB360 from ABB [78].

These companies specialize in industrial robots, meaning robot arms, delta/parallel robots (Figure 2-7) or linear axis robots. The robots are created for many different operations, such as welding, assembly, machining, packaging, transferring objects and painting. Payload capabilities range from 0.5 to 800kg, and size and reach usually increase with higher payload capabilities [73-77]. The end effector decides what the robot can do, and a robotic arm can often use a wide range of end effectors. An example is the *KUKA KR 1000 titan*, which can do palletizing, packaging, plastics processing, handling metal die casting machines, cutting, fastening, assembly/disassembly, coating, machining, waterjet cutting, measuring and inspecting, welding, mounting, laser cutting and more by changing the end effector [79].

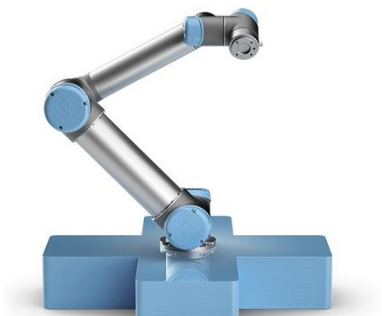


Figure 2-8: UR3 robot arm from Universal Robotics [80].

An interesting new contender in the robot arm market that already has a wide array of end effectors is Universal Robots. They are a Danish start up that is only a few years old, but already making headway into the international market. They offer cheap robotic arms that are very easy to program, the UR3 model is shown in Figure 2-8. In that way the robot can be integrated everywhere, and not only in an industrial setting with a dedicated programming team [80]. The robotic market is continually moving forward in new and exciting directions, and a quick look at what start-ups and large companies are presenting in robotics right now at large expos like CES was done. The automotive industry and smart helpers for the home are the main industries where computer augmentation and robotics is being implemented. These smart helpers are unable to interact with their environment, and work more akin to a smart phone helper like Siri [81].

2.6 Competing solutions

As shown in the chapter above, the industrial robots are an indirect competitor to the robotic hand market, and will therefore be omitted here. 38 competing solutions have been placed in a table showing their different characteristics; actuation type, weight, number of joints and degrees of control, sensors used, dimensions, transmission, speed and forces are all compared. Price is omitted as a factor since nearly every project is a scientific research project, with only the Brunel Hand being sold for an upfront price at £1.500. Every other hand that is commercially available only gives price upon contact.

The table below shows averaged values of the 38 hands that have been compared. The table is an extended version of table 3 from [22] and can be found in its entirety in appendix I. *Table of hands*.

Table 2-3: A table showing the average characteristics of 38 different robotic hands.

Characteristics	Average
Fingers	3 or 5
Degrees of freedom	Between 14 and 15
Degrees of control	Around 10
Number of actuators	Around 12
Type of actuator	(Remote) DC motors
Transmission type	Tendons, pulleys and sheaths
Position sensors	Encoders
Force /torque sensors	No consensus. Usually torque or tendon tensions sensors. Dependant on hand design.
Contact sensors	No consensus. Theory suggest tactile sensors are what will be most common.
Weight	Around 1.4kg
Force created	Around 60 N
Speed	Around 0.64s to lock/close the grasp of the hand.
Purpose	Prosthetics

From Table 2-3 the average robotic hand characteristics can be seen. As previously stated, the DOF and DOC requires reduction to make the hand controllable and possible to create within the constraints set by the human hand. The average ended up being around 15 DOFs and 10 DOCs. An interesting observation is that the average number of actuators is higher than the DOCs, hinting at the fact that some hands have redundancy in controlling the hand. The other characteristics are also interesting, but give less useful information. All sensors are very dependent on hand design, e.g. tendon tension sensors can only be used on hands using cables. The total weight often includes an arm harness in prosthetics, and the hands where weight was without actuators have been removed. Force measurement methods varied slightly for the different hands and does not necessarily correlate with grip force or payload capabilities. The speed characteristic is sometimes theoretical from the maximum motor movement and not from testing.

2.7 Limiting design factor

According to this thesis' theory, a difficult aspect when creating an anthropomorphic hand is replicating human hand functions in a very constrained space. Especially recreating the muscle complexity and tendon interactions when trying to create a design that will fit within the human hands size constraints without using any motors in the forearm.

Motors are limiting due to it being hard to find a motor with the correct torque and characteristics at a reasonable price for the hand. Since the hand is stated to be modular, the motors must be small enough to fit into a normal human palm. With smaller motors comes even more limiting torque and force constraints, which affects transmission choice as well.

The transmission system determines what characteristics the hand has. A mechanical transmission creates a stiff hand, while tendons can create compliance and passive joints. Certain transmission systems are more optimal with certain motor types. For example, a gear transmission system usually works best with a rotary motor. Since the transmission system can gear the motor output up or down between the thumb and the motor, the transmission is the limiting design factor for finding a motor. This means that a designed transmission system is required before installing the motor, which is why the transmission is the limiting design factor.

3 METHOD

In this chapter the methods used in this report will be reviewed and explained, including methods for finding optimal solutions and how to ensure that the problem statements are answered.

3.1 Methods and tools

These are the methods and tools used in this report to find the optimal solutions.

Integrated product development (IPD)

IPD is a product development method which aims to do the right things at the right time in a coordinated development cycle, and ensuring that important aspects are remembered throughout the development process [82]. The IPD methodology is presented in the figure below.

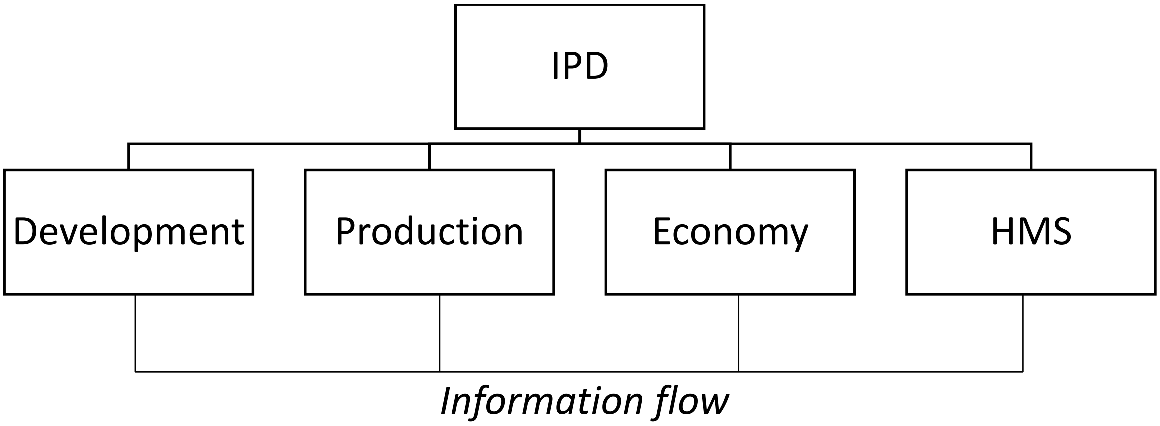


Figure 3-1: Main elements in the IPD methodology.

Where IPD diverges from other product development methods is that it functions from end to start. Instead of creating a product and then finding a market, IPD aims to uncover the requirements, costumer wishes and market before the product is created. When the requirements are found, specifications can be set, and integrated along with the costumers to find the correct price already in the development stage. Because of this, development becomes interdisciplinary and encompasses economical, psychological, environmental and safety factors as well as the engineering issues [83, 84].

Pughs method

Pughs method is a selection tool for objectively finding the optimal solution, commonly called the decision-matrix methodology. The different solutions can score -1, 0 or 1, where -1 means this solution has a negative impact, 0 is neutral, and 1 is positive. Using weighted criteria on a scale total to e.g. 100%, the solutions will get a score for each criterion set. From these scores each solution will get a result total, and the one with the highest total is the most suited solution. The criteria will be chosen directly from importance in the theory, and will be weighed according to the most important aspects for the costumer, and therefore the product goals [85, 86].

3.2 Quality assurance

To ensure that both the product and the thesis is correct, these different standards in the table below will be adhered to and used in the product creation, both indirectly and directly.

Table 3-1: Standards used in the thesis.

Standard	Reference	Description
IEC 60529 NEK EN 60529:1991	[87] [88]	Standardised protection rating for dust and water ingress in electronic equipment.
ISO 128	[89]	Technical drawings
ISO 9000	[90]	Guidelines for quality assurance in production and assembly.
ISO 13482	[91]	Safety demands for personal helper robots
ISO 8373	[92]	Standardized terms in robotics.
Eurocode 3	[93]	Construction and strength calculations

Following these standards assure that everything in the thesis is done correctly, and the standards probably encompasses the certifications needed if the design will be mass-produced.

4 PRODUCT SPECIFICATION

In this chapter the specifications needed to design the hand will be set. These specifications will be based on what Halodi has expressed as their interest, what the theory states and what is achievable within the time frame set for the project.

4.1 Product goals

Main product goal:

- Develop a simple and robust robotic thumb with at least one backdrivable joint, capable of a 15 N minimum grip strength.

Other product goals:

- Simple and inexpensive design with low-cost components.
- Design must fit within the human hands relative size.
- Minimize weight.
- Minimize friction.
- Minimize backlash.
- Create the possibility of robust prehensile grips.

Through achieving these goals, a viable solution for a robotic thumb should be found. The thumb will use backdrivability for safe use with humans, while still being small, strong and robust enough to rival current solutions. Designing for robotics will be the focus area at first, and if the design works well, looking at incorporation with current prosthetics can also become a possibility.

4.2 Rating product requirements

Externally tested product requirements

A questionnaire was done during the subject TIP300 at NMBU, where the subject chosen was designing a robotic hand. Three employees at Halodi Robotics (Phong, Elling and Przemyslaw) were told to range the different features in the table below according to importance. The most important was rated 1, and the least important was rated 8. Questionnaire with answers can be found in appendix VII. *External testing done in TIP300*.

Table 4-1: Table showing feedback on importance from selected Halodi Robotics employees on eight selected features. A good (low) score is green and a bad (high) score is red.

Feature	Phong	Elling	Przemyslaw	Sum
An IP67-rating. This means that the hand has no dust ingress, and is water-proof down to 1 m.	5	8	8	**21**
Modular.	8	4	2	**14**
Lift a payload of 8 kg or more	1	3	3	**7**
Non-underactuated design	7	6	7	**20**
Low weight	3	2	1	**6**
Cheap	4	1	6	**11**
Quiet	6	4	4	**14**
Back-driveability	2	7	5	**14**

As can be readily seen, the three most important features are low weight, low cost, and that a hand can lift a payload of 8kg or more. Features that should not be focused on is a high IP-rating and non-underactuated designs. The three features scoring 14 need some debate. Certain design calls for backdrivability, and the way the robot is designed right now, the hand must be modular. The hand should be as quiet as possible, but it is no deal breaker if this is unachievable.

Rating product features:

A selection of the most important product requirements is shown in table Table 4-3. These criteria are based on literature and theory, as well as requirements set by Halodi robotics. The different features are rated on a scale from 1 to 7 and explained in Table 4-2.

Table 4-2: Rating critera

Rating	Meaning
1	Unwanted feature
2	Of very little importance
3	Less important
4	Positive addition, but not necessary.
5	Add if possible
6	Wanted feature
7	Must have feature

Table 4-3: Importance of different product requirements

Product features	Importance
Functions	
Prehensile grips	7
Individual control of thumb, index and middle finger	7
Low weight	7
Payload of 8kg	7
Non-prehensile grips	2
Backdrivable fingers	1
Backdrivable thumb	7
Finger sensing	5
In-hand manipulation	4
Low friction	4
Design	
Human form factor with robotic looks	6
Aesthetically pleasing design	4
Simple service	3
Robustness	6
Modularity	7
Economics	
Cheap	7
Environmentally friendly	4
Produced in Norway	2
Safety	
Safe for use with humans	5

This table above includes some criteria set by Halodi, such as individual control of thumb, index and middle finger is irrelevant in this thesis. The purpose of this statement is that the thumb design should be independent of the other fingers design. Other than that, the most important aspects are weight, price and a thumb with the desired functions.

4.3 Metric product requirements

Here the product requirements set in the chapter above are translated into metric quantities. Metric product requirements are quantifiable, which makes testing and ensuring that the correct components are chosen much easier. Metric requirements can be seen in the table below.

Table 4-4: General hand requirements.

Requirements	SI	Min	Optimal	Max
Grasp force	N	15	80	120
Payload	kg	3	8	15
Impact strength (23°C)	kJ/m^2	5	50	>70
Weight	g	200	500	1000
Compliance	°	0	45	90
Backdriveable joints	#	0	1-2	9
Prod. price per hand	Kr	500	1000	1500
Fingers	#	3	5	5
Noise level	db	0	> 30	50 <
IP-rating	-	00	67	77
Motor strength; Thumb	Nmm	20	120	>200

In the table above the different requirements have been quantified. Some of the max values could be removed, as well as some of the minimal requirements, some are also irrelevant for the thumb. The table serve as guidelines for where to start and to see what can be excluded at a glance.

Table 4-5: Size requirements for the hand [94].

Size requirements [mm]	Min	Optimal	Max
Size in x-direction			
Fingers	50	78	100
Thumb	40	54	100
Palm	50	97	120
Size in y-direction			
Fingers	15	18	30
Thumb	20	28	40
Palm	80	91	110
Size in z-direction			
Fingers	15	17	30
Thumb	15	18	30
Palm	40	51	80

The measurements shown in the table above is taken from an average human female, since the robots name is Eve. The directions are shown in Figure 4-1. Using measurements that are 10 to 20% larger will most likely work well since it is still within the relative human hand size. However, these gives an estimate on the transmission system, motor and other components size. Following the exact human hands form factor is optional, but a rounded design is both safer and more in tune with how the robot is designed and should therefore be strived for. Albeit, retaining a mechanical appearance is important, as a too human-like look can provoke the uncanny valley feeling.

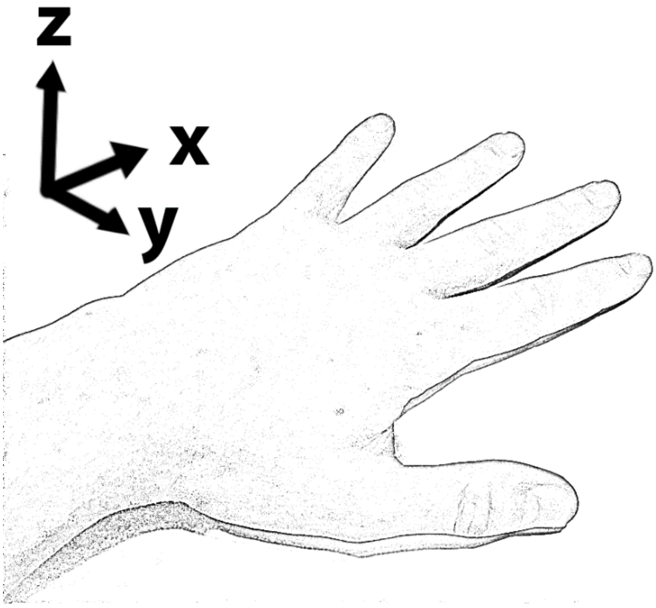


Figure 4-1: Illustration showing the x, y, z-axes used in: "Table 4-5: Size requirements for the hand [94]"

4.4 Preliminary force calculations

The thumb must have the ability to handle large static forces and many small dynamic forces in one day. One component especially at risk is the cable connecting the motor and thumb. The robot can lift a maximal payload of 8kg. These forces may all act upon the thumb, but using the maximum grip force set in the product goal at 15 N is a more reasonable start. To find some preliminary forces acting upon the cable, a cable with a 1mm diameter is assumed. Also, assuming that forces act directly upon the cable:

$$A_{cable} = \frac{\pi d^2}{4} = \frac{\pi * 1^2}{4} = 0.785\ mm^2 \tag{1}$$

$$\sigma_{cable} = \frac{F_{cable}}{A_{cable}} = \frac{15\ N}{0.785\ mm^2} = 19.1\ MPa \tag{2}$$

A 19.1 MPa load should pose no problem even for a small cable, but in the thumb, there will be a lever creating twisting motions and a force multiplication. Assuming the thumb will be 60mm long with a 20mm joint, and a 15 N force acting upon the utmost thumb location. A simplified illustration shows this scenario in Figure 4-2.

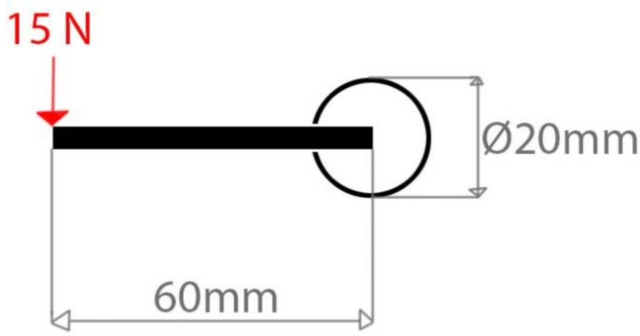


Figure 4-2: Illustration showing size and where the forces act upon the thumb.

$$M_{thumb} = F * l_{thumb} = 15\ N * 60mm = 900\ Nmm \tag{3}$$

Examining shear forces in the joint:

$$W_{thumb} = \frac{\pi}{32} * d^3 = \frac{\pi}{32} * (20mm)^3 = 785.4\ mm^3 \tag{4}$$

$$\tau_{joint} = \frac{M_{thumb}}{W_{thumb}} = \frac{900\ Nmm}{785.4\ mm^3} = 1.15\ MPa \tag{5}$$

The joint will have no problems holding the load with an applied torque of 1.15 MPa in the joint.

Assuming the cable must hold the entire load created from the momentum will result in large stresses within the cable. Using the same joint diameter gives:

$$F_{cable\ at\ joint} = \frac{M_{thumb}}{r_{thumb\ joint}} = \frac{900\ Nmm}{10\ mm} = 90\ N \tag{6}$$

$$\sigma_{cable\ thumb\ joint} = \frac{F_{cable\ at\ joint}}{A_{cable}} = \frac{90\ N}{0.785\ mm^2} = 114.65\ MPa \tag{1}$$

The stresses in the cable will be great, and a sturdy cable should be selected. 114.65 MPa means that the minimum young's modulus for cables in the chapter 4.5 *Early material considerations* should be set at around 200 MPa.

Using the momentum calculation, how powerful the motor driving the cables should be can be found. Assuming a maximal gearing ratio of 30:1, the theoretical maximum ratio for a backdrivable capstan mechanism [95].

$$M_{motor} = \frac{M}{i} = \frac{900\ Nmm}{30} = 30\ Nmm \tag{7}$$

Assuming the full 8kg load acting upon the thumbs end creates the need for a more powerful motor. This can be an inefficient working load, but the thumb must support forces up to this threshold.

$$M_{thumb} = F * l_{thumb} = (8\ kg * 9.81) * 60 = 4708.8\ Nmm \tag{3}$$

$$M_{thumb\ motor} = \frac{M}{i} = \frac{4708.8\ Nmm}{30} = 157\ Nmm \tag{7}$$

This is a rather powerful motor if not geared, and finding something that will work well while still producing this much torque can be difficult. For the hand to handle all these high loads, the correct material must be chosen as well.

4.5 Early material considerations

Choosing the right material is highly important for the final product, and less important for a prototype. Maximising strength and stiffness to price can make a large difference in end consumer price, and different materials call for different designs. A material that can be (injection) moulded can be used as an exoskeleton, whereas something that can only be machined should have parts that are as simple as possible. Something that can be cast, like steel, also requires relatively simple parts.

Materials for the thumb:

To find materials that may be suitable, a rough material requirements outline is set in CES EduPack 2017. How the materials may be processed is omitted in this first check.

- A maximum price of 5000 NOK/kg
- A maximum density of 5000 kg/m^3
- A minimum Youngs modulus of 200 MPa
- A minimum fracture toughness of 5 $MPa\sqrt{m}$
- A minimum melting point of 60 °C
- The materials must at least endure fresh water, weak acids and UV radiation tolerably.

The materials were then placed in a graph as shown below, where the y-direction shows specific stiffness and the x-direction shows price in NOK/kg material.

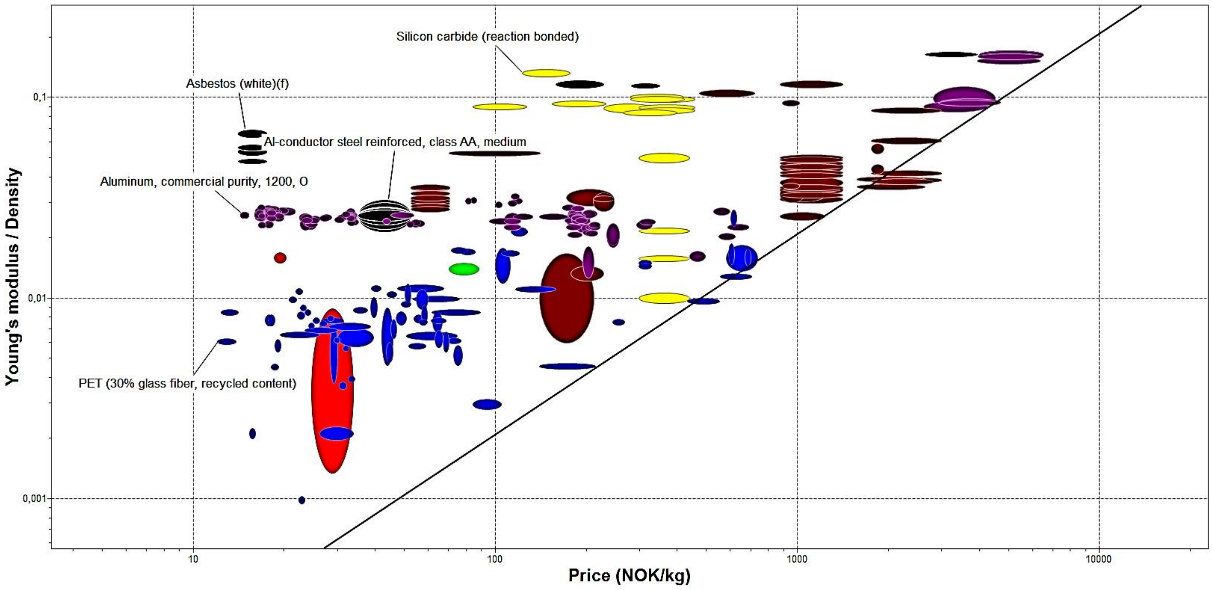


Figure 4-3: Specific stiffness to price, with given conditions. The line has a slope of 1, and eliminates the less interesting alternatives that show a lower specific stiffness and a higher price.

A wide variety of different material families made it through the selection as can be seen in the figure above. There are metals and alloys, plastics, elastomers, technical ceramics, composites as well as fibres and particulates. Asbestos was the material that had the highest specific stiffness to price, but can not be used due to health reasons. Slightly below that is a large aluminium alloy grouping, and below that is different plastic alloys, example shown is PET with 30% glass fibres.

Very little material is needed for the thumb (and hand). The different components used will probably be the highest contributor to a heavier thumb and hand. That means higher prices can be researched if these materials turn out unsuited. The robot will most likely never be in contact with water, and therefore using metals with different galvanic potential will also pose no issue. Since different galvanic potential is no problem, if one part is subject to large stresses it can easily be exchanged to a stronger material.

Cables:

To use cables, they need to possess certain stiffness properties, including certain strength and elongation properties. Different cables have dissimilar properties and must be used differently. Certain cables are too stiff to bend around tight corners, and will therefore wear out very quickly from a too high bending radius. The thumb and hand will pose these problems due to the small enclosure and therefore the cable requirements below have been set.

Cable requirements:

- Low minimum bending radius
- Little to no elongation
- High strength
- Low weight
- Small diameter
- Max price of 10 000 NOK/kg

Doing a test with these requirements on wires, fibres and particulates in CES EduPack gives the following results presented in the figure below:

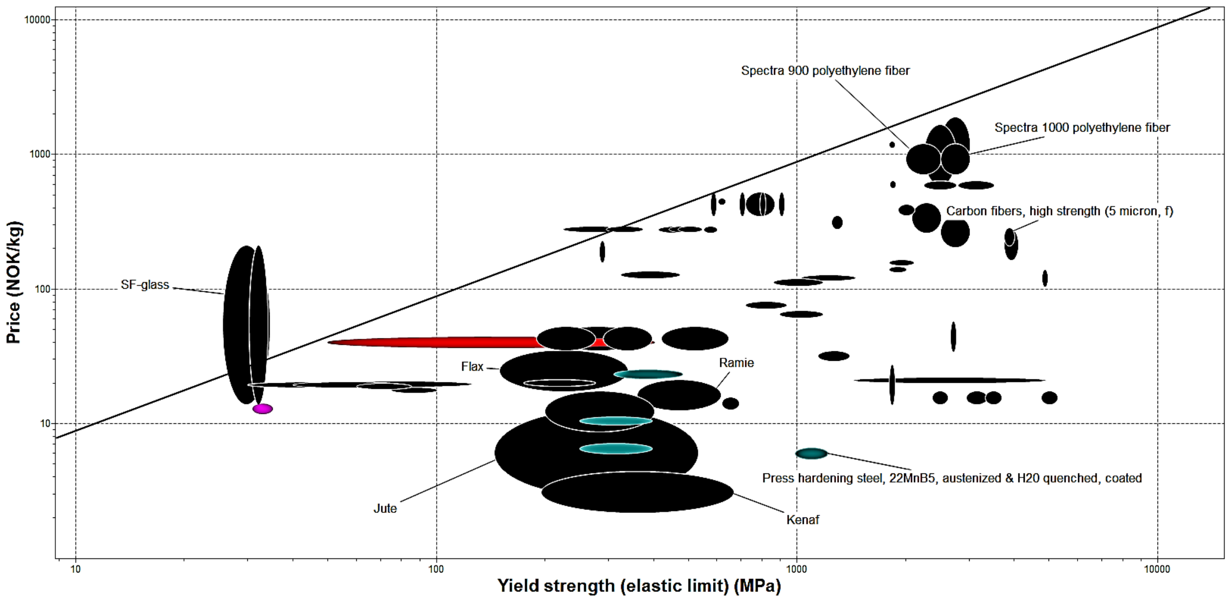


Figure 4-4: A table showing possible cables with price in NOK per kg on the y-axis and yield strength in MPa on the x-axis. Line with slope of 1 eliminates less interesting options.

Another test was done to check elongation, and is presented below.

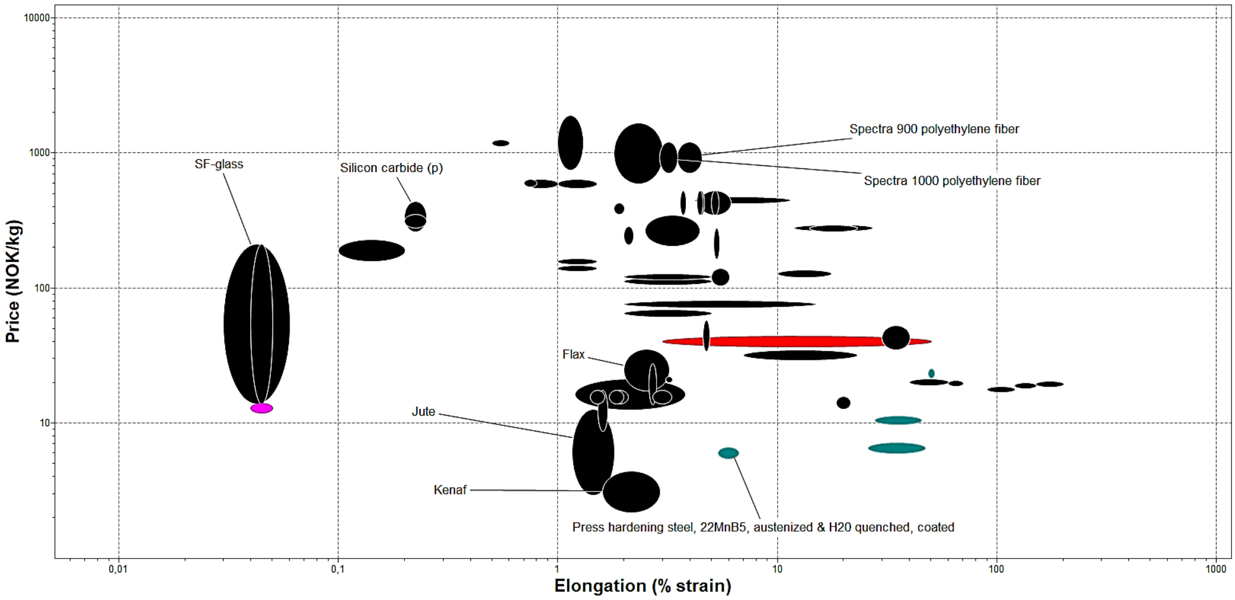


Figure 4-5: A table showing possible cables with price in NOK per kg on the x-axis and elongation in % strain on the x-axis.

An interesting find is the Spectra material. This is a fibre that has been developed by Dyneema and is used in braided fishing lines. The major benefit of these fishing lines are that they have basically no elongation at all, and that they can take a large strain. A braided fishing line can also be bent with almost no minimum bending radius [96].

If only wires are checked in CES; Kevlar 149 aramid fibre is the clear winner.

5 Function specifications

In this chapter different functions for the robotic thumb will be presented, along with the mechanical solution for these functions. A simple function analysis will be undertaken so the function alternatives can be linked to a specified task.

5.1 Function analysis

This function analysis assumes two actuators, a thumb with one joint and a trapeziometacarpal joint for positioning. The thumb joint uses a cable that only works in the pull direction and needs a spring to return to its original position. A function analysis on how to achieve prehensile grips is presented in the figure below.

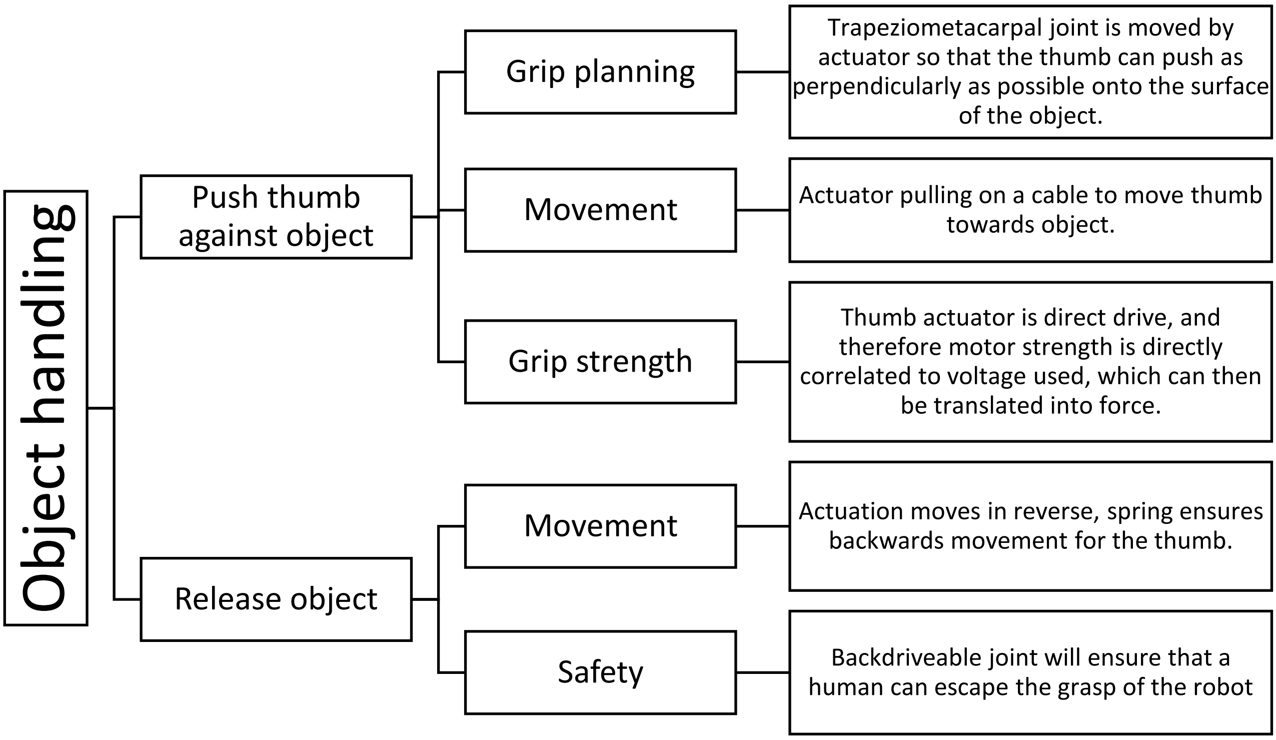


Figure 5-1: A small function analysis for how a robotic thumb will achieve prehensile grips.

The figure above shows the basic functions the thumb needs to encompass for handling objects. Varying slightly depending on design. Most functions here are self-explanatory, and what will be most difficult to implement is proper grip planning and making the backdrivability work effortlessly so the safety factor can be fulfilled. Proper grip planning is dependent on several external factors. Two are sensors in the hand and visual guidance. Visual guidance will be crucial for a well-functioning grip planning. This way an object can be placed correctly inside the palm before any gripping is done.

5.2 Function alternatives with sketches

The different functions and possible solutions that can be used in a hand is presented below. The table explains how the different solutions work, along with their positive and negative aspects in reference to the theory. Some pros and cons are linked to specific solutions or specific requirements which is usually specified.

Table 5-1: A table showing different function alternatives with descriptions along with positive and negative aspects

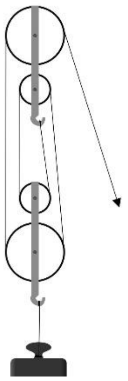
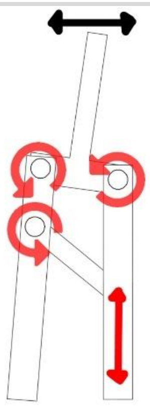
		Illustration	Description	Pros and cons
Transmission	**Tendons w/sheaths**	 *Figure 5-2: Cable routed through a sheath.*	Cables routed through sheaths.	+ Motor remote from joint + Simple and cheap solution + Easy cable routing + Low weight + Little backlash + Low inertia + Very small system - Creates friction and therefore non-linearity in controls - Not very reliable - Not stiff - No gearing in transmission system
	Tendons with pulleys	 *Figure 5-3: Cables with pulley example.*	Cables or belts routed using pulleys and bearings.	+ Motor remote from joint + Low weight + Little backlash + Very low inertia + Small system + Very low friction + Can include gearing in transmission - Not very reliable or robust - Can induce slippage - More expensive than sheaths
	Linkages	 *Figure 5-4: Linkages. Example is an adjustable lock plier.*	Direct linkage between joints using for example a lever arm.	+ High stiffness + Reliable + Works in two directions, can push and pull - Heavy - Large - Possibly large backlash - High inertia - High friction - Gearing ratio limited by possible mechanism length

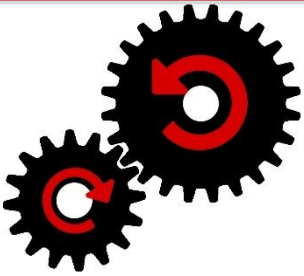
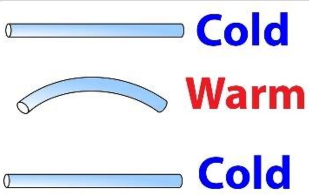
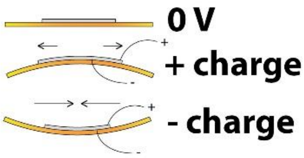
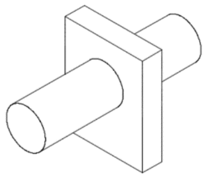
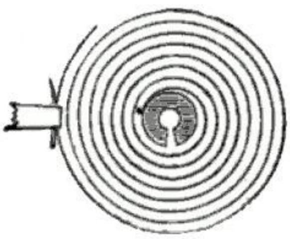
		Illustration	Description	Pros and cons
Transmission	Gears	 *Figure 5-5: Gears*	Direct connection between motor and joint using gears.	+ High stiffness + Low friction + Very reliable + Can push and pull + Can achieve very high gearing ratio in a small space - Heavy - Large - Moderate backlash amount - High inertia - Induce non-linearity and hysteresis in control systems
	Combination		Using different systems in combination to achieve the wanted system. e.g. gears and pulleys Linkages and pulleys	+ Can create new possibilities + May allow for movement over edges - Increases complexity and cost - More can go wrong - More components
Actuation	Linear actuator	 *Figure 5-6: Picture of a linear actuator which converts rotation movement to linear motion.*	A linear actuator moves a rod forwards and backwards, allowing for movement using direct linkages or a tendon pulling the fingers down.	+ High possible gearing ratio + Can take a heavy payload + Small + Can be driven from a DC-current, using solenoid magnets or through pneumatics or hydraulics - Expensive - Not direct drive - Power measurement needs extra sensor
	Rotating DC motor	 *Figure 5-7: Hitec HS-55 rotating DC servo.*	A rotating servo that can pull a cable or drive a belt	+ High possible gearing ratio + Can take a heavy payload + Small + Can be direct drive and measure force directly + Good efficiency + Inexpensive - Very high RPM if direct drive, needs a geared transmission - Low torque unless geared
	SMA	 *Figure 5-8: Shape memory alloy. Modified from* ***[97].***	A shape memory alloy that can pull or push on a joint. It may even be the hands structure, or placed directly in a joint.	+ Very high power to weight ratio + Space efficient - Very low efficiency - Not suited for many quick movements, hindered by thermals - Expensive and not very widespread in use

		Illustration	Description	Pros and cons
Actuation	**Ultrasonic motor**	 *Figure 5-9: Piezo element used in ultrasonic motor. Modified from* ***[98].***	A small "vibrating" element used to create either linear or rotary motion.	+ Can take a large payload + Self-locking + Very high efficiency + Works well with quick start and stop mechanisms + Very accurate movement + No fall in efficiency with smaller size - Expensive - Not widespread use in larger equipment
Joints	**Shaft**	 *Figure 5-10: Illustration of a shaft running through a hole.*	A simple shaft and socket connecting the joints.	+ Non-complex system + Cheap + Very low weight - High friction due to direct contact between materials - Material will deform and may create dust
	Bearings	 *Figure 5-11: Ball bearings example.*	Joints with ball bearings.	+ Low weight + Low friction + Allows large forces to act upon the shaft while still having smooth motion. - Can become expensive, needs to use standard dimensions - Increases complexity
	Flexible material	 *Figure 5-12: 3D-printed finger in SemiFlex material.*	Entire fingers or joints created using a flexible material like rubber.	+ Non-complex system + Can be created in one part + Inherently compliant system + Allows using pull only systems, with material ensuring fingers return to starting position - Material can be expensive - Solid fingers in rubber can become heavy - Increases force needed to move the fingers
	Springs	 *Figure 5-13: "Flat spring" by Fredrick J. Britten (1898).*	Needed when using transmissions systems that can only pull, used in tandem with any other solution.	+ Allows for finger to automatically return to starting position without a motor pushing them + Low weight + Cheap - Increases complexity - Increases force needed to move the fingers

6 TESTING LIMITING DESIGN FACTOR: TRANSMISSION ALTERNATIVES

This chapter aims to solve the process goal of finding the optimal transmission for a backdrivable thumb. Simple prototypes for transmission systems for the thumb will be created, referencing chapter 2.7 *Limiting design factor* for why testing on transmission systems are done first. Something that works well in theory, does not always transfer to a feasible solution.

These are the two most important goals to find in this testing:

- Is the transmission backdrivable?
- Can the transmission transfer the necessary amount of force?

Other goals are finding out:

- How much slack and possible backlash will there be in the systems?
- How much friction will there be in the system?

6.1 Transmission alternatives

In this chapter the different transmission alternatives are presented in the table below.

Table 6-1: Table explaining the different transmission alternatives.

Transmission alternatives

Figure 6-1: Prototype with tendons using idle pulleys with gearing inlaid in the palm.

Tendons with idle pulleys and gearing in the palm:
The above picture shows the assembled tendon driven transmission prototype. Hemp was used as cable and wound around three pulleys made in a 2:1 scale. All the parts were created by laser cutting 6mm MDF sheets and gluing them together. The pulleys were then fastened to a 9mm MDF plate using M10 bolts and nuts.

Transmission alternatives

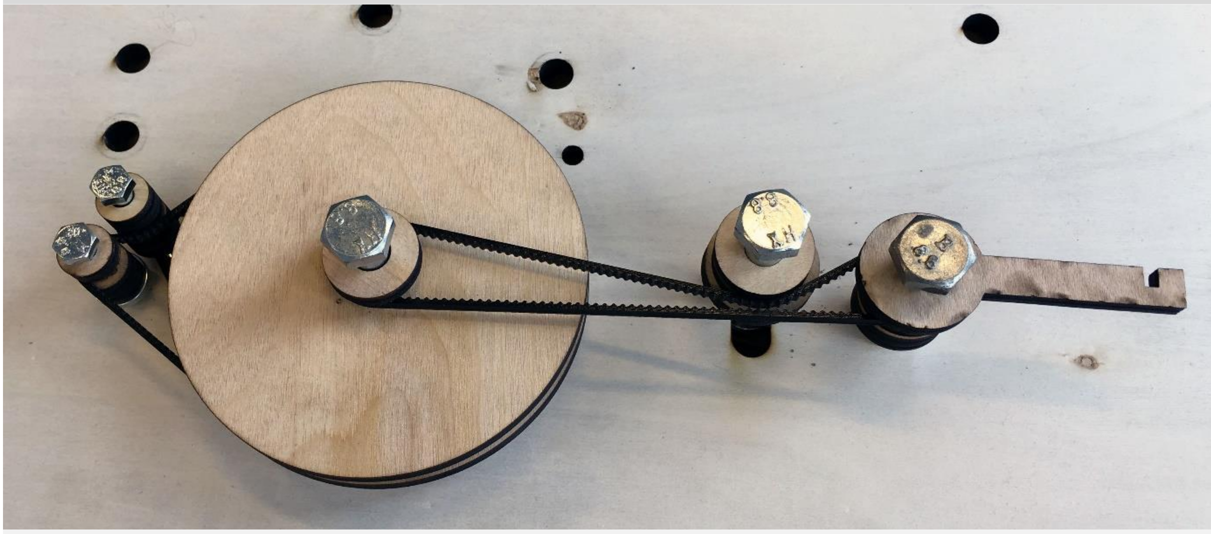


Figure 6-2: Prototype using timing belts with idle pulleys and inlaid gearing in the palm.

Timing belts with idle pulleys and gearing in the palm:
The picture above shows the assembled prototype using timing belts as tendons. Every component is as large as they would be in the hand. The belts and pulleys use the GT2-standard for teeth design. All the parts were laser cut using 6mm MDF sheets and glued together. The timing belts were 3D-printed on a FlashForge Guider 2 using the material SemiFlex. A primitive cable tensioning system was also created by cutting slots into the underlying MDF plate, allowing a freely rotating pulley to tighten the slack.

Figure 6-3: Prototype for linkages using design from adjustable lock pliers.

Adjustable lock pliers used as linkages:
This design is based on adjustable lock pliers, and is a possible solution using direct linkages. All the parts were laser cut using 6mm MDF sheets and the assembly is held together using M6 screws and nuts. Washers are placed between the screws, nuts and MDF sheets to allow for movement without turning the screws and nuts loose.
The design is scaled up to twice the size, except the thumb which is to scale. This means that the gearing ratio will be half of what is measured.

Transmission alternatives

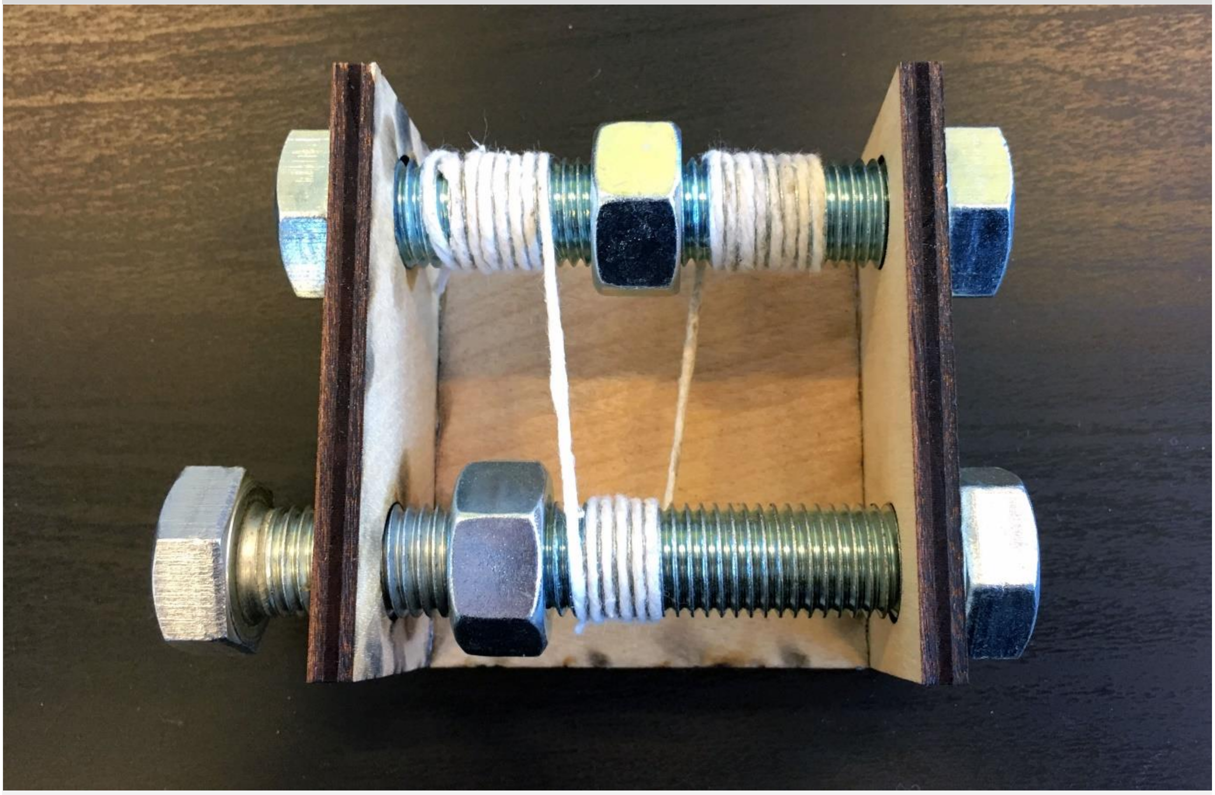
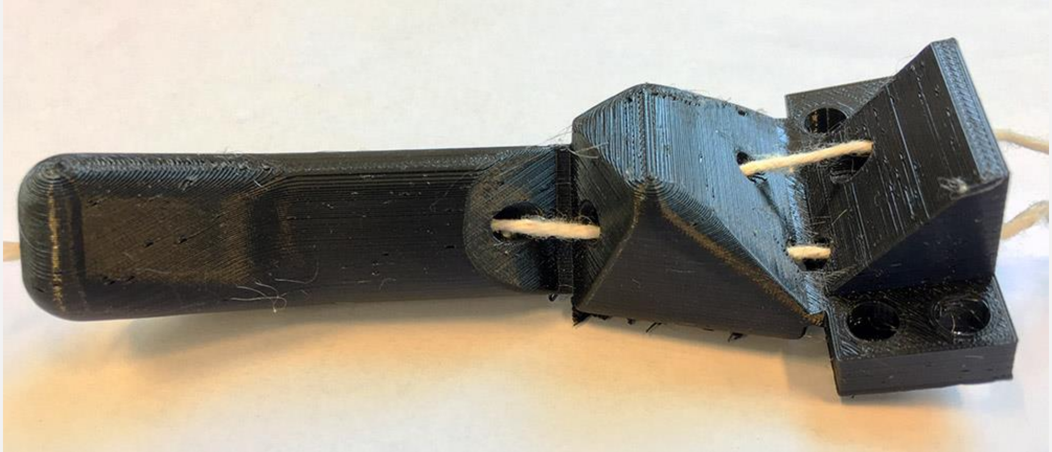
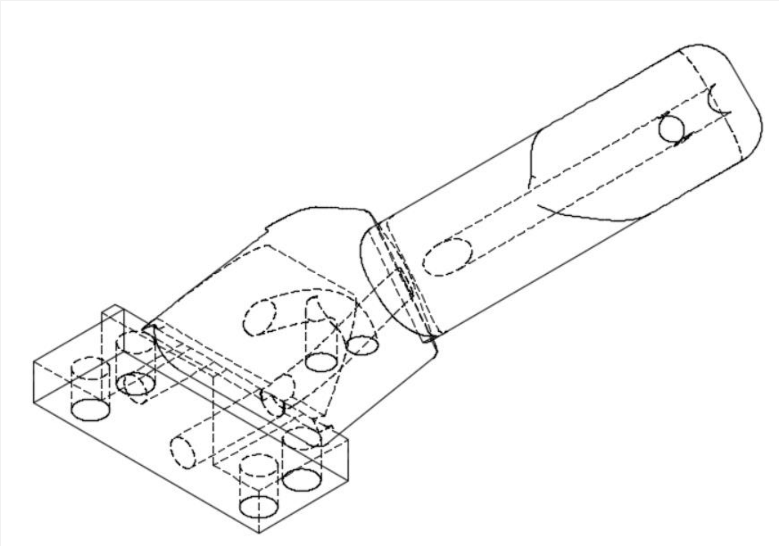


Figure 6-4: Prototype for oppositely threaded screw-like transmission system.

Oppositely threaded screw-like transmission prototype:
This prototype uses threaded shafts, allowing the cable to wind up and down on a shaft during movement. Since the cable follows the threads it won't travel too far and put pressure on components it is not supposed to. In this prototype four M16 screws were used. They were connected using a nut, and a base to hold everything was laser cut using 6mm MDF sheets. Hemp was used as cable.

Transmission alternatives
 *Figure 6-5: 3D-printed prototype for testing tendons running through sheaths.*  *Figure 6-6: Drawing of prototype showing the routing for the tendons. The stippled lines are hidden lines.*
Tendons with sheaths using flexible filament: This prototype has no gearing and was made to test how well using tendons with sheaths may work. The thumb has two joints, and was printed using a FlashForge Guider 2 with the material SemiFlex. Hemp was used as cable. The metacarpophalangeal joint is rotated 45° degrees.

As can be seen in the table above, 5 different transmission solutions were tested. These are the alternatives that theory suggested would work best in a backdrivable system. Gears are omitted by this reasoning, as theory stated that gears exhibit friction, backlash and a high chance of breaking due to large stress concentrations on the gears teeth.

6.2 Testing

Tested aspects:

- Backdrivability (y/n): The system was tested to see if it works in both directions.
- Force transferred (kg): How much force could be transferred from input to output before problems started to arise. Optimal is 8kg.
- Slack (degrees): How many degrees the transmission can be moved without movement on the output axis.
- Friction (kg): How much friction there was in the system.
- Gearing ratio (i): The gearing ratio created by the system.

Table 6-2: Results amassed from transmission testing.

Transmission	Backdrivable	Force	Slack	Friction	Gearing
Tendons	Limited	1.5kg	15°	>0.5kg	10:1
Timing belts	Yes	3.5kg	90°	>0.5kg	10:1
Linkages	Yes	4kg	0°	0.5 kg	2:1
Screws	Yes	Hand	1-2°	Negligible	1:1
Sheaths	Limited	1kg	-15°	Up to 4kg	1:1

The table above show the results amassed during the testing. Timing belts and threaded gears stand out as being able to transfer a decent force amount with little slippage and low friction. All the chosen transmission systems performed worse than anticipated, as explained further in appendix II *Testing limiting design factor: transmission alternatives*.

6.3 Analysis

The transmission systems tested did not work as intended. This was partly due to these being prototypes without proper tensioning systems, and not being made optimally. On the other hand, a sub-optimally created solution working decently is positive when correlated with robustness. A thumb will be used much and roughly, and if it cannot function without completely optimal parameters it is an unsuited fit for the task. This is especially apparent if the system needs to work reliably while being backdrivable.

Nearly all systems worked decently backdrivable. Using tendons with pulleys, slippage occurred frequently when pushing the system from output to input, which granted it a limited score on backdrivability. The timing belt prototype did also start to skip, but to a much lesser degree. The flexible material could not hold a weight larger than 1kg and started to flex backwards, which means it will be unable to transfer a decent force amount.

Forces transferred were much lower than what was desired. Each system should have exhibited a possible force transfer of 8 kg, and a minimum of 15 N, which roughly equals 1.5kg. All systems managed the 1.5 kg minimum, but none got close to the 8kg mark. The linkage transmission could most probably hold 8kg if it was made from something else than wood. The wood started creaking and the bottom slot was visibly bulging from the weight. There are no quantified data on the threaded screw-gears since it was not possible to fit the force measurer into the system, but using as much hand force as possible in opposite directions on the input and output axis posed no problem for the system. The transmission exhibited no signs of slippage either.

Slippage occurred much more frequently and quicker than expected in the transmissions. As mentioned, this is partly due to improper cable tensioning. The timing belts were used without a filament, which allowed the belts to elongate quite a bit. Therefore, the timing belt slack is very large, and using a belt with steel or Kevlar filament will reduce this significantly. This issue was not apparent with linkages or screws. Little to no slippage was expected when using linkages, but there may be larger slippage using threaded gears when a gearings ratio is introduced into the system. Friction also tended to increase with higher gearing ratios.

Friction was much higher in the pulley systems than they would be in real life due to not being fitted with bearings. Alas, the friction became quite large when the cables were tensioned, dragging the pulleys sideways and rendering the entire system bent. Adding tensioners to the timing belt system also increased the friction. Linkages posed large frictions, just as expected. The friction will still be much smaller in a real system where there will not be semi-tightened screws to hold the linkages together. Tightening the screws more rendered the linkages unusable. There was no noticeable friction in the threaded screw-like transmission system, but this was expected due to it not having any gearing ratio. Friction in the sheaths became massive due to the cable rubbing along a sheaths edge, and became excessive when the material started to flex. Total resistance in the material when bended normally seemed to be around 0.5kg, but when the metacarpophalangeal thumb joint was pulled down with enough weight to make the entire thumb flex, resistance up to 4 kg was noted.

6.4 Results

The most suitable solution is using timing belts with idle pulleys and/or threaded screw-like gears. They exhibited backdrivability with the possibility of transferring large forces with little backlash and friction, as well as a decent gearing ratio.

7 CONCEPT SCREENING

In this chapter the concepts for solving different thumb aspects will be tested against each other. By doing this, a final solution can be found. This selection will use a weighted Pughs method as a basis to ensure the best solution according to set product goals is chosen.

7.1 Selection matrix using Pughs method

Pughs method was explained in section 3.1 *Methods and tools*, and this is the matrix that will be used to choose the most viable solution for the thumb. Solutions needed found are:

- Actuation for the thumb
- Transmission for the trapeziometacarpal thumb joint
- Transmission for the metacarpophalangea thumb joint
- Trapeziometacarpal thumb joint type
- Metacarpophalangeal thumb joint type

The solutions will be weighted using differing criteria, since they have different requirements. This will be explained for every solution. A scale to a 100% will be used, where 100% is signified as 1. The criteria will be weighed according to importance found in product goals like in this example below:

Table 7-1: Table explaining how the weighted scores are found.

Function	Grip force	Backdrivability	Low price	Low friction	Sum
Importance	7	7	7	4	25
Weighted score	$\frac{7}{25} = 0{,}28$	$\frac{7}{25} = 0{,}28$	$\frac{7}{25} = 0{,}28$	$\frac{4}{25} = 0{,}16$	1
Score 1	1	1	0	0	-
Result	0,28	0,28	0	0	**0,56**

The calculations for all weighted criteria can be found in appendix VI. *Calculated scores for concept screening*. Score importance can be found in chapter 4.2 *Rating product requirements*.

7.2 Concept screening

In this chapter the solutions mentioned will be tested using Pughs Matrix to find the most suitable solution for the robotic thumb.

7.2.1 Actuation for the thumb

In solving actuation for the thumb, the following criteria are set:

- Backdrivability: Force can be transferred from input to output and vice versa.
- Power-to-weight: The actuator can deliver high power per weight unit.
- Price: Cheaper is better.

Table 7-2: Pughs matrix for actuation in the thumb

	Criteria	Backdriveable	Power to weight	Price	
Concept	**Weight**	**0,3**	**0,35**	**0,35**	**Sum**
Solenoid actuator		0	0	0	0
DC motor		**1**	**0**	**1**	**0,65**
SMA		-1	1	-1	-0,3
Ultrasonic		-1	1	-1	-0,3

Using direct current motors are the best choice for actuation in the thumb, and are selected for both joints to reduce complexity. Different motors could probably be used for optimal results.

7.2.2 Transmission for the trapeziometacarpal thumb joint

For finding the best transmission for the thumb, these criteria were chosen:

- Prehensile: Can achieve prehensile grips, that means a 15N grip force or higher.
- Backdrivability: Force can be transferred from input to output and vice versa.
- Robustness: The system is robust and has a small chance of malfunctioning.
- Low friction: Little power is lost due to friction in the system.
- Small size: The system takes up as little space as possible inside the hand.

Table 7-3: Pughs matrix for transmission for the trapeziometacarpal thumb joint.

	Criteria	Prehensile	Backdriveable	Robustness	Low friction	Small size	
Concept	**Weight**	**0,241**	**0,207**	**0,207**	**0,138**	**0,207**	**Sum**
Tendons w/sheats		1	-1	0	-1	1	0,10
Tendons w/pulleys		0	0	0	1	1	0,34
Timing belts w/pulleys		**1**	**1**	**0**	**0**	**1**	**0,66**
Linkages		1	1	1	-1	-1	0,31
Gears		1	-1	1	-1	-1	-0,10
Screw gear		1	1	0	0	0	0,45

For the trapeziometacarpal thumb joint transmission; timing belts with pulleys were selected. This transmission system can both push and pull, thus creating full joint control.

7.2.3 Transmission for the metacarpophalangeal thumb joint

To uncover the optimal transmission for the thumb, these criteria were set:

- Prehensile: Can achieve prehensile grips, that means a 15N grip force or higher.
- Backdrivability: Force can be transferred from input to output and vice versa.
- Low friction: Little power is lost due to friction in the system.
- Small size: The system takes up as little space as possible inside the hand.
- Allows bending Allows the system to work when the trapeziometacarpal thumb joint bends 90°

Table 7-4: Pughs matrix for transmission for the metacarpophalangeal thumb joint.

	Criteria	Prehensile	Backdriveable	Low friction	Small size	Bending	
Concept	**Weight**	**0,233**	**0,200**	**0,133**	**0,200**	**0,233**	**Sum**
Tendons w/sheats		0,233	-0,200	-0,133	0,200	0,233	0,10
Tendons w/pulleys		0,000	0,000	0,133	0,200	0,000	0,33
Timing belts w/pulley and screw gear		0,233	0,200	0,000	0,200	0,233	**0,63**
Screw gear		0,233	0,200	0,000	0,000	0,233	0,43

Timing belts with pulleys and a threaded screw-like gear was chosen as transmission for the outer thumb joint. This option should allow the trapeziometacarpal joint to operate independently of the metacarpophalangeal joint, and allow the outer joint to function optimally without regard to the trapeziometacarpal joints position.

7.2.4 Trapeziometacarpal thumb joint type

These are the criteria set for finding what the trapeziometacarpal thumb joint type will be:

- Low friction: Little power is lost due to friction in the system.
- Robustness: The system is robust and has a small chance of malfunctioning.
- Low weight: The system adds as little weight as possible.
- Price: Cheaper is better.

Table 7-5: Pughs matrix for choosing the trapeziometacarpal thumb joint type.

	Criteria	**Low friction**	**Robustness**	**Low weight**	**Price**	
Concept	**Weight**	**0,167**	**0,250**	**0,292**	**0,292**	**Sum**
Shaft		-1	-1	1	1	0,000
Bearings		1	1	0	-1	0,167
Flexible material		-1	0	0	0	-0,167
Bushings		1	1	1	-1	**0,333**

Bushings are the best fit for the trapeziometacarpal thumb joint, but since bushings are less common for applications such as these the prototype will most probably use bearings instead.

7.2.5 Metacarpophalangeal thumb joint type

These are the criteria set so the best trapeziometacarpal thumb joint type can be found:

- Low friction: Little power is lost due to friction in the system.
- Creates PaP: Allows a system that can only pull to function as a “Push and Pull” (PaP) by adding the push function.
- Low weight: The system adds as little weight as possible.
- Price: Cheaper is better.

Table 7-6: Pughs matrix for choosing the metacarpophalangeal thumb joint type.

	Criteria	Low friction	Creates PAP	Low weight	Price	
Concept	**Weight**	**0,16**	**0,28**	**0,28**	**0,28**	**Sum**
Shaft		-1	-1	1	1	0,12
Bearings		1	-1	0	-1	-0,4
Flexible material		-1	1	0	0	0,12
Bushings		1	-1	1	-1	-0,12
Bearings with springs		1	1	0	-1	**0,16**

Bearings with springs was the best result for the metacarpophalangeal thumb joint type. This is especially prevalent since a method for offsetting push and pull was needed with a transmission system that could only pull.

7.3 Summary of chosen concepts

List with a summary of chosen solutions.

Table 7-7: Summary of chosen concepts

Solution for	Result
Actuation for the thumb	DC motor
Transmission for the trapeziometacarpal thumb joint	Timing belts w/pulleys
Transmission for the metacarpophalangeal thumb joint	Timing belts w/pulleys and screw gear
Trapeziometacarpal thumb joint type	Bushings
Metacarpophalangeal thumb joint type	Bearings with springs

These solutions are chosen as optimal for creating a robotic thumb prototype. Certain aspects may be changed since some components are difficult to find, and e.g. bearings may be used instead of bushings.

8 PRODUCT ARCHITECTURE AND CONCEPT DESIGN

In this chapter the design for the proof of concept thumb will be explained. Since the thumb proportions are based upon its human counterpart, the thumb will be designed and the tested to see if it is dimensioned for the assigned load cases.

8.1 Materials

Chapter *4.5 Early material considerations* gave some ideas as to what material types should be used for the prototype. Since this will be a proof of concept prototype, materials for the thumb are limited to rapid prototyping materials. For that reason, ABS was chosen as the material for the thumb. Finding the correct cable is a bigger issue. The early material considerations assumed that spectra cable was a possible fit. Since this is what most braided fishing lines use, and fishing line is easily obtainable, spectra will be considered.

Checking CES EduPack 2017, Spectra 1000 polyethylene fibre has a 2900 MPa ultimate tensile strength. This is assumed as max stress allowed on the cable, and a safety factor of 3 will be used. The full 8kg load is tested, and the thumb is 60mm long with a 22mm joint diameter.

$$\sigma_{spectra} = \frac{2900MPa}{Safety\ Factor} = \frac{2900\ MPa}{3} = 966.7\ MPa \tag{8}$$

$$M_{max} = 8\ kg * 9.81\frac{N}{kg} * 60\ mm = 4710\ Nmm \tag{3}$$

$$F_{cable} = \frac{4710\ Nmm}{11\ mm} = 428.2\ N \tag{6}$$

$$\sigma_{spectra} = \frac{F_{cable}}{A_{cable}} = \frac{F_{cable}}{\frac{\pi * d^2}{4}} => \tag{2}$$

$$d = \sqrt{\frac{4 * F_{cable}}{\pi * \sigma_{spectra}}} = \sqrt{\frac{4 * 428.2\ N}{\pi * 966.7\ MPa}} = 0.75\ mm \tag{9}$$

Using the full load, the minimum cable diameter is 0.75mm using only spectra 1000 fibre. If 15 N maximum grip strength is assumed:

$$F_{cable} = \frac{15\ N * 60\ mm}{11\ mm} = 81.81\ N \tag{6}$$

$$d = \sqrt{\frac{4 * 81.81\ N}{\pi * 966.7\ MPa}} = 0.33\ mm \tag{9}$$

With a 15N max load a cable with a 0.33mm minimum thickness can be used. Not adding the safety factor allows a cable with a 0.19mm minimum thickness.

8.2 Structure optimization using FEM

A thumb with a trapeziometacarpal joint was designed in Fusion360 and tested with 3 different load cases. The thumb is based upon the size requirements set in chapter 4.3 *Metric product requirements*, and is approximately the same size as the average female human thumb. The thumb is mounted in a 30°-degree angle on the metacarpal thumb phalange, this also in accordance with how a real thumb appears.

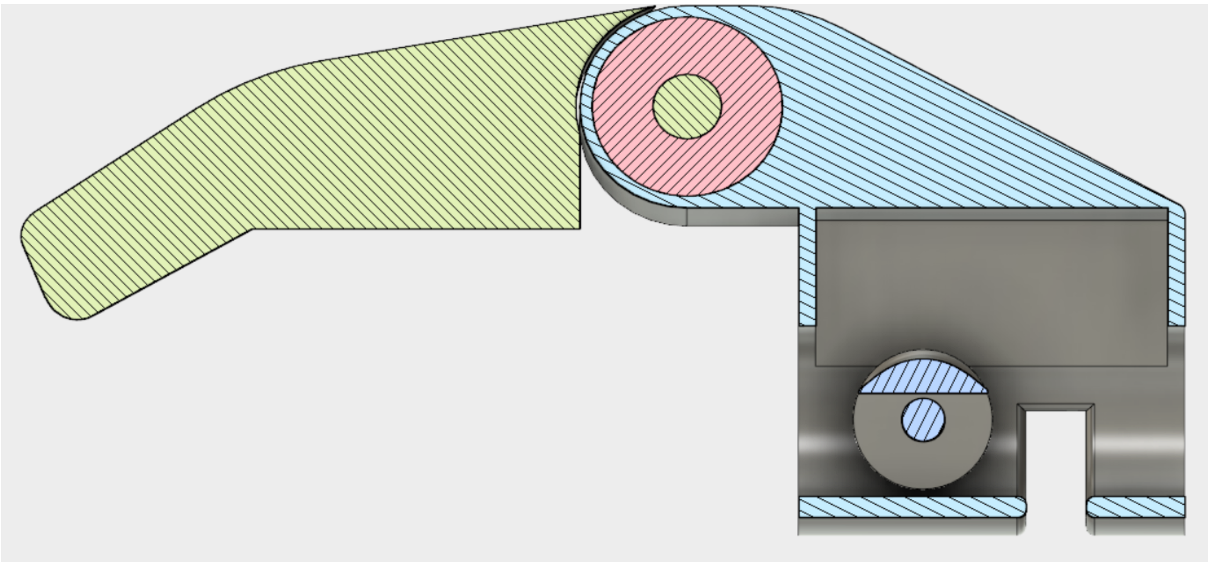


Figure 8-1: A sliced view of the simulation model used. The yellow area is the thumb with the joint connected. The red area is the bearing and the blue area is the entire trapeziometacarpal joint.

In every simulation the thumb and metacarpal link is modelled with the material PC/ABS plastic, and the bearings are modelled using steel. PC/ABS plastic was used since it behaves closer to 3D-printed ABS than the ABS material in fusion which assumes injection moulding. The yield and ultimate tensile strength is slightly higher than real strength, but the FEM testing is only needed to ensure the prototype will hold.

Material	PC/ABS Plastic
Density	3.573E-07 kg / mm^3
Young's Modulus	2780 MPa
Poisson's Ratio	0.4
Yield Strength	54.4 MPa
Ultimate Tensile Strength	54.1 MPa
Thermal Conductivity	2.4E-04 W / (mm C)
Thermal Expansion Coefficient	6.7E-05 / C
Specific Heat	2133 J / (kg C)

Figure 8-2: Material properties for PC/ABS Plastic.

Material	Steel
Density	7.85E-06 kg / mm^3
Young's Modulus	210000 MPa
Poisson's Ratio	0.3
Yield Strength	207 MPa
Ultimate Tensile Strength	345 MPa
Thermal Conductivity	0.056 W / (mm C)
Thermal Expansion Coefficient	1.2E-05 / C
Specific Heat	480 J / (kg C)

Figure 8-3: Material properties for steel.

8.2.1 Load case 1: 8kg payload on the thumbs end

This load case assumes an 8kg payload on the thumbs inside. The model is constrained from motion in all directions.

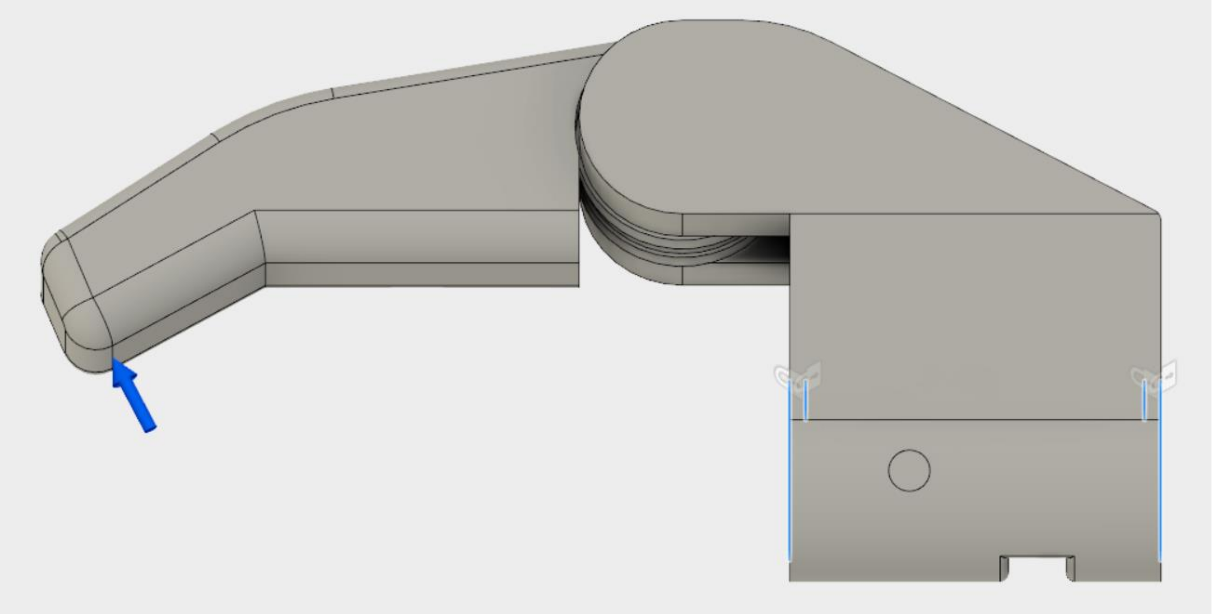


Figure 8-4: Load case 1. The thumb has an 80N load on the outermost part of the thumbs inside. Constraints are shown as blue lines, and constrains for movement in all directions.

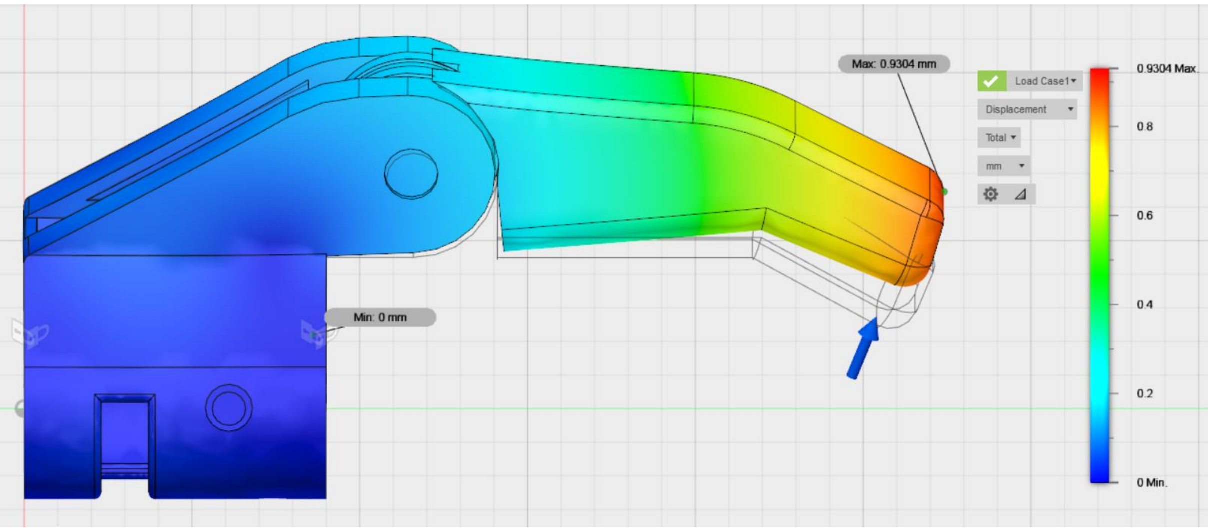


Figure 8-5: Defomation results for load case 1. Max deformation is 0.93mm. Scale from 0 to 0.93 mm. Results are adjusted and looks 5% larger than real deformation.

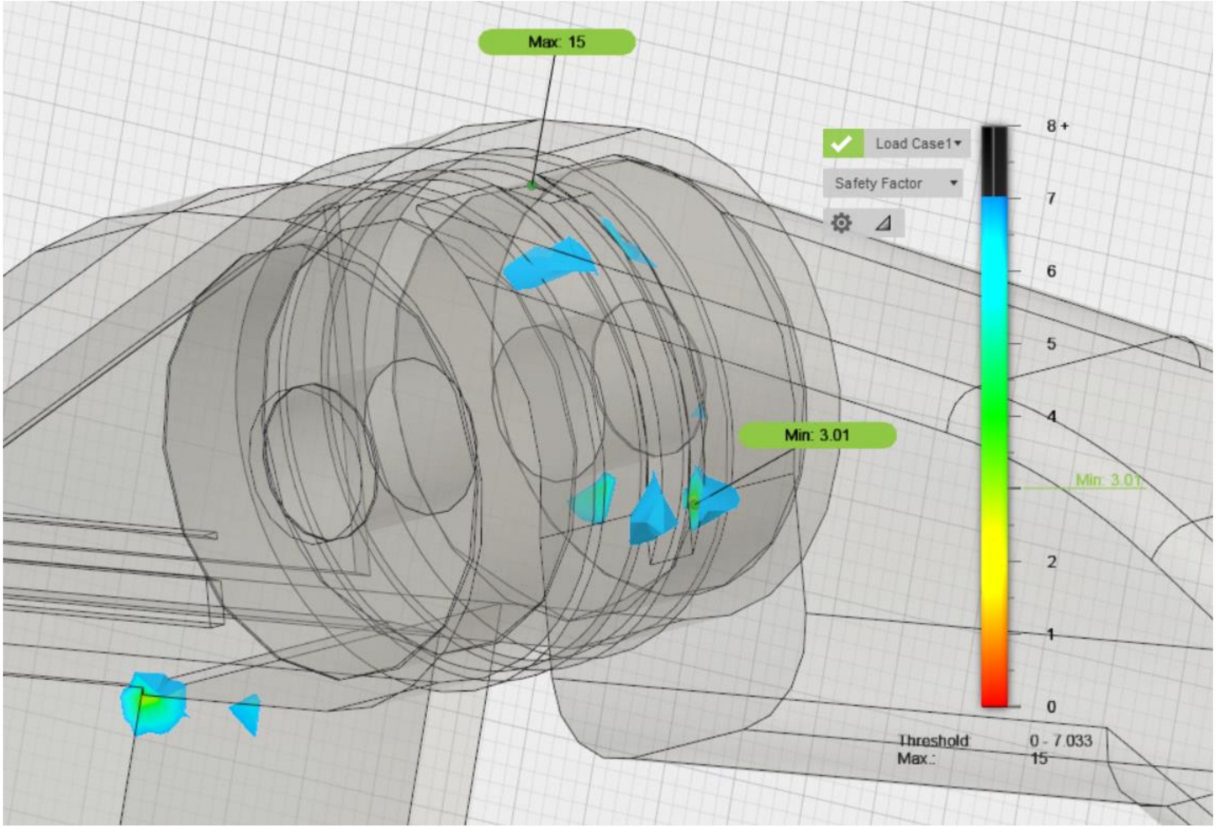


Figure 8-6: Safety factor results for load case 1. Minimal safety factor is 3. Scale is from 0 to 7, which means every part with a safety factor larger than 7 is transparent.

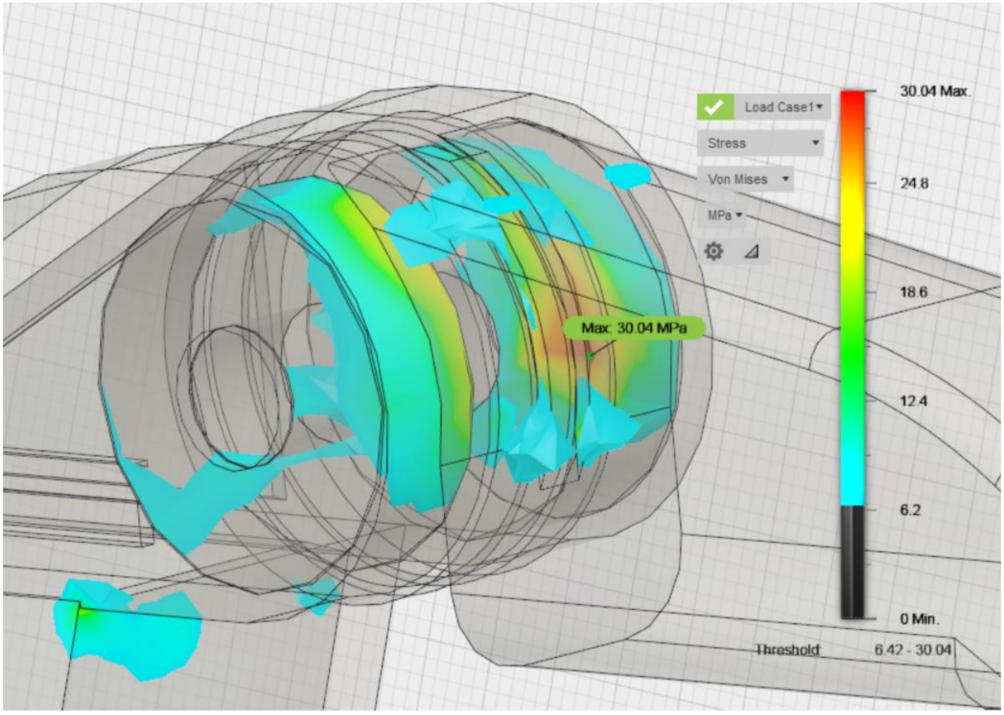


Figure 8-7: Von Mises Stress results for load case 1. Max stress is 30 MPa. Scale is from 6.4 to 30 MPa, which means every load under 6.4 MPa is transparent.

These results show that the thumb can handle the 8kg payload well. With a safety factor of 3, there is no danger of the thumb breaking during normal operations, and there are no excessive deformations.

8.2.2 Load case 2: Reverse 8kg payload on end

This load case assumes an 8kg payload on the thumbs outside and outermost part. The model is constrained from motion in all directions.

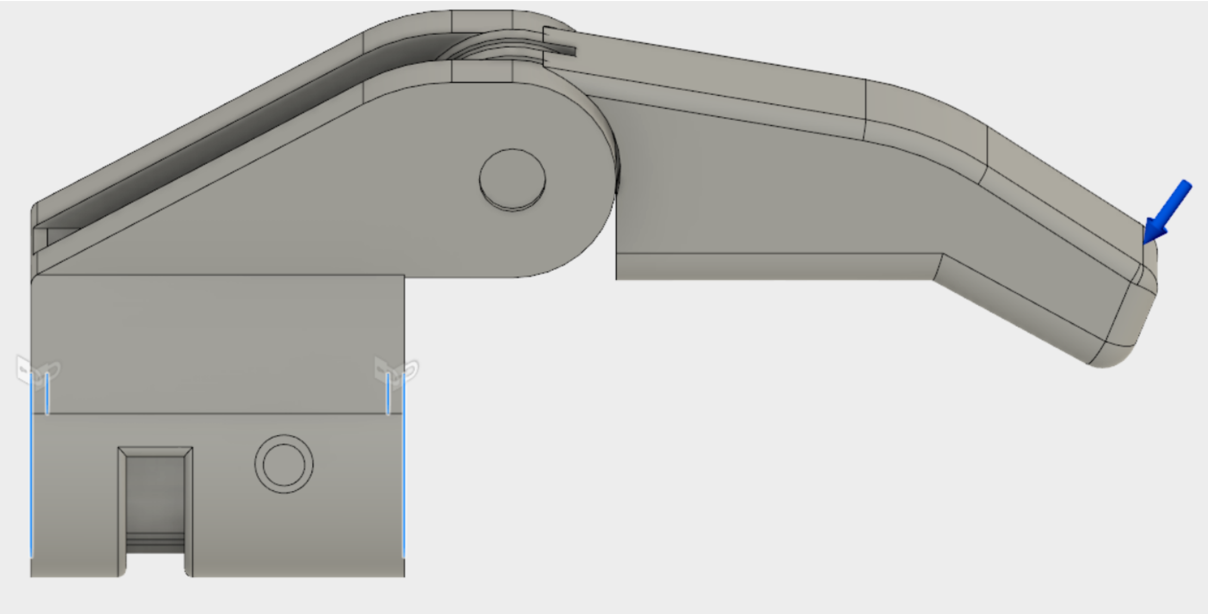


Figure 8-8: Load case 2. 80N is pushing downwards on the thumbs top. Constraints are marked as blue lines, and the model is constrained from movement in all directions.

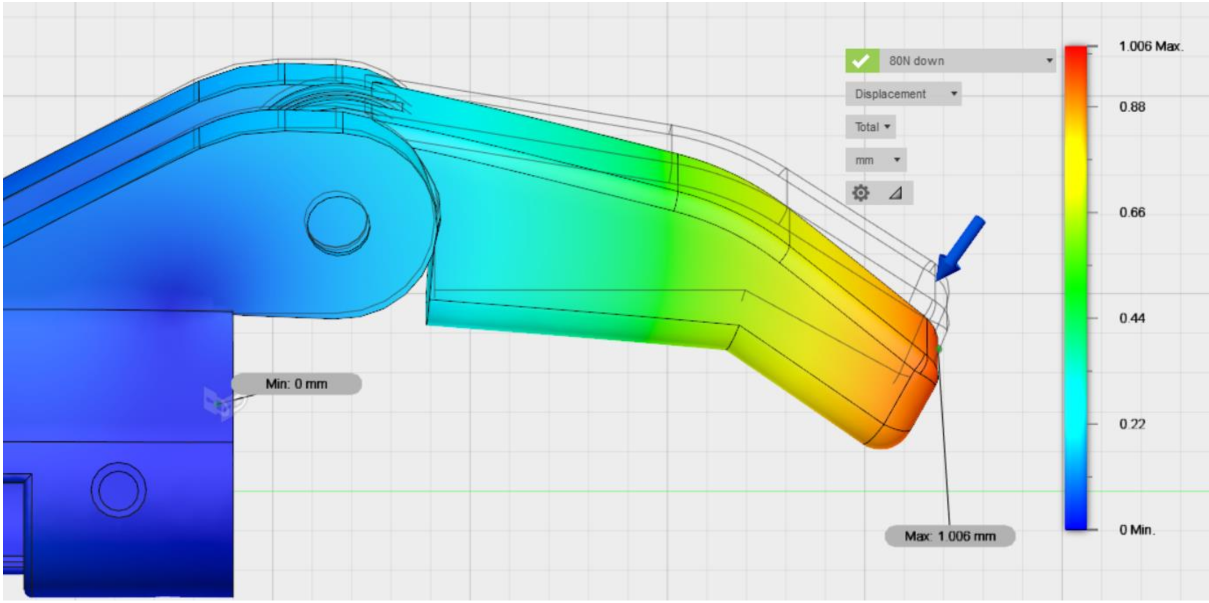


Figure 8-9: Displacement results for load case 2. Max deformation is 1mm. Scale is from 0 to 1mm and results are adjusted to look 5% larger than they are.

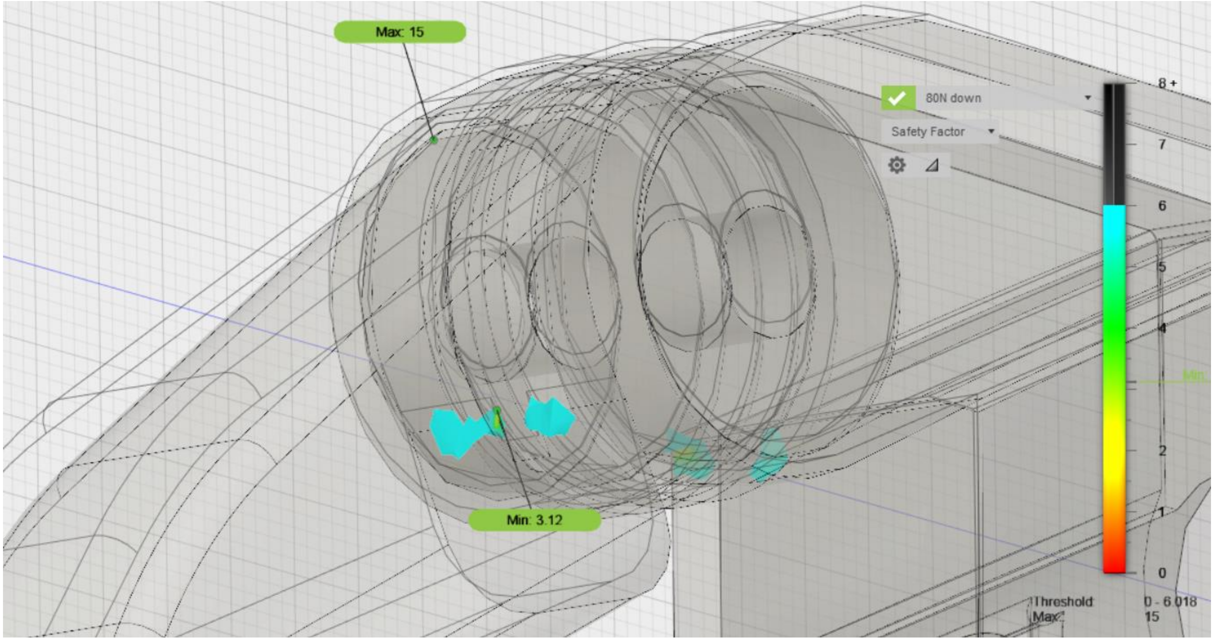


Figure 8-10: Safety factor results for load case 2. Minimum safety factor is 3.1. Scale is from 0 to 6, meaning every area having a higher safety factor than 6 is transparent.

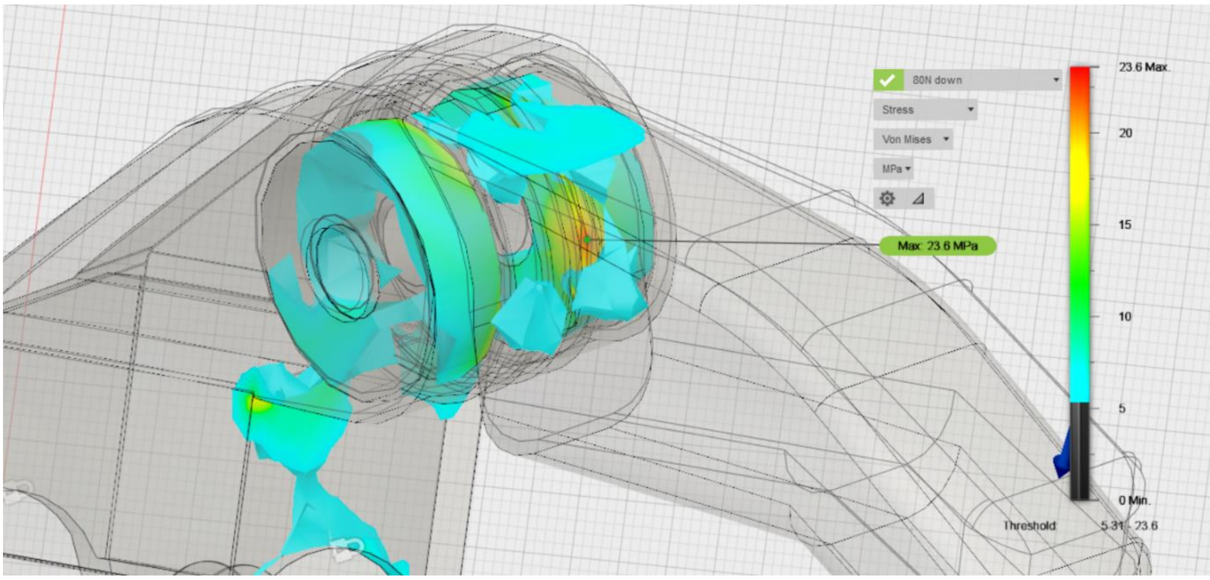


Figure 8-11: Von Mises Stress results for load case 2. Max stress is 23.6 MPa. Scale is from 5 to 23.6 MPa, which means every load under 5 MPa is transparent.

These results show that the thumb can handle the 8kg payload well when applied onto the thumbs top. With a safety factor of 3.1 there is no danger of the thumb breaking during normal operations, and there are no excessive deformations.

8.2.3 Load case 3: Combined 40 N sideways and 40 N on the thumbs inside

This load case assumes a 4kg load on the thumbs inside, and a 4kg load on the thumbs side, both on the thumbs outermost part. This is to ensure that the joints can handle a substantially skewed load. The model is constrained from motion in all directions.

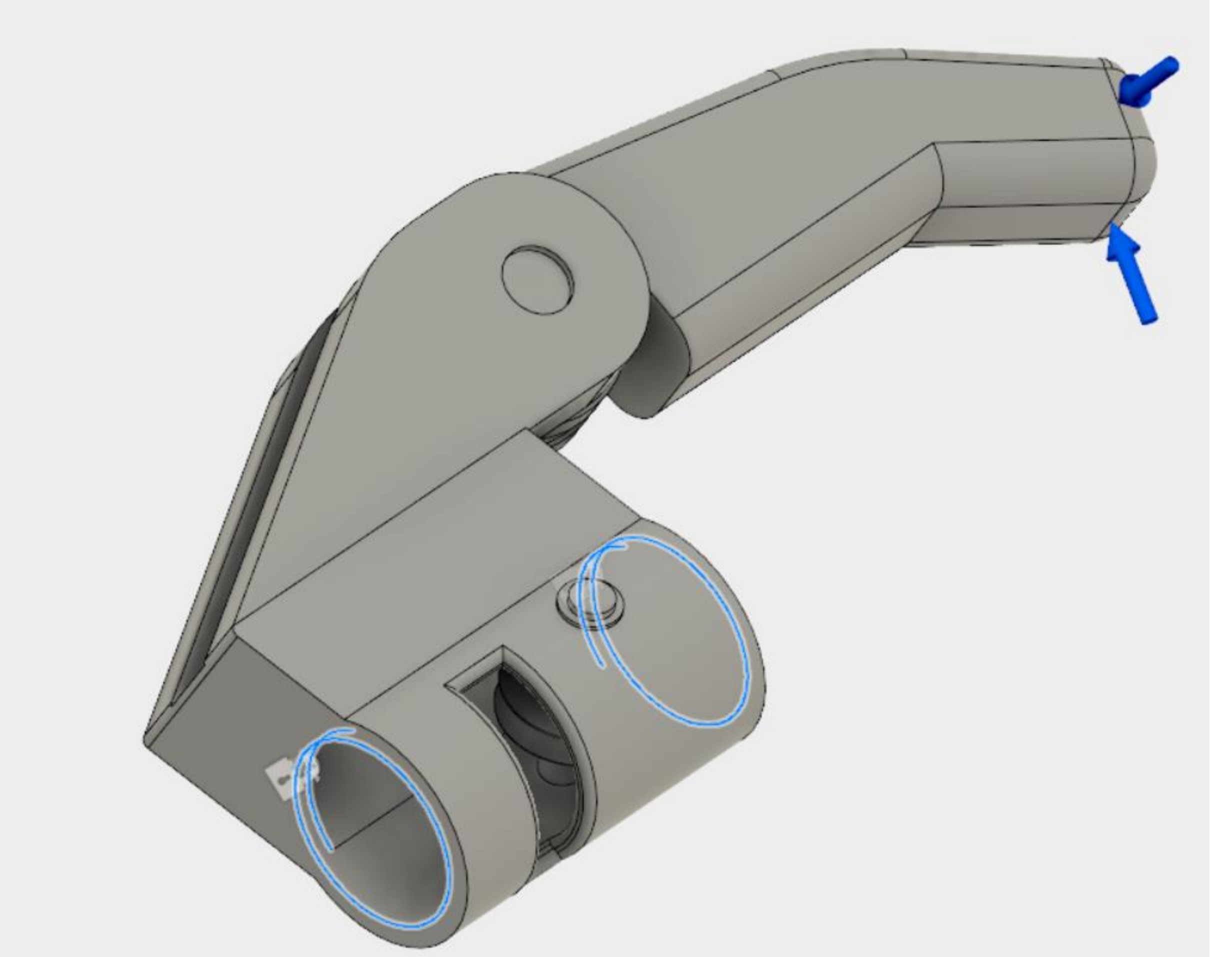


Figure 8-12: Load case 3. 40N works on the thumbs side and inside. Constraints are marked with blue lines and the model is constrained from motion in all directions.

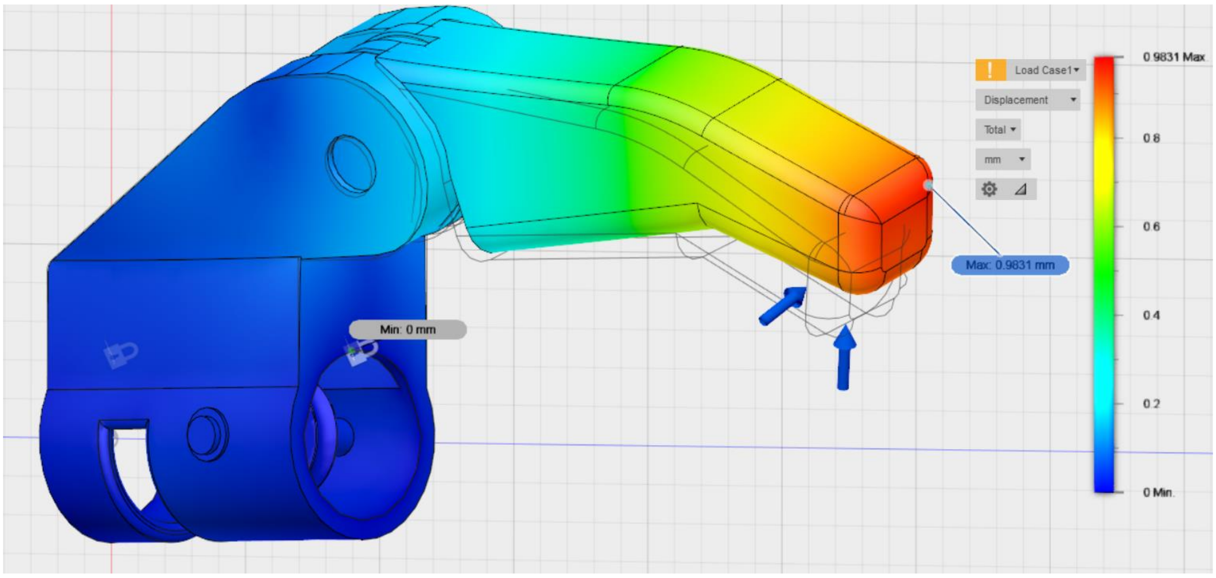


Figure 8-13: Displacement results for load case 3. Max displacement is 0.98mm. Scale is from 0 to 0.98mm, and displacement is adjusted to look 5% larger than real results.

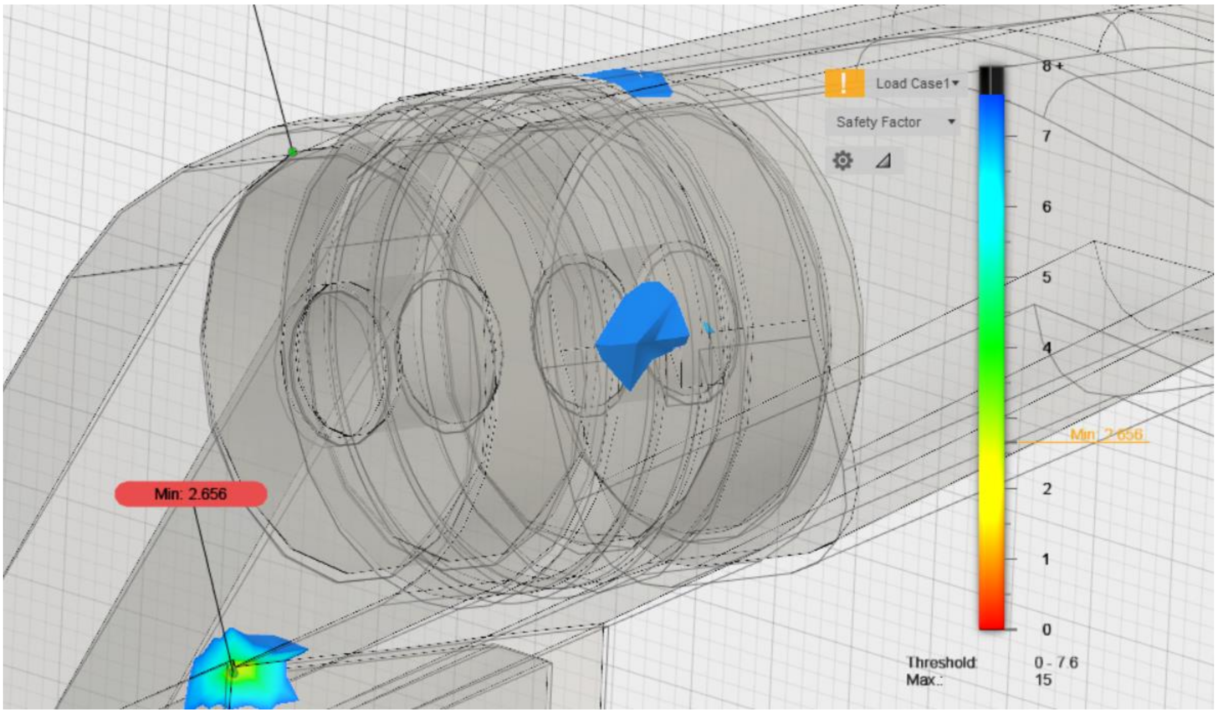


Figure 8-14: Safety factor results for load case 3. Minimum safety factor is 2.36. Scale is from 0 to 7.6, meaning all results larger than 7.6 is transparent.

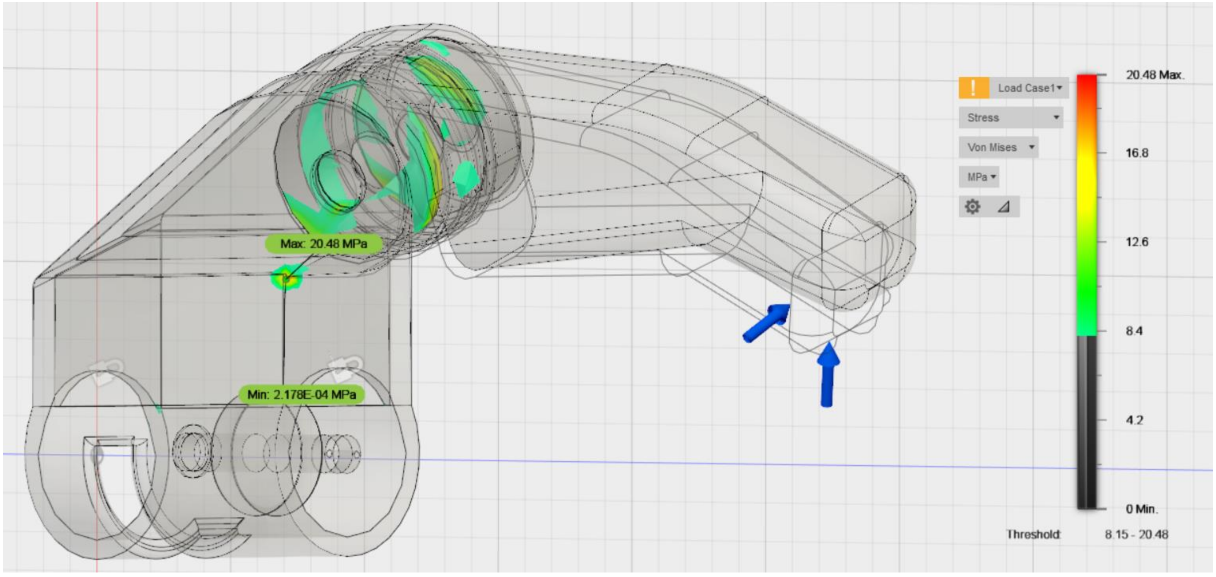


Figure 8-15: Von Mises Stress for load case 3. Largest stress is 20.5 MPa. Scale is from 8.1 to 20.5 MPa, meaning every result under 8.1 is transparent.

The combined load case gave a safety factor below 3, which usually means that the design should be revised. In this case it will be overlooked since a combined load like this won't be tested. The stress concentration occurs on a spot where three lines make a wedge, creating very small and thin features. This can create singularities in FEM-simulations where a number approaches 0 or infinity, leading to much higher stresses than actual. Therefore, stresses are probably significantly lower than the simulation shows, and is deemed good enough as a proof of concept. The design also shows no excessive deformations during the load case.

8.3 Finished design

In this chapter the finished design is presented in its entirety.

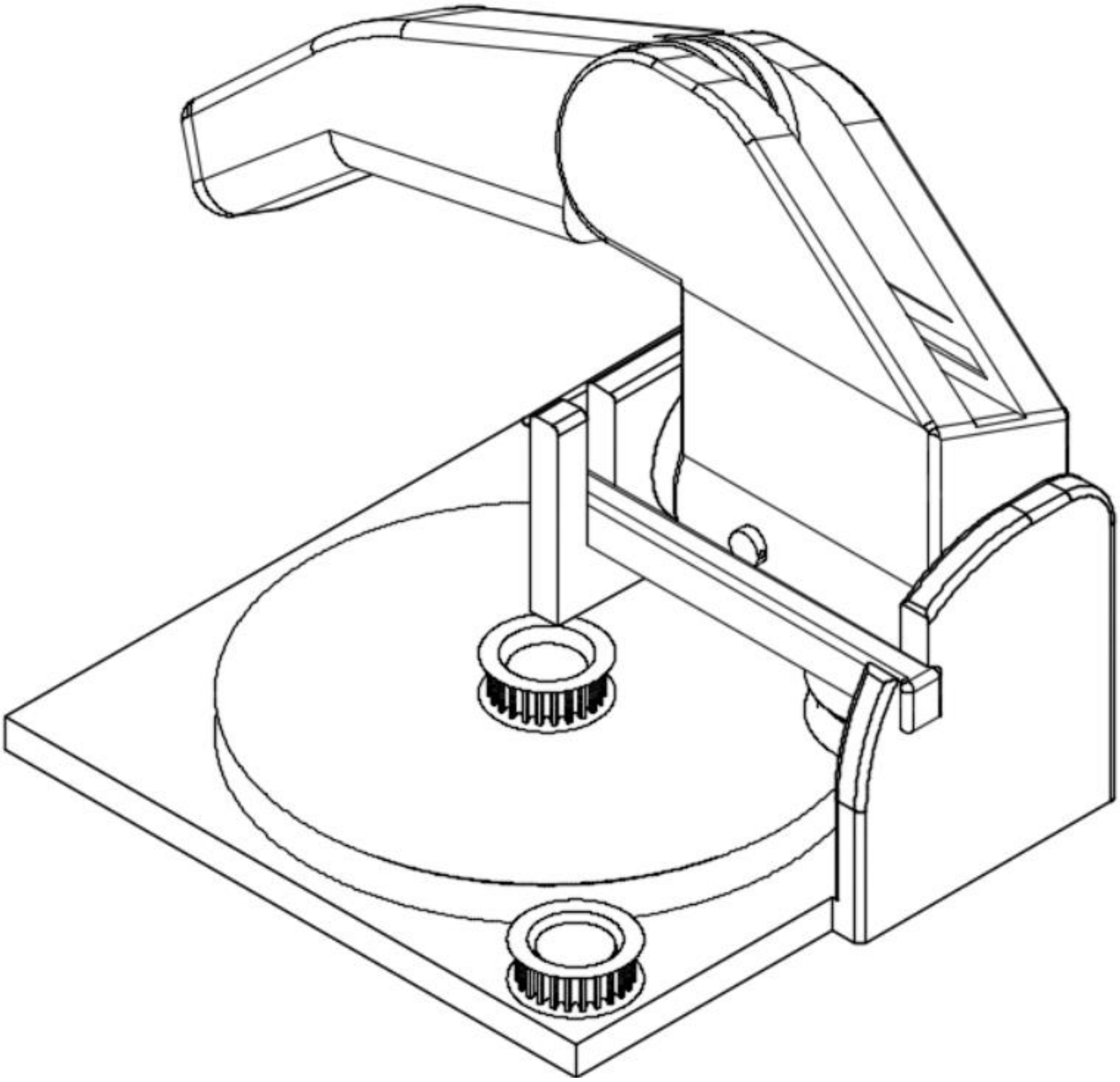


Figure 8-16: Drawing of the assembled design.

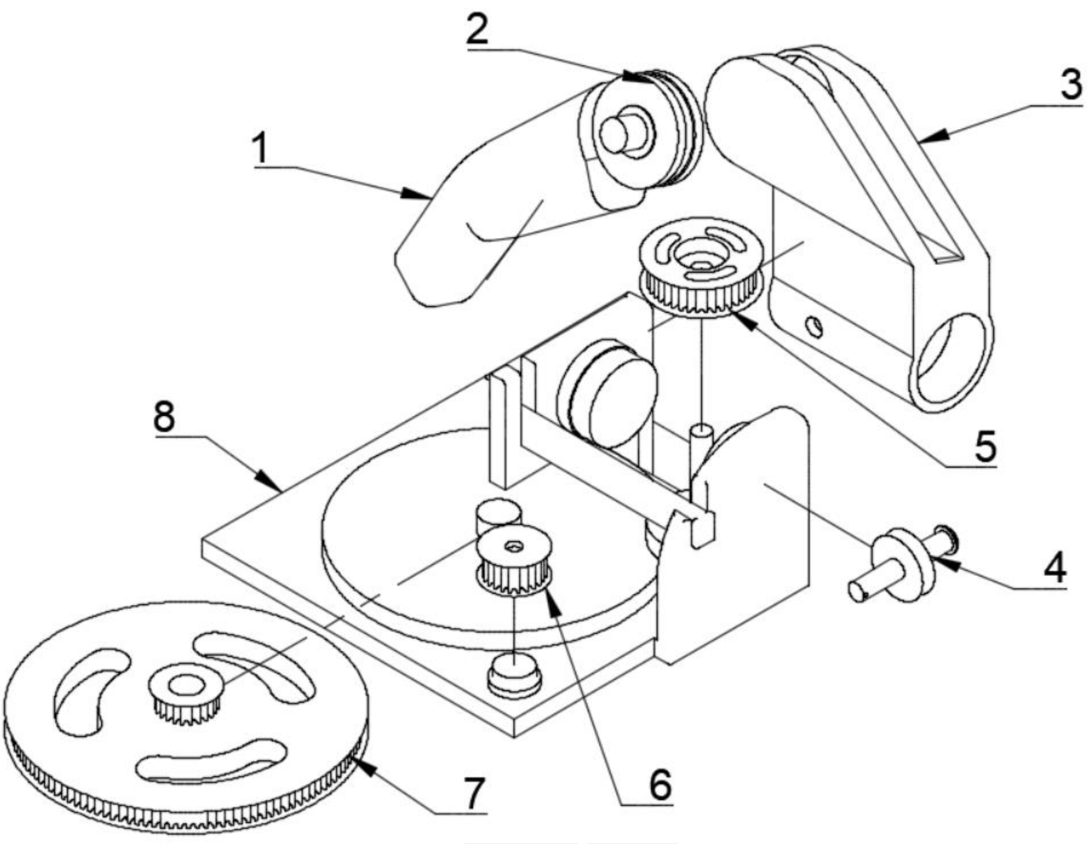


Figure 8-17: Exploded view of the design.

Table 8-1: Part overview from "Figure 8-17: Exploded view of the design."

#	Part
1	Thumb
2	Metacarpophalangeal thumb joint
3	Trapeziometacarpal joint
4	Inner metacarpal pulley
5	25mm GT2 pulley
6	15mm GT2 pulley
7	Combined 80 and 15mm pulley
8	Base/mounting platform.

Table 8-2: Part weight overview.

Component	Weight	Material
Thumb, metacarpophalangeal joint and trapeziometacarpal joint	56.2g	ABS
15mm pulley	0.5g	ABS
25mm pulley	2.5 g	ABS
80mm pulley	23.9g	ABS
GT2 belt	Approx. 20g	Rubber and steel filament
3x 608-Z bearings	4x13g=52g	Mixed, steel
4x 604-RS bearings	4x11g=44g	Mixed, steel
Total weight	**166.1g**	

As can be seen from Table 8-2, the thumb design weighs very little. This calculation does not include the actuation unit. The actuation unit will most likely contribute a large weight portion to the total hand weight, and the estimate above is therefore just an early estimate on what the final design might weigh.

8.4 Designing the main elements

A break-down of the main elements in the design.

Table 8-3: Overview of the main elements used in the proof of concept thumb.

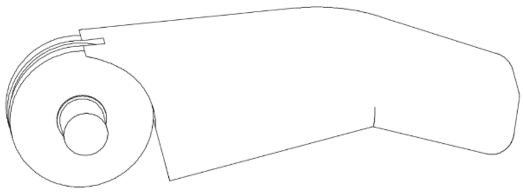
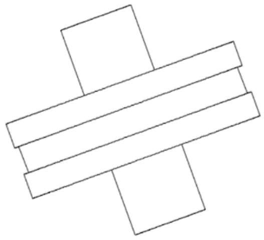
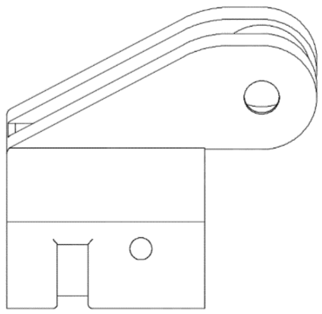
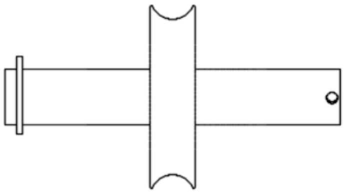
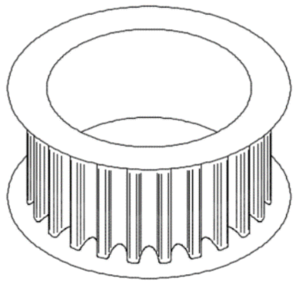
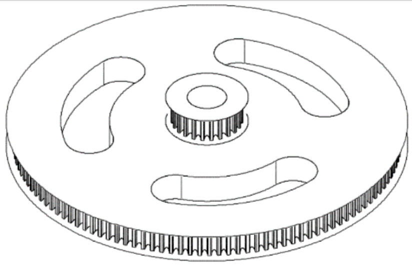
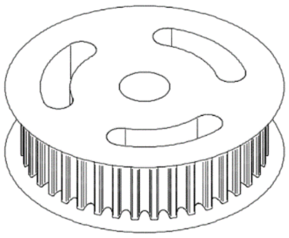
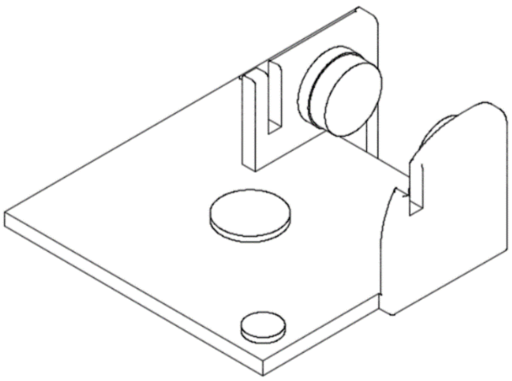
Image	Description
	**Thumb:** The thumb is made using ABS plastic and has a honeycomb structure on the inside for higher strength and stiffness with lower weight. Here shown with the metacarpophalangeal thumb joint attached. It has about the same size as an average female thumb, and the interphalangeal joint is set at a constant 160-degree angle to mimic a resting human thumb.
	**Metacarpophalangeal thumb joint:** The thumb joint is made using ABS plastic with a honeycomb structure inside. It has an axle allowing using 608-RS bearings.
	**Trapeziometacarpal joint:** The trapeziometacarpal joint is made using ABS plastic with a honeycomb structure. It is 2mm thick and has a 22mm opening allowing using 608-RS bearings. There is a slot in the structure to let the gears lying in the palm protrude into the structure.
	**Inner metacarpal pulley:** The inner metacarpal pulley is made using ABS plastic with a honeycomb structure. It is there to ensure that the cable from the screw gear is pulled in the same relative direction, independent of the trapeziometacarpal joints position.
	**15mm GT2 pulley:** Has 24 teeth. It was planned to 3D-printed this using Z-ultrat with 100% infill, but the walls were too thin and warped. The same design was laser cut using acrylic, without the belt guards at the top and bottom. This is the input gear that would be connected to the motor. Pulley has space for a 604-Z bearing.

Image	Description
	**15 + 80mm GT2 pulley:** Upper pulley has 24 teeth, lower pulley has 126 teeth. Printed using Z-ultrat and a honeycomb structure. The second (and third) gear in the transmission. There is space for a 608-RS bearing inside the large pulley.
	**25mm GT2 pulley:** Has 40 teeth. Printed using Z-ultrat and a honeycomb structure. The last pulley in the transmission. There is space for a 604-Z bearing inside the pulley.
	**Base/hand:** Made to simulate the hand in this proof of concept.

As can be seen from the table above, few special components are needed. Most pulleys and shafts can be purchased as standard parts, even though they have been designed specifically in this prototype. This was due to it being simpler to 3D-print and test than to order parts which take several weeks to ship, as for example the inner pulley.

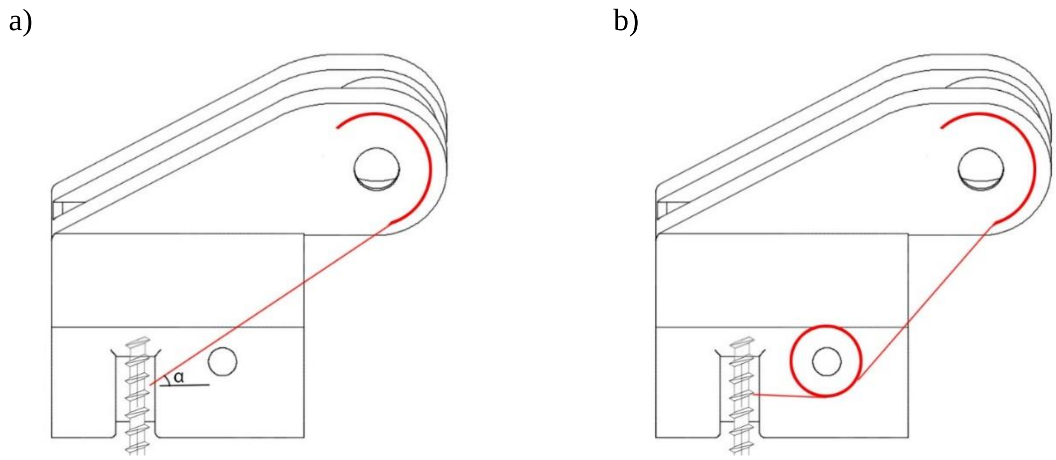


Figure 8-18: Why the inner metacarpal pulley is included. As can be seen in a), the cable (red) will be pulled in at a large angle α without the pulley. When the pulley is included this angle is nearly eliminated, as can be seen in b). Illustrated screws have a much higher thread angle than actual screw used.

Imagining what the inner metacarpal pulley does may be difficult. Figure 8-18 illustrates why this pulley is included. When the cable is pulled at a large angle, the cable may wind over the threads and therefore quickly travel much higher up on the screw than supposed to. This can lead to the thread slipping above the top and the cable fraying from rubbing against an edge on the threads. Using the pulley nearly eliminates the angle, and ensures that the cable is wound correctly on the screw. The figure also highlights that the cable in the prototype will rub against a wall in the trapeziometacarpal joint.
A passive trapeziometacarpal joint was designed in this prototype. Since testing backdrivability in the metacarpophalangeal thumb joint is the most important aspect, it was therefore decided not to use valuable time on designing a controllable trapeziometacarpal joint. This joint merely requires stiffness, allowing it to use gears, timing belts, linkages, or even a motor placed inside the hand directly controlling its position.

8.5 Standard parts and electronics

A break-down of the standard parts used is shown in the table below.

Table 8-4: Standard parts overview.

<table>
<tr><th>Image</th><th>Description</th></tr>
<tr><td>

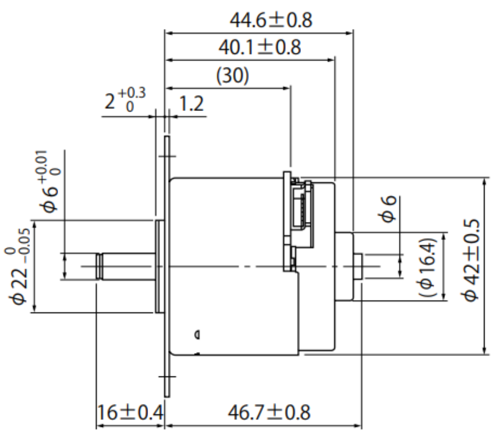


Figure 8-19: DIX42B20 motor dimensions [99].

</td><td>

Motor:
The last calculation on minimum motor torque in chapter 4.4 *Preliminary force calculations*, can be redone with the new 44.4:1 gearing ratio:

$$M_{motor} = \frac{4708.8\ Nmm}{44.4} = 106.1\ Nmm \quad (7)$$

A possible solution is the Brushless DC motor DIX42B20 from Minebea with a 120 Nmm max torque at 3 amperes. It has a 42mm diameter and a 46mm length, meaning it can fit into the hand. Weighing in at 190g is also good enough [99].

</td></tr>
<tr><td>

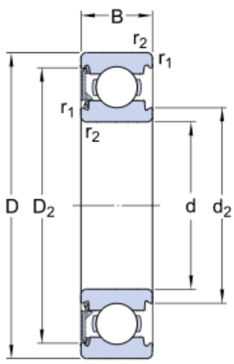


Figure 8-20: 608-RS bearing measurements. Image courtesy of SKF [100].

</td><td>

608-RS bearings [100]:

d		8	mm
D		22	mm
B		7	mm
d_2	≈	10.55	mm
D_2	≈	19.2	mm

These bearings were used because it was the best available solution that was in stock at NMBUs workshop.

</td></tr>
</table>

Image	Description

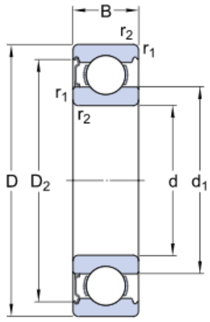


Figure 8-21: 604-Z bearing measurements. Image courtesy of SKF [101].

604-Z bearings [101]:

d		4	mm
D		12	mm
B		4	mm
d_1	≈	6.1	mm
D_2	≈	9.8	mm

These bearings were used because it was the best available solution that was in stock at NMBUs workshop.

Figure 8-22: Illustration of an M4 screw.

Screws:
M4
M5
M8

Used as an axle for pulleys and to keep components in place.

Figure 8-23: Illustration of two M8 nuts.

Nuts:
M4
M8

Used to fasten screws to the base plate, and to fasten components on the screws.

Figure 8-24: Illustration of two M8 washers.

Washers:
4mm
8mm

Used to create distance, dissipate stress over a larger area and to allow for easier movement.

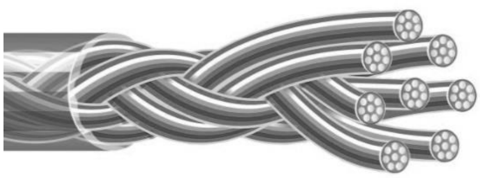


Figure 8-25: Illustration of braided fishing line from [102].

Braided fishing line:
30kg load capacity is the minimum needed.

9 TESTING THE PROOF OF CONCEPT SOLUTION

In this chapter the final solution that was presented in Product architecture and concept design will be tested on how well it functions.

9.1 Proof of concept goals

The Product goals chapter set these as the most important goals for the prototype:

Main goal:

- One functioning backdrivable joint in the thumb.

Other goals:

- Little friction and backlash.
- Functions in all possible trapeziometacarpal joint positions.
- Capable of prehensile grips; a stable 15N minimum strength.

If all these goals are achieved the robotic thumb solution is viable and should be further developed. If the main goal, but not all the other goals are achieved, some revisions are required. Fulfilling the main goal may also mean the process goal has been achieved. If the main goal is not achieved, the proof of concept has shown that this is not a good solution for this problem and other possible solutions should be considered.

9.2 Proof of concept test rig

This chapter will explain the robotic thumbs design process, how the thumb was produced and assembled.

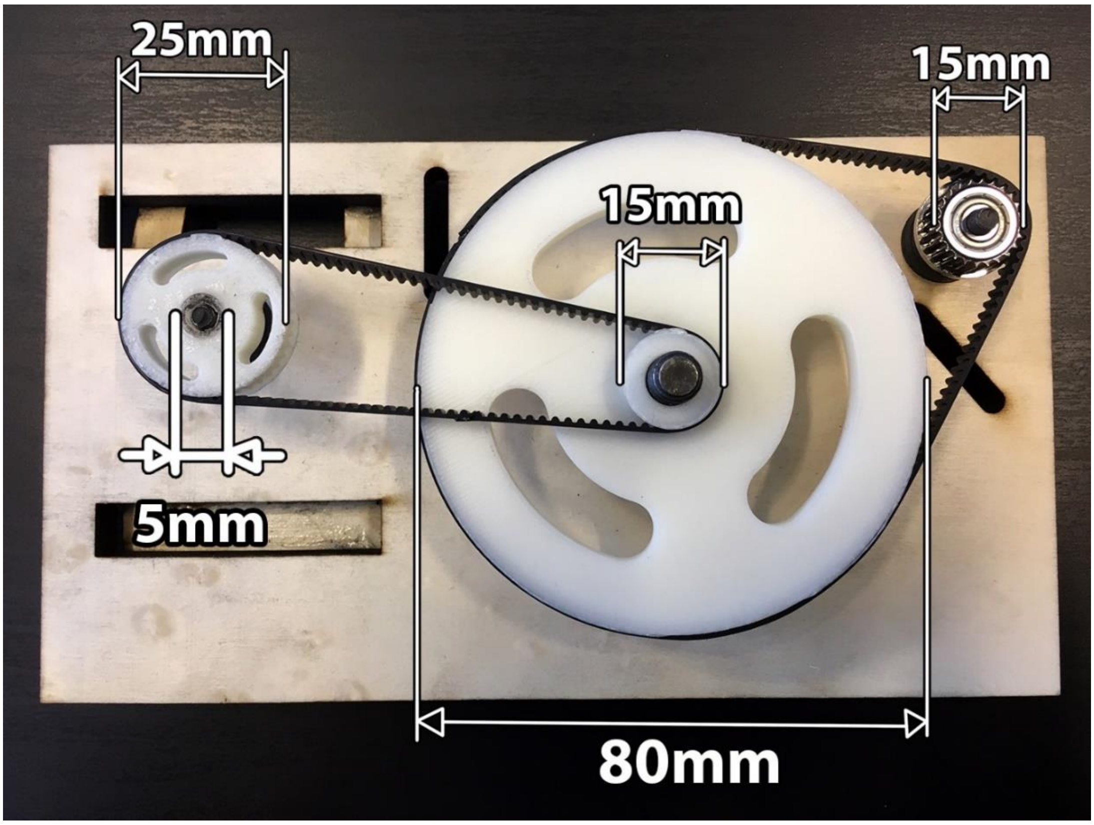


Figure 9-1: Transmission system sizes. Screw is not yet mounted for clarity purposes.

Figure 9-1 shows the different pulley sizes used in the transmission system. This transmission system gives a gearing ratio of:

$$i = \left(\frac{80}{15}\right) * \left(\frac{25}{15}\right) * \left(\frac{25}{5}\right) = 44.4 \tag{7}$$

That means a total force amplification of 44.4, assuming 100% efficiency.

Figure 9-2: A picture of the assembled proof of concept test rig.

The thumb and trapeziometacarpal joint (black parts, shown in Figure 9-2) were printed using ABS on a FlashForge Guider 2 3D-printer. The white pulleys were printed on a Zortrax M200 3D-printer using the material Z-Ultrat, which gives a harder print with less shrinkage than ABS. Z-Ultrat is therefore better suited for pulleys needing accurate tolerances. The smallest 15mm pulley was laser cut from acrylic. This is because the walls were too thin, so when using a 3D-printer the walls warped inwards and both weakened the part and made it unusable due to incorrect mechanical tolerances. The timing belts use the GT2 standard and has a steel thread filament on the inside to prevent elongation, which makes it much easier to tighten the belts properly.

Not pictured is the *Norsjø* multifilament fishing line wound around an M4 screw connected to the thumb joint. This multifilament line is rated for a 15kg max load and has a diameter 0.18mm. This cable is dimensioned with very little safety factor per the minimum Spectra line diameter found, but was the only possible candidate from the limited supply at local shops.

9.3 Testing

Pre-check:

Before any proper testing could be undertaken, the rudimentary testing rig functions were checked.

Rotating the start pulley moved all the other pulleys, and a wound cable around the screw allowed for pulling down the thumb. This worked independently of the trapeziometacarpal joints position. Since this system cannot push the thumb to its starting position, the thumb was pushed outwards to keep the cable tight while the pulleys were rotated in the opposite direction. The cable was released evenly and the thumb could return to its starting position.

The pulley connected to the cable ended up being mounted slightly skewed, which caused the belt to pull off the pulley if kept unchecked. Apart from that, the testing rigs rudimentary functions all work as intended. Backdrivability was not tested yet.

Testing backdrivability:

The main prototype goal was achieving one backdrivable joint. To test whether this worked or not the thumb was pulled down by rotating the pulleys and tightening the cable. When the thumb was fully pulled down, it was attempted to push the thumb outwards to its starting position while the system was free. This was all done using hand forces. Since backdrivability is to ensure safe human operation, the force amount is not highly relevant to this test. The cable created some issues when testing backdrivability.

At first the fishing cable was only glued onto the finger, and this resulted in the cable slipping through the glue. Then a knot was made so that the cable should be unable to slip through the glue. This resulted in the cable snapping due to large stresses on the knots small cross section. To alleviate some stresses off the cable and onto the structure, a slot was glued onto the thumb joint which the cable could be wound around. Now the cable held, with some small slippage in the knot due to the cable having a surface with little friction. The cable holding resulted in the screw that was fastened to the pulley to come loose from where it was glued. The input axle never moved when used from output to input.

Testing was therefore unable to check whether the system is backdrivable or not, but the preliminary testing suggests that the transmission is not backdrivable. What became apparent from the testing was that trying to run the system in reverse is much more difficult than anticipated. The static breakaway friction to create movement when pushing the thumb was large and may be one reason why achieving backdrivability in such a small system can be difficult.

Other goals:

Subjectively the system showed positive traits for a backdrivable system. It had little friction and little backlash when tightened properly. The thumb functioned in all trapeziometacarpal positions as mentioned in the pre-check. The transmission system was too erratic to create stable prehensile grips.

9.4 Testing analysis

Testing showed that pushing on the thumb to overcome the static (breakaway) friction proved a larger issue than anticipated. In chapter 4.4 *Preliminary force calculations* the maximum gearing ratio of 30:1 was set for a capstan drive after Perret & Vercruysse [95]. That is why the design tried to maximize potential gearing within the palm by using as few components as possible in the gearing system and not exceeding 30:1 by a large margin. With a total gearing ratio of 44:1 it was near impossible to move the system from output to input.

Researching further showed that Tobias Nef and Peter Lum have worked on improving backdrivability in geared rehabilitation robots. Solving for a moving system is straightforward. The kinetic friction can be accounted for by using velocity sensors and rotating the motor in reverse. Compensating for the breakaway friction is a bigger challenge since the system needs to know which direction the user wants to move the system in before the movement happens [103].

Further research showed that Kaminaga et al. has made a formula for friction hysteresis (a lag between input and output due to for example slack in the system) in transmissions [104]. This formula is shown in (10).

$$\tau_{output}^{backdriveable} > \left(\prod_{i=1}^{n} K_i\right) * \tau_{input}^{min} \tag{10}$$

Here “K” is a value related to torque loss due to friction in the transmission. τ_{input}^{min} is the lowest torque that must be exceeded for the system to be backdrivable, and $\tau_{output}^{backdrivable}$ is the torque applied at output. “n” is the number of geared transmissions, and the formula makes it apparent that with more transmissions, the backdrivable traits degrade.

The proof of concept prototype did not function with backdrivability, and showed several other problem areas. Mainly the problem is that the components are not strong enough to hold the forces working on the system. The cable snapped, slipped or ripped off other components when an external force was placed upon the thumb. The pulleys became skewed due to laser cut MDF being too soft and having too lose tolerances. This was especially prevalent on the 25mm pulley. On that pulley the bearing was easier to mount and was therefore allowed more lateral movement. This resulted in the pulley skewing too much from the tensioned cable forces to work correctly.

The 0.18mm diameter cable showed the most problematic behaviour. If it could hold the minimum grip strength set at 15N this is how much stress there would be in the cable:

$$A_{cable} = \frac{\pi * d^2}{4} = \frac{\pi * 0.18^2}{4} = 0.0255\ mm^2 \tag{1}$$

$$M = F * l = 15\ N * 60\ mm = 900\ Nmm \tag{3}$$

Assuming all the momentum is held by the cable at the joint radius distance:

$$F = \frac{M}{r} = \frac{900\ Nmm}{11\ mm} = 81.81\ N \tag{6}$$

This translates to about 8kg force, which the cable should be able to handle. Looking at the stress in the cable:

$$\sigma_{cable} = \frac{F}{A_{cable}} = \frac{81.81\ N}{0.0255\ mm^2} = 3208.2\ MPa \tag{2}$$

The cables stress is very high, and the cheap cable can most probably not take this stress level very well. There is little doubt that a cable under a 3208.2 MPa load might break, and since pushing on the thumb very easily can create higher stresses than this in the cable, it will probably break quickly. Especially considering this is 300 MPa higher than what Spectra 1000 fibre is rated for.

To check when the cable theoretically snaps, the system will be checked in from cable to external applied load. Assuming 15kg load on the cable gives its maximum rated loading capacity:

$$F_{cable\,\max load} = 15\ kg * 9.81 = 147.15\ N \tag{11}$$

$$\sigma_{max\ stress} = \frac{F}{A_{cable}} = \frac{147.15\ N}{0.0255\ mm^2} = 5782.6\ MPa \tag{2}$$

This max stress is suspiciously high. Spectra 1000 fibre had a 2900 MPa ultimate tensile strength, and these stresses are nearly twice that. Continuing with an assumed max load on the cable in the joint. This will check how much external force applied at the thumbs end achieves a breaking load on the cable.

$$M_{joint} = F_{cable\ max\ load} * r_{thumb} = 147.15\ N * 11mm = 1618.65\ Nmm \tag{12}$$

$$F_{thumb} = \frac{M_{joint}}{l_{thumb}} = \frac{1618.65\ Nmm}{60mm} = 26.98\ N \tag{3}$$

$$maximum\ kg\ load = \frac{26.98\ N}{9.81\,\frac{N}{kg}} = 2.75kg \tag{13}$$

Theoretically the cable should therefore be able to hold the load, even if common practice would deem the stresses excessive. Assuming no faults in the cable it can take a 2.75 kg max load on the thumbs end, something that can easily be much higher if a human push against it. The maximum load also leaves relatively little wiggle room considering the maximum grip strength is rated at 15N, and there most certainly resides some friction in the system. Assuming 0.5kg friction:

$$\%\ possible\ force\ surge = \frac{Maximum\ load - grip\ strength - friction}{Maximum\ load} * 100\% =$$

$$\frac{2.75kg - 1.5kg - 0.5kg}{2.75\ kg} * 100\% = 27\% \tag{14}$$

This means that if the force applied is 27% larger than anticipated, the cable will snap. That will most certainly happen quickly if a human is to use it.

10 Production and production costs

This chapter will give a brief overview on how the prototype was produced and the costs associated with the production.

10.1 Production methods

To create the different parts, a small variation of manufacturing methods was used and shown in the table below.

Table 10-1: An overview of what rapid prototyping methods were used to create the different parts in the proof of concept.

Part	Manufacturing
Thumb	3D-printed: - FlashForge Guider 2 - ABS
Metacarpophalangeal thumb joint	3D-printed: - FlashForge Guider 2 - ABS
Trapeziometacarpal joint	3D-printed: - FlashForge Guider 2 - ABS
Inner metacarpal pulley	3D-printed: - FlashForge Guider 2 - ABS
80 and 15mm pulley	3D-printed: - Zortrax M200 - Z-Ultrat
25mm pulley	3D-printed: - Zortrax M200 - Z-Ultrat
15mm pulley	Laser cut: - 6mm Acrylic
Base plate	Laser cut: - 9mm MDF
Fastening plates for the trapeziometacarpal joint	Laser cut: - 6mm MDF
Shaft for the trapeziometacarpal joint	3D-printed: - Zortrax M200 - Z-Ultrat

As can be seen in the table above, 3D-printing was heavily used to create the proof of concept. This is due to the ease of production and how quickly the parts can be made while needing little to no modification.

10.2 Costs

In this chapter an approximated cost for the project is created. There are no human labour costs, but these are important costs to think about during a real project where human labour is not free. This cost approximation is meant for the proof of concept prototype. All costs are in Norwegian kroners. Hourly wages are based on average beginner salaries for engineers in Norway [105].

Table 10-2: Overview of costs for human labour in designing the product and writing the thesis.

Work	Hours	Cost	Sum
Theory	150	500	75 000
Market research	50	500	25 000
Testing solutions	100	500	50 000
3D-drawings	100	500	50 000
Documenting work	200	500	100 000
Prototyping	100	500	5 0000
Finishing thesis/report	150	500	75 000
Total	**850**		**425 000**

Costs are an estimate for renting 3D-printers at an inexpensive rate, material is counted as total bulk purchased and not the exact amount used. Hourly wage here is set higher due to special competence in rapid prototyping needed.

Table 10-3: Costs associated with creating the first prototype.

Post	Hours	Cost	Quantity	Sum
3D-printing	10	100	-	1000
Material	-	300	1 kg	300
Assembly	10	700	-	7000
608-Z bearings	-	50	1 pack of 8	50
608-RS bearings		100	1 pack of 8	100
GT2 belt	-	89	2 m	178
Screws	-	10	4 pcs.	40
Nuts	-	2	8 pcs.	16
Fishing cable	-	250	1 roll	250
Total				**8934**

It is apparent that the material costs for the prototype are negligible compared to the labour costs. Had the labour cost been removed, the prototype would have cost 1934 NOK. If the calculations had been done using exact material amounts needed this number would be even lower.

11 PRESENTATION

The proof of concept will be presented here.

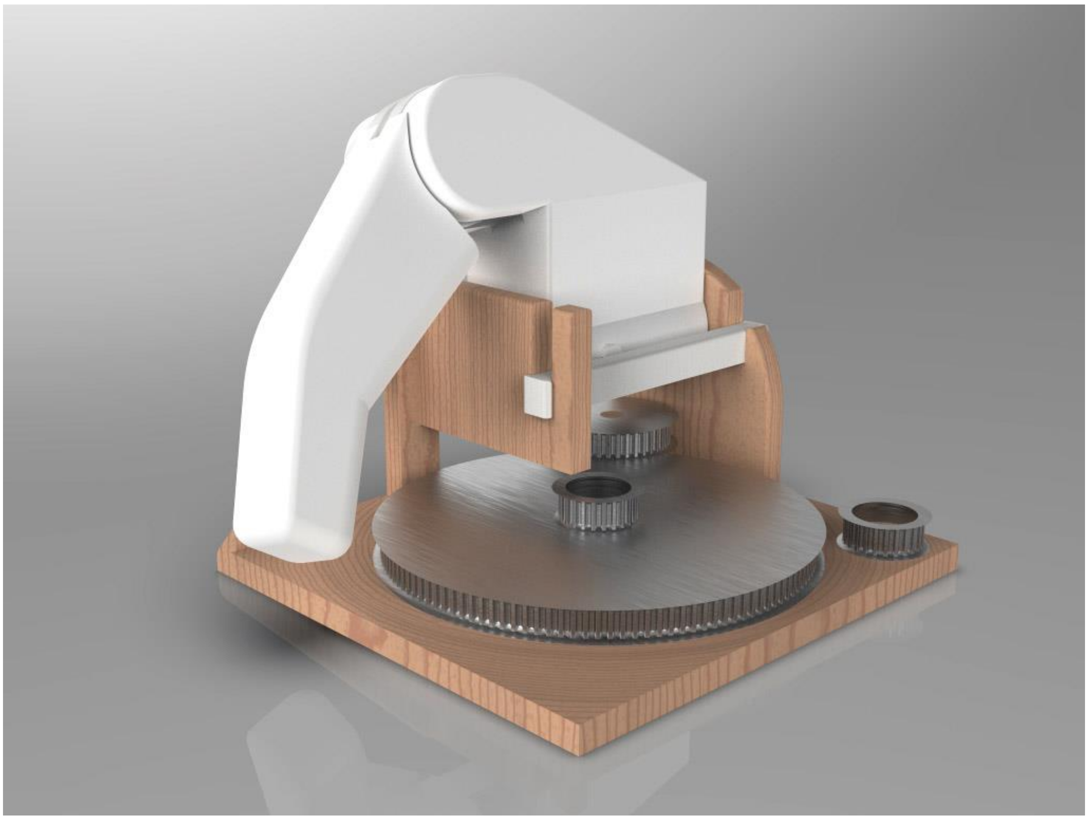


Figure 11-1: Finished assembly render. Base plate is wood, and the gears are casted aluminium.

Figure 11-2: Render showing the assembled thumb and base (in acrylic) prototype from above.

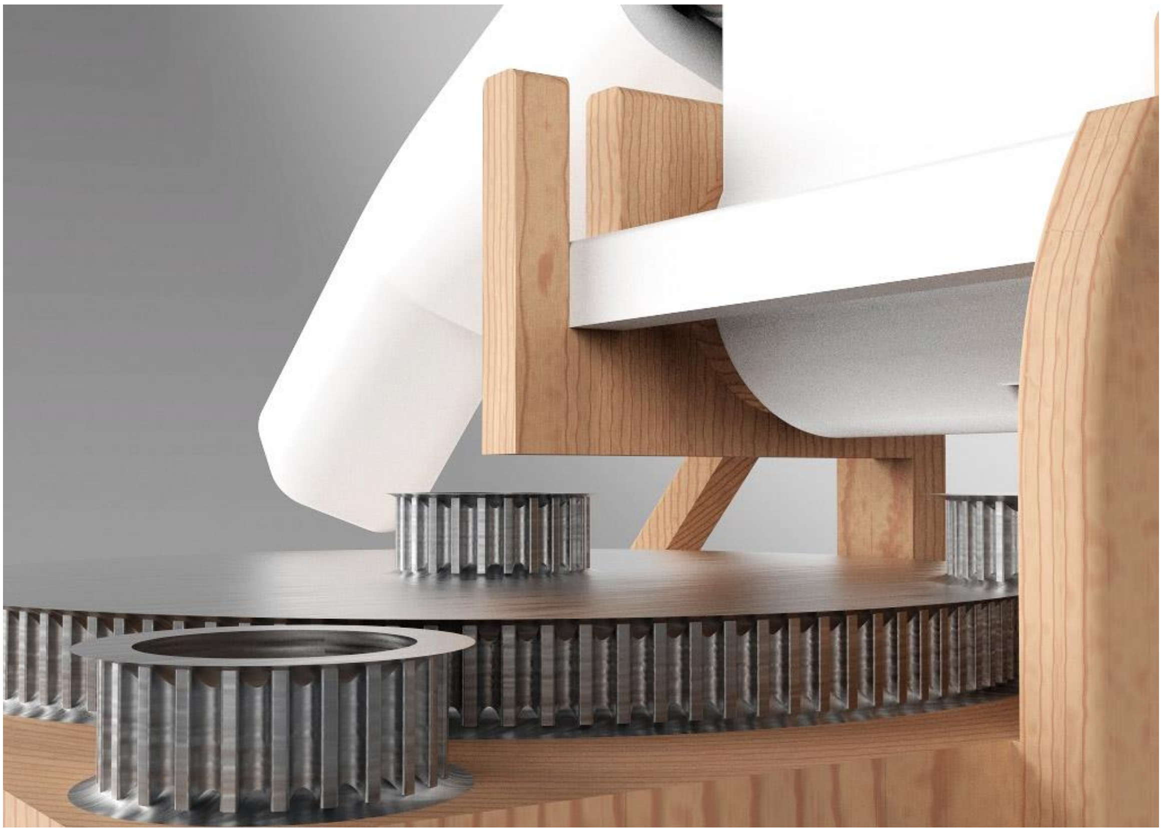


Figure 11-3: Render showing the pulley transmission without the belts.

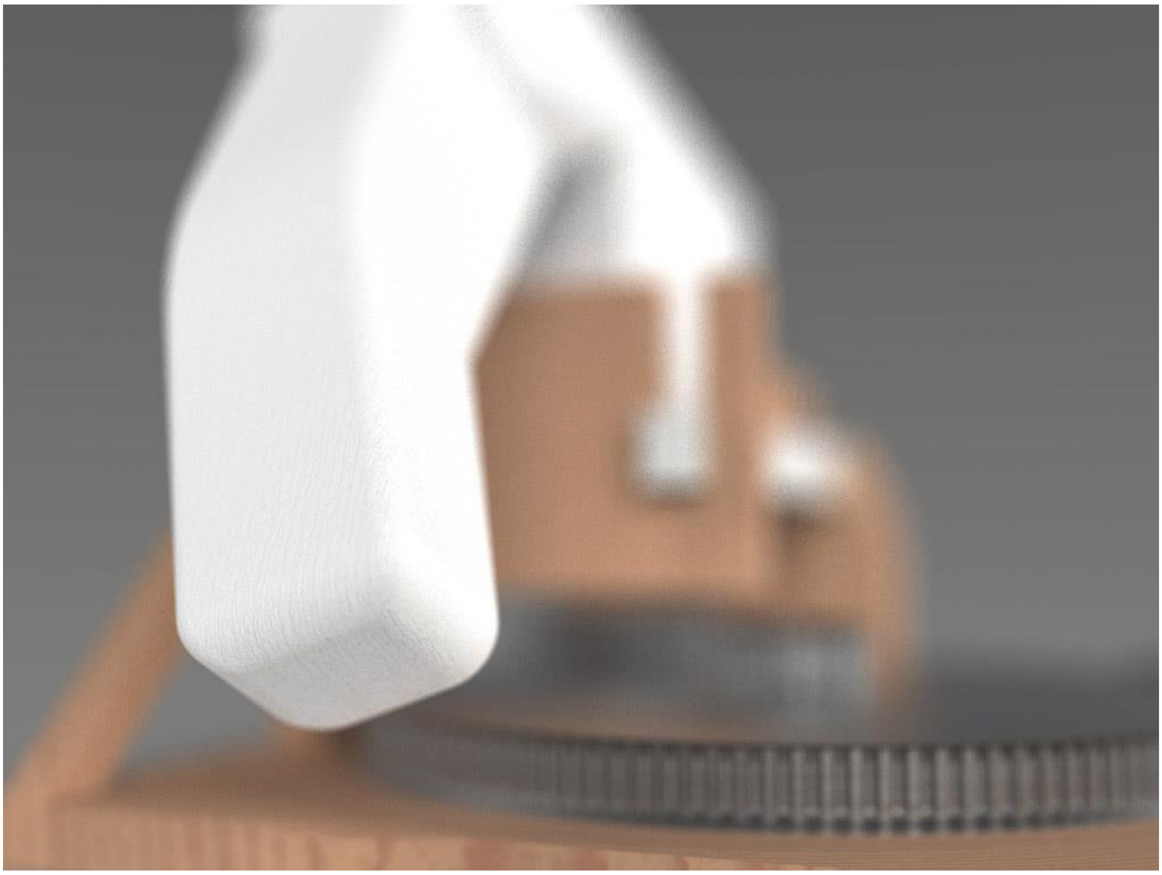


Figure 11-4: Detail render of the thumb.

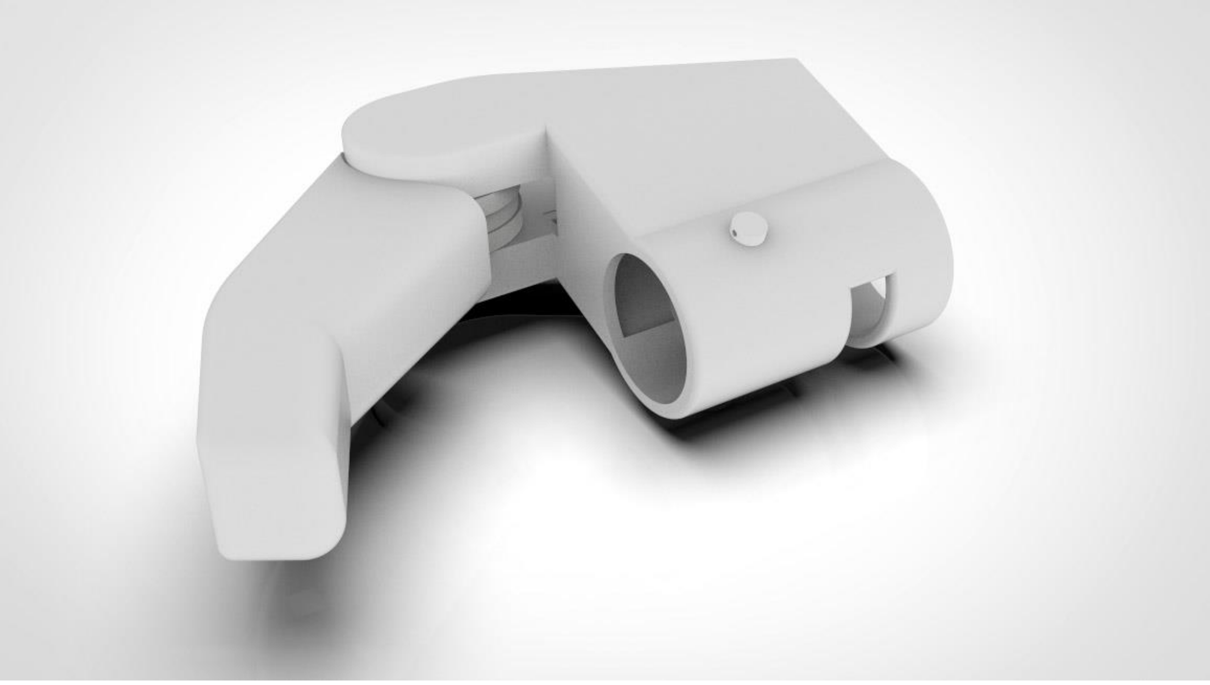


Figure 11-5: Detail render of the thumb with the trapeziometacarpal joint seen from the side.

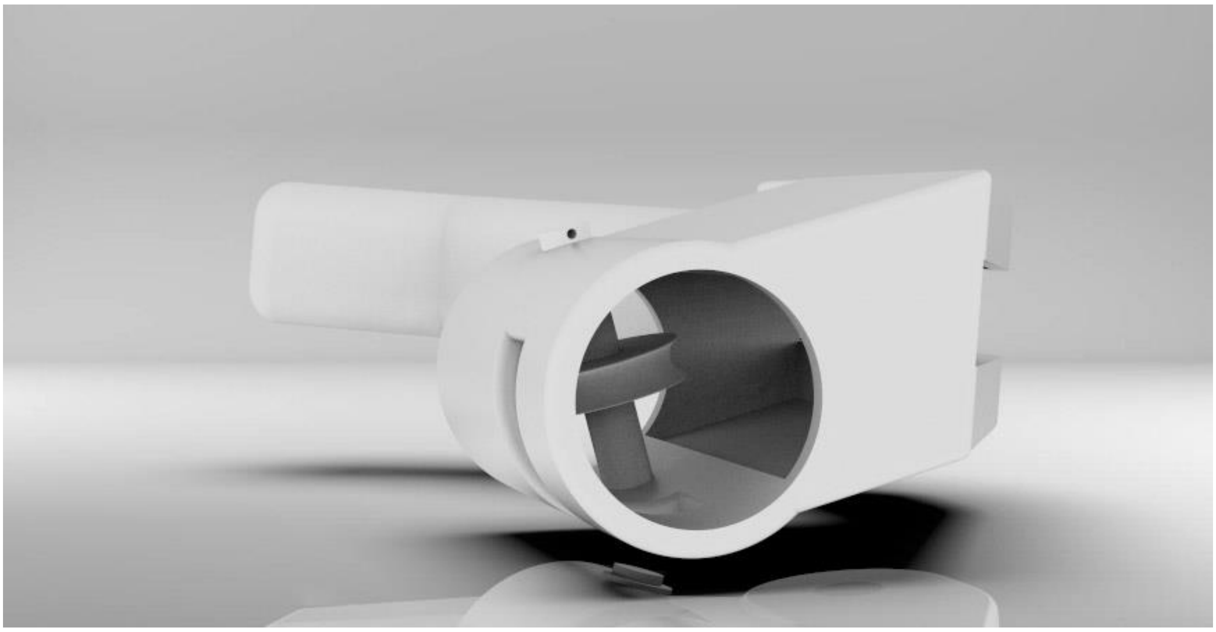


Figure 11-6: Render showing the pulley on the inside of the trapeziometacarpal joint.

Figure 11-7: Render showing where the thumb is assembled on the trapeziometacarpal joint.

12 Discussion

In this chapter the results found will be discussed, along with what possibilities the results create for further work.

12.1 Relations in backdrivability and geared systems

The product goal was to develop a backdrivable thumb, and the process goal aimed at finding the optimal transmission for a backdrivable thumb. These findings help further those two goals.

As mentioned in chapter 9.4, it was difficult to overcome the static friction in the transmission. This backdrivable geared friction issue was unmentioned in the theory, and the sources used on backdrivable robotic hands never talked about the gearing ratio used. If the gearing ratio was mentioned at all, it merely stated that a small gearing ratio was used. After testing the prototype it was found that Nef & Lum discovered that to overcome static friction, the transmission needs to know in which direction it must move before the movement happens [103]. The difference between compensating for kinetic and static friction is illustrated in Figure 12-1. Some ideas on how to compensate for the breakaway friction in a robotic thumb will be presented in further work.

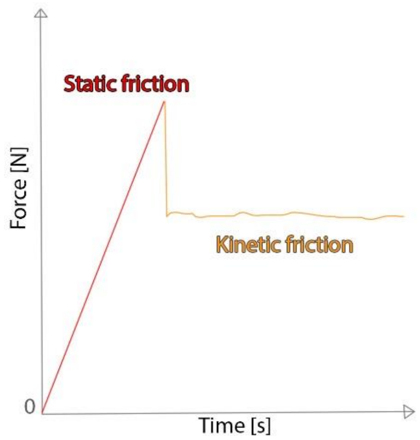


Figure 12-1: The relation between static and kinetic friction.

After Kaminagas postulations on backdrivable geared systems [104], some calculations will be done to investigate how large the breakaway friction may be in the proposed proof-of-concept design created in this thesis. Gearing ratios throughout the transmission is shown in the table below.

Table 12-1: Gearing ratios in the proof of concept prototype.

Transmission	Gear 1 to 2	Gear 2 to 3	Gear 3 to 4
Ratio	80/15	25/15	25/5
Total ratio (i)	5.33	8.89	44.44

All pulleys are assumed the same diameter in the calculations. This allows force at input to be equal to force in every pulley, instead of calculating for torque dependant on distance. Done for clarity. Assuming a 2 N force transferred from the motor to output and no friction is involved in the system, this is the output power:

$$F_{output} = F_{input} * i = 2\ N * 44.44 = 88.88\ N \tag{7}$$

Doing the same calculation from output to input and assuming the same 2 N force applied gives this force at the input:

$$F_{input} = \frac{F_{output}}{i} = \frac{2\ N}{44.44} = 0.045\ N \tag{7}$$

This is barely any force at all, but it is undesired that the output should put strain on the motor at input and therefore this outcome is wanted. So far there are no problems, and friction will be introduced into the system. An even 1 N friction in every transmission is assumed, and at first the friction is calculated from motor to output:

$$F_{total\ friction\ input} = \frac{F_{friction\ gear}}{i_{gear\ n}} = 1N + \frac{1\ N}{5.33} + \frac{1\ N}{8.89} + \frac{1\ N}{44.44} = 1.32\ N \tag{7}$$

Table 12-2: Calculated friction values in the proof of concept prototype from input to output.

Transmission	Gear 1	Gear 1 to 2	Gear 2 to 3	Gear 3 to 4	Sum
Flat friction	1 N	1 N	1 N	1 N	
Friction felt at start from gears	1 N	0.19 N	0.11 N	0.023 N	**1.32 N**

As can be readily seen from the table above, friction throughout the system becomes very small for the motor at the start. When pushing at this system with 2 N, the breakaway friction is easily overcome and the system will move. If the same scenario is applied when using the system in reverse:

$$F_{total\ friction\ output} = F_{friction\ gear} * i_{gear\ n} =$$

$$1\ N + 1\ N * 5.33 + 1\ N * 8.89 + 1\ N * 44.44 = 59.67\ N \tag{7}$$

Table 12-3: Calculated friction values in the proof of concept prototype from output to input.

Transmission	Gear 4	Gear 4 to 3	Gear 3 to 2	Gear 2 to 1	Sum
Flat friction	1 N	1 N	1 N	1 N	
Friction felt at start from gears	1 N	5.33 N	8.89N	44.44 N	**59.67 N**

As can be seen from the above table, overcoming the breakaway friction from the output is much more difficult. Nearly 60 N is needed just to overcome the static friction and get the system to move, and that assumes that the motor is exerting no resistance. Clearly overcoming this static friction is a large issue in correlation with creating backdrivable transmissions.

12.2 Transmission

The thesis statement set was to help solving the issue of creating a humanoid robotic hand, and the process goal was to find the optimal transmission for a backdrivable thumb. After reviewing the theoretical background there were still no apparent suitable solution for a backdrivable transmission system. Five different transmission systems were tested, gear to gear connections was ruled out as unsuited according to theory. Tendons with idle pulleys, tendons with sheaths, timing belts with idle pulleys, linkages and threaded screw-like gears was the five options tested. Test results can be seen in chapter 6.2.

What the testing made apparent was that incorporating backdrivability into a geared transmission system set higher requirements for low friction and backlash than anticipated. This was apparent after uncovering backdrivability and its correlation with friction in the above chapter. When relating that every transmission could handle relatively low force transmissions to the excessive static friction build-up when running the system from output to input, it is clear why most transmission systems worked worse than predicted. The transmission also had an extra amount of friction to overcome since no bearings were used in the prototypes, even though the gearing ratios were low.

Another factor to consider is that the gearing ratio of 44:1 acquired in the proof of concept is still very small for a DC motor. These work at a maximum approximate 8.000-12.000RPM, and the 90° thumb movement only requires a quarter rotation. Meaning that the motor needs to rotate 11 rotations before the thumb has moved 90° with the acquired gearing ratio. A much higher gearing ratio is desired for a DC motor to work optimally. This underlines the issue of getting a small system to work well, especially when a backdrivable system requires low friction gearing and high efficiency in motors to work optimally.

12.3 Proof of concept prototype

The proof of concept prototype exhibited low friction and little backlash in the driving direction, while fitting within the confines set by the human hand. As has been discussed in chapter 12.1, incorporating backdrivability in such a small space will prove difficult. The friction exhibited from output to input degraded the prototypes backdrivability by too large a margin. The prototype did not fulfil the product goal of having one backdrivable joint with a minimum 15 N grip strength, but gave great insights into what should be changed.

What worked well:

- Relatively low friction and virtually no backlash
- Small and low weight solution.
- Thumb worked independently of trapeziometacarpal joints position.
- Thumb and trapeziometacarpal joint felt robust.

The main issues with the prototype was the cable, materials and imprecise build quality. These changes should be incorporated in a new design:

- Stronger cable fasteners. Threaded gear most probably needs more than one connection point.
- Stronger cable with a larger cross-section and less slippery surface.
- Every 3D-printed part needs more accurate mechanical tolerances, especially pulleys and the trapeziometacarpal joint.
- Base not laser cut, nor created from MDF. It is too soft and allows mounting the screws at an angle. (See Figure 12-2 below.)
- Adding an extra pulley or revising the design so the cable does not rub against an edge. (Illustrated in Figure 8-18.)

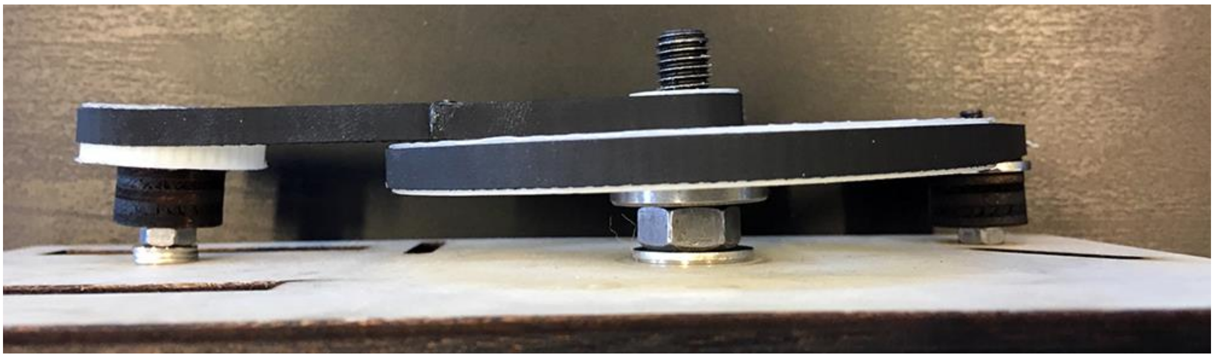


Figure 12-2: Picture showing how skewed the pulleys became with the timing belts mounted.

Figure 12-3: A bearing encasement broke because the mechanical tolerances were too small.

These are the issues that made backdrivability and general operations difficult. With a more accurate set up, this proof of concept might be worth pursuing, that is if the friction can be reduced to negligible levels in the transmission. Yet, the more pressing issue seems to be how to incorporate backdrivability. Clearly incorporating backdrivability will be difficult when using a geared transmission and a DC motor when everything ought to be within the human hand size constraints. If a larger motor could be placed outside the hand, a solution akin to this is viable. If not, other possible solutions for incorporating backdrivability-like function into the hand should be researched. Some possibilities will be presented in further work.

13 Conclusion

This thesis main goal was to develop a backdrivable robotic thumb with a 15 N minimum grip strength. By solving this issue, a mechanical hand with passive fingers and few sensors can be constructed. The process goal was to find the optimal transmission system for a backdrivable thumb.

After testing the different transmissions systems, it became apparent that finding a transmission system which could incorporate all product goals would be difficult. Not enough force could be transferred without achieving large friction in the system, and both slack and slippage was rampant, no clear optimal solution was found for the process goal.

Table 13-1: Results amassed from transmission testing, Reader is referred to Table 6-2 for further details.

Transmission	Backdrivable	Force	Slack	Friction	Gearing
Tendons	Limited	1.5kg	15°	<0.5kg	10:1
Timing belts	Yes	3.5kg	90°	>0.5kg	10:1
Linkages	Yes	4kg	0°	<0.5 kg	2:1
Screws	Yes	Hand	1-2°	Negligible	1:1
Sheaths	Limited	1kg	-15°	Up to 4kg	1:1

Timing belts and threaded screw-like gears showed promise for handling relatively large forces in comparison to their size and both seemed to work reasonably well with regards to backdrivability, which is why they were used in the prototype.

It was unable to determine if proof of concept prototype functioned with backdrivability, but some other product goals were accomplished:

- The prototype had a simple and inexpensive design, using only low-cost components, not including the motor which has not yet been chosen.
    - Total cost of prototype including labour: 8934 NOK
    - Total cost of prototype excluding labour: 1934 NOK
    - Prototype consists of 4 special made components. The rest can be purchased as standard components.
- The entire design fit inside the space allocated by the human hand.
- It was light, a total of 166g excluding motor, using only plastic parts and some bearings.
- In comparison to many other transmission solutions; the prototype had little friction and backlash.

What became apparent was that the cable was especially suspect to breakage, and one of the critical points in the design. It put too much strain on the other components. Especially concerning was that the screw used to wind up the cable was torn straight off. This means that one connecting point most probably is not enough to hold the forces exerted on it, and a second fastening location is needed within the confines of the trapeziometacarpal joint.

In conclusion the design did not work well for its intended purpose of being backdrivable, even though it worked well when compared to the other product goals. Many aspects of why incorporating backdrivability with geared transmissions have been uncovered, and will help further the understanding of how to create a humanoid robotic hand.

14 FURTHER WORK

In this chapter further work that remains or ideas sprung from this work is stated.

As mentioned in chapter 12.1 *Relations in backdrivability and geared systems*, the relation between friction and backdrivability should be researched further. In small space such as the hand, force amplifications are needed to create a functioning thumb, especially if using a direct drive motor is required. As Nef & Lum discovered; to compensate for static friction, the system needs to know what direction it should move in before the actual movement occurs. [103] To create this possibility in a robotic hand, a proper visual guidance analysis is required. Then a human hand can be detected, and by making assumptions for when the thumb will be pushed onto, the motor can compensate for static friction by e.g. applying a small backwards torque, which allows for easier external thumb movement.

Another proof of concept design where all the improvements mentioned in chapter 12.3 are implemented should be made. Tests on how small the friction can be should be checked in a new prototype, including finding the max load.

Research should be done on alternatives to backdrivability; such as force reduction drives, worm gears and other possibilities for controlling the thumb without impacting the motor negatively. Since the robot created by Halodi Robotics might not have detachable end effectors, having some motors inside the robots' forearm may be a possibility worth considering. There is already very little space inside the forearm, but everything that can be placed somewhere else than inside the hand increases the amount of possible solutions.

Materials should be researched more thoroughly. The design using ABS plastic was very limited in its capacity, and the present design with the current materials does not have a high enough safety factor and will most probably break quickly under a large load. By first knowing what material to use, a different design can be found by utilizing the materials strengths as well.

Motors need to be evaluated or considered designed from the ground up. Finding a motor with good compatibility with backdrivability is challenging and will require much testing.

A freedom to operate (FTO) analysis needs to be completed to ensure that the design does not infringe upon any existing patents or copyrights.

A better humanoid robotic hand can lead to more agile and safer prosthetics, it can lead to natural human-robot interaction and a future where getting help from a robot is just as natural as using a phone. The elderly can have their own personal caretaker, space can be explored with remote astronauts and those who have lost a limb may be able to reacquire their original quality of life! It is merely a question about minimizing friction, better actuator technology and smart sensing. It is especially recommended to continue work on minimizing and compensating for friction in small geared transmissions.

15 SOURCES

Litterary sources

[1] D. J. Sturman, "Whole-hand input," Massachusetts Institute of Technology, 1992.

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16 APPENDIX

I. Table of hands

Table 16-1: Part 1 of the competing solutions table

Name	#	Year	Fingers	Joints/DOC	N° actuators	Actuation type
Human hand	**1**	-	5	22/18	38	Intrinsic and extrinsic muscles
Belgrade	**2**	1969	3	13/1	1	Remote DC motors
Okada hand	**3**	1978	3	9/9	9	Remote DC motors
Stanford/JPL hand	**4**	1981	3	9/9	12	Remote DC motors
Utah/MIT Hand	**5**	1982	4	16/16	32	Remote pneumatic actuators
The Hitachi Robot hand	**6**	1984	4	12/12	48	Remote SMA
Belgrade/USC hand	**7**	1988	5	18/4	4	Remote DC motors
Barrett hand	**8**	1988	3	18/4	4	Brushless DC motors
UB hand II	**9**	1992	5	13/13	13	Remote DC motors
NTU hand	**10**	1996	5	17/17	17	Micro DC motors
DLR hand I	**11**	1997	4	16/12	12	Micro Brushless DC motor
DIST hand	**12**	1998	4	16/16	20	Remote Brushless DC Motors
LMS hand	**13**	1998	4	17/16	16	Remote DC motors
Robonaut	**14**	1999	5	20/12	12	Remote DC motors
MANUS	**15**	1999	5	8/2	2	Brushless DC motors
DLR hand II	**16**	2000	4	17/13	13	Brushless DC motors
TUAT/Karlsruhe hand	**17**	2000	5	17/1	1	Remote ultrasonic motor
Southampton REMEDI hand	**18**	2001	5	13/6	6	DC Motors
High speed hand	**19**	2001	3	8/8	8	DC Brushless motors
GIFU hand II and III	**20**	2001	5	20/16	16	DC Brushless motors
Shadow hand	**21**	2002	5	23/23	36	Remote Pneumatic actuators (McKibben muscles)
RTR II	**22**	2002	3	11/2	2	DC Motors

Sensorhand speed	**23**	2002	3	3/1	1	DC Motor
UBH III	**24**	2003	5	20/20	20	DC Brushless motors
IOWA-hand	**25**	2004	5	11/11	11	-
Karlsruhe hand	**26**	2005	5	15/15	15	Pneumatic actuators (flexible fluid actuators)
I-Limb	**27**	2007	5	11/5	5	DC motors
Vanderbilt Hand	**28**	2007	5	17/6	6	Remote Gas actuators
SmartHand	**29**	2008	5	16/4	11	DC Motors
SDM hand	**30**	2008	4	8/1	1	Remote DC Motor
BeBionics	**31**	2010	5	11/5	5	DC Motors
CEA dextrous hand	**32**	2014	5	24/20	20	Rotary DC motors
Roboray	**33**	2014	5	14/12	12	Remote DC motors
iRobot-Harvard-Yale	**34**	2014	3	8/5	5	Remote DC motors
iCub hand	**35**	2014	5	20/9	9	Remote DC motors
RBO-hand 2	**36**	2015	5	–/4	7	SMA
Brunel hand	**37**	2016	5	9/4	4	DC linear actuators
Biomimetic hand	**38**	2016	5	About human	10	Remote DC motor

Table 16-2: Part 2 of the competing solutions table.

Sensors			
#	**Position**	**Force/torque**	**Contact**
1	About 17,000 mechanoreceptors for touch, pressure, pain and temperature detection, and musculo-tendinous receptors for proprioceptive information		
2	–	–	Finger tip tactile sensors
3	Encoders	Torque sensors	–
4	Encoders	Tendon tension sensors based on strain gauges	Fingertip force sensors 8 × 8 tactile sensors array
5	Encoders and joints angle sensors based on Hall effect	Tendon tension sensors based on Hall effect	Capacitive tactile sensors
6	–	–	–
7	Encoders	–	Tactile sensors
8	Encoders	Torque sensors based on strain gauges	–
9	Encoders and joints angle sensors based on Hall effect	–	6-axis sensors
10	Joint position sensors	–	Tactile sensors
11	Hall motor sensors motors, PSD-LED joint sensors	Torque sensors based on strain gauges	Tactile sensors
12	Encoders and joints angle sensors based on Hall effect	–	3-axis fingertip force sensors
13	Encoders and potentiometers	Force obtain by means of tendons elongation	–
14	Encoders, joint sensors	Force sensors	FSR tactile sensors
15	Encoders and joints angle sensors based on hall effect	Sensors based on hall effect	–
16	Encoders, potentiometers	Torque sensors based on strain gauges	Tactile sensors

Sensors			
#	Position	Force/torque	Contact
17	–	–	–
18	Encoders	–	–
19	Encoders	Sensors based on strain gauges and 6-axis force sensors	Tactile sensors
20	Encoders	–	Tactile sensors (859 detecting point)
21	Joints angle sensors based on Hall effect	Pressure sensors	Tactile sensors
22	Joints angle sensors based on Hall effect and encoders	Sensors based on strain gauges	FSR sensor
23	Encoder	Sensor based on strain gauges	SUVA sensor
24	Bending sensors (Piezoresistive effect)	Sensors based on strain gauges	Intrinsic tactile sensors
25	–	–	–
26	Joint sensors	–	Tactile sensors
27	Encoder	–	–
28	–	Tension sensors	–
29	Joints angle sensors based on hall effect and encoders	Sensors based on strain gauges	LED and photo detector
30	Joints angle sensors based on Hall effect	–	LED and photo detector
31	Encoders	–	–
32	Encoders	Voltage encoder	Algorithm
33	–	–	–
34	Magnetic encoders and accelerometers	Magnetic encoders and flexure deformation	Tactile and flexure deformation
35	17 hall effect sensors	48 pressure sensors	12 tactile sensors
36	-	–	–

Sensors			
#	Position	Force/torque	Contact
37	–	–	–
38	-	–	–

Table 16-3: Part 3 of the competing solutions table.

#	Weight [Kg]	Dimensions	Transmission	Force[N]/Speed [s]	Purpouse	Reference
1	0.4	1	Net of tendons and sheats	400/0.25	Multipurpose	
2	–	1	Linkages	–/–	Prosthetics	[34]
3	–	1	Tendons	–/0.2	Object-handling system for manual industry	[33]
4	5.5	1.2	Tendons, pulleys and sheats	45/–	Machine dexterity	[32]
5	3.2	2	Tendons, idle pulleys	32/0.1	Machine dexterity, fingertips, phalanges, palm manipulation	[52]
6	4.5	<1	Tendons, pulleys and sheats	20/–	–	[106]
7	–	1.1	Linkages	22/2	Prosthetics	[34]
8	1.2	1	Gears	15/1	Multipurpose end-effector	[35]
9	–	1	Tendons, pulleys and sheats	–/–	Machine dexterity	[107]
10	1.57	>1	Spur gears	10 / 1	Industrial and prosthetics applications	[54]
11	1.8	2	Tendons, and pulleys	–/0.5	Grasping control and telemanipulation	[47]
12	<1	1	Tendons, pulleys and sheats	–/–	Grasping control and telemanipulation	[47]
13	1	–	Tendons, pulleys and sheats	–/–	Grasping control and telemanipulation	[48]
14	1.2	–	Linkages, flexible shafts, and cams	–/–	Space operations	[108]
15	1.2	1.2	Linkages, and tendons	40/–	Prosthetics	[109]
16	–	1.5	Bevel gears	40/–	Space operations	[110]

#	Weight [Kg]	Dimensions	Transmission	Force[N]/Speed [s]	Purpouse	Reference
17	0.125	1	Linkages	–/–	Humanoid robot	[111]
18	1	0.4	Linkages	9.2/0.8	Prosthetics	[112]
19	0.8	1	Gears	28/0.1	Catching and dexterous manipulation by vision	[30]
20	1	1.4	Gears	5/0.1	Tele-operation and dexterous manipulation	[113]
21	4	1	Tendons, pulleys and sheats	16/0.5	Tele-operation and dexterous manipulation	[114]
22	0.35	1	Tendons, pulleys and sheats	–/1.5	Prosthetics	[115]
23	0.4	1	Linkages	100/1	Prosthetics	[116]
24	–	1	Tendons and sheats	10/0.85	Humanoid robot	[117]
25	0.09*	1	Tendons and sheats	–/–	Prosthetics	[118]
26	0.15	1	Direct drive	12/0.1	Prosthetics and Humanoid	[119]
27	0.518	1	Flexible rackets	–/–	Prosthetics	[120]
28	1.6 (whole arm)	1	Tendons and sheats	150/0.5	Prosthetics and humanoid	[121]
29	0.560	1	Tendons, pulleys and sheats	45/1.2	Prosthetics	[29]
30	0.16*	1	Tendons, pulleys and nylon conduits	–/–	Multipurpose end-effector	[122]
31	0.539	1	Linkages	–/–	Prosthetics	[123]
32	4.2	1,2	Tendons and pulleys	60/ 0,21m/s	Robotics	[61]
33	1,56	1	Tendons	15/-	Robotics	[124]
34	1,35	0,8	Tendons	220/-	Robotics	[125]
35	–	–	Tendons	–/–	Robotics	[126]
36	<1	1	Flexible material	16/-	Multipurpose end-effector	[127]
37	0.371	1	Tendons	80/–	Robotics	[128]
38	0,942	1	Tendons and sheats	–/–	Prostethics and limb regeneration	[129]

II. Testing limiting design factor: transmission alternatives

In this chapter simple prototypes for transmission systems for the thumb will be created. Referencing chapter 2.7 *Limiting design factor* for why testing on transmission systems are done. The thumb poses some design difficulties, and therefore possible solutions must be tested before a design can be created. Something that works well in theory, does not always transfer to a feasible solution.

These are the two most important goals to be found in this testing:

- *Can the transmission transfer the necessary amount of force?*
- *Does the transmission work from input to output and vice versa?*

Other goals are finding out:

- How much slack and possible backlash will there be in the systems?
- How much friction will there be in the system?

The experiments will follow a slightly modified version of the scientific method as used in Colby College. [130]

1. A hypothesis will be set. This will be broad, and consider how well a certain solution might fit into the hand.
2. A brief overview of the test rig and its creation process will be written.
3. Several predictions about the solution will be stated. These will be set according to theory and what further needs to be examined for a solution to be viable.
4. Experiments to test each prediction will be done. These will be as measurable and re-creatable as possible, but some results will still be partly subjective.
5. Results of the experiment will be analysed and discussed. The analysis is connected to the metric product requirements, as will the discussion, along with subjective notes on how well the test worked.
6. A short conclusion will be written.

i. Palm gear prototype using tendons with idle pulleys

The point of this prototype was to see how well a cabled gearing might work.

a) Hypothesis

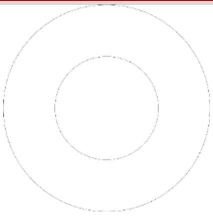
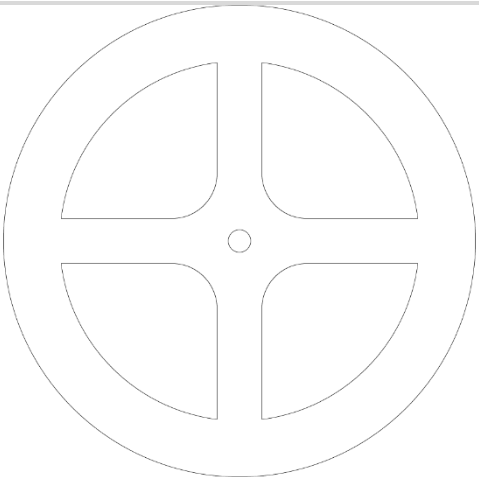
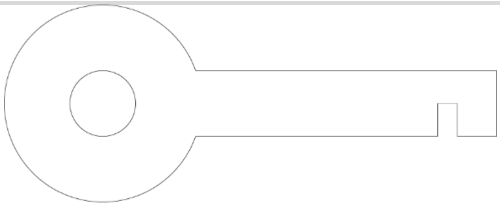
The point of this prototype was to see how well a cabled gearing might work.

“Cables wound around pulleys cannot transfer power with little loss from a rotating engine.”

b) Set up

A simple testing rig was designed using a few different components. This will give a theoretical gearing ratio of 10:1.

Table 16-4: Overview of parts used in the test rig.

Illustration	Description
	This is the small gearing wheel. - 20mm in diameter - Two 30mm wheels were used on both sides of the small gearing wheel to ensure that the cable stays in place.
	This is the large gearing wheel. - The gearing wheel is 200mm in diameter. - Two larger wheels of 210mm was used as guards ensuring that the cable kept in place.
	This is the simplified thumb. - The length to the middle of the slot is 54mm, which is the average female thumb length. This slot will be used to test the strength of the system.

The parts were created using 5mm sheets of MDF and laser cutting into the needed pieces. All the pieces were assembled onto M10 screws with a flat part at the top. The bottom part of the screws was fastened to a plate, and simple thread was looped around the main gearing parts.

Figure 16-1: Assembled test rig.

c) Predictions

These are the predictions set for this system:

- There will be little slippage in the system
- The system can transfer nearly 8kg of force.
- It will be possible to achieve little slack in the cables and system during assembly.
- There motion will be smooth both from input and from output.
- The system will be partially compliant.

d) Experiments and results

The gears were turned on both sides, and the mechanism turned smoothly and equally from input to output and from output to input. Being significantly easier to turn one way from input than output, which is what was intended. This also means the system is inherently compliant, but since the gearing wheel in this scenario is relatively large and there is a higher gearing ratio to move the thumb, the system will not work perfectly in quick collisions, but when force amasses over time it will work well.

A visual inspection showed that there was quite a bit of slack in the cables, even though they were assembled with care to keep the cables under tension. Assembling the cables and avoiding slack will not be easy.

As can be seen in the figure there was about 15 degrees of slack in the thumb joint using simple thread and no pretension on the cables.

Figure 16-2: Slack shown on thumb joint.

Using a spring weight to pull on the thumb while keeping the rest of the system static, slippage occurred at around 1.5kg of force. Slippage occurred in the same gearing system as the thumb, in the small wheel attached to the large gear. This is not unexpected since the large gearing wheel has a larger surface area and therefore more friction.

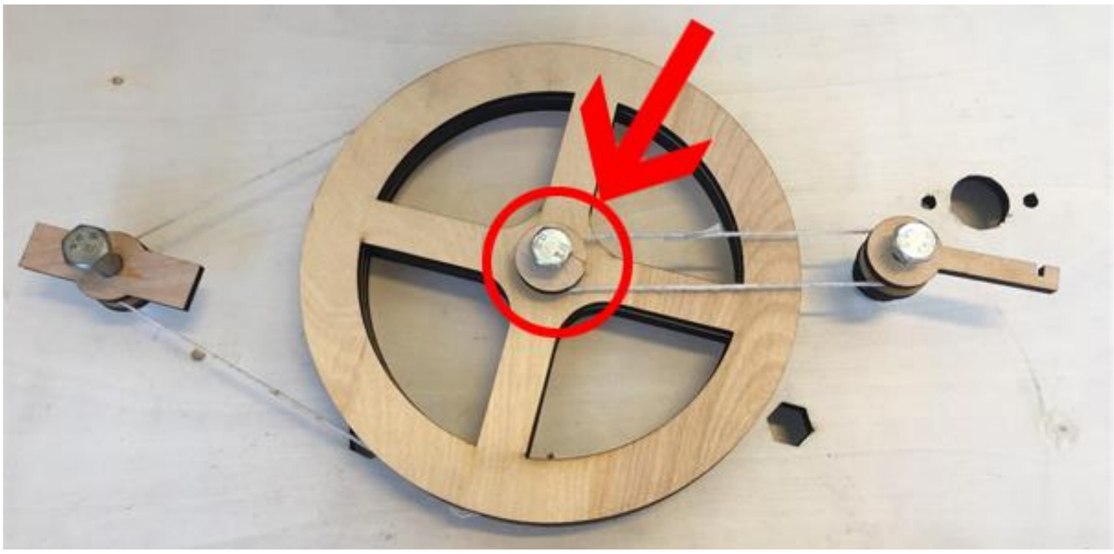


Figure 16-3: Slippage occured here.

A higher number of cable windings led to less slippage, but also more friction between the cables, and using three windings instead of two led to a noticeably larger force needed to make the wheels rotate.

e) Discussion

The test rig is not constructed well enough.

Slippage occurred quickly, most probably due to a lot of ash still being present in the gearing wheels after having cut the wood using a laser.

Using a glue gun, the adhesion between the plates were not good enough and they often broke. Superglue posed the same problem, but less frequent. This won't be a problem in the real prototype, since the gearing wheels then will be produced in one whole part.

Finding a way to increase the tensions in the cable must be done, or it needs to be tightened so that it only pulls in one directions and springs are used to reset the system. Another cable than string should be used, as this one snapped when too much tension was put on it.

f) Conclusion

The hypothesis that this gearing system cannot transfer a decent amount of force from the motor with little loss is still true. If the slippage cannot be prevented, this solution is limited to small forces.

ii. Palm gear prototype using timing belt tendons with idle pulleys

The point of this prototype was to see how well a cabled gearing using timing belts might work.

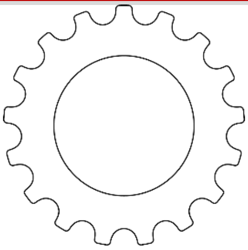
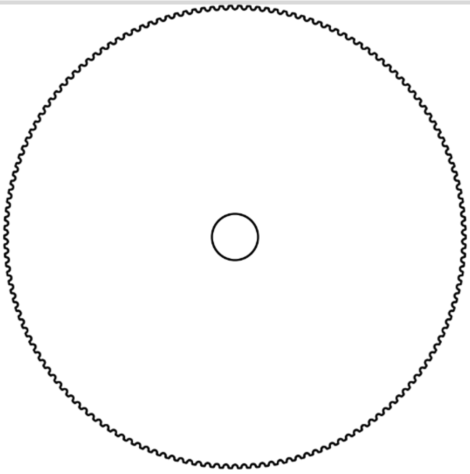
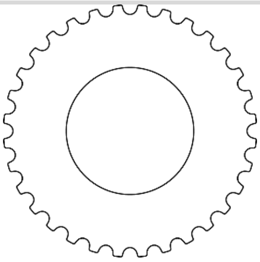
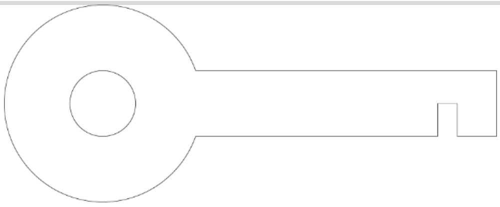
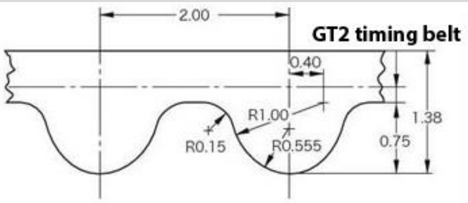
a) Hypothesis

"Timing belts with pulleys cannot transfer power with little loss from a rotating engine."

b) Set up

A simple testing rig was designed using as few components as possible. The rig will give a theoretical gearing ratio of 10:1.

Table 16-5: Overview of parts used in the test rig.

Illustration	Description
	The system starts with a 10mm pulley with 17 teeth using the GT2 belt standard. A 6mm hole was cut to place it on a M6 screw without threads at the upper end.
	The large gearing wheel is 100mm with 158 teeth. A 10mm hole was cut in the middle so that it could be mounted onto a 10mm screw without threads at the upper end.
	The gearing between the large gear and the thumb is two 20mm gears with 36 teeth in a 1:1 gearing ratio. This also used a 10mm hole.
	This is the simplified thumb. - The length to the middle of the slot is 54mm, which is the average female thumb length. This slot will be used to test the strength of the system.
	The timing belts were 100mm and 110mm in diameter, with a height of 3mm and width of 2.3mm.

The gearing wheels were cut using 5mm sheets of MDF and the timing belts were 3D printed using the material SemiFlex on a Flashforge Guider 2. A simple tensioning system was also devised. This consisted of slots adjacent to the timing belts. Screws with a flat part was fastened so that a cut MDF part was free to rotate along the belt, making sure that there was enough tension on the belt to ensure that it won't skip out of the slots on the pulleys.

Figure 16-4: The tension system.

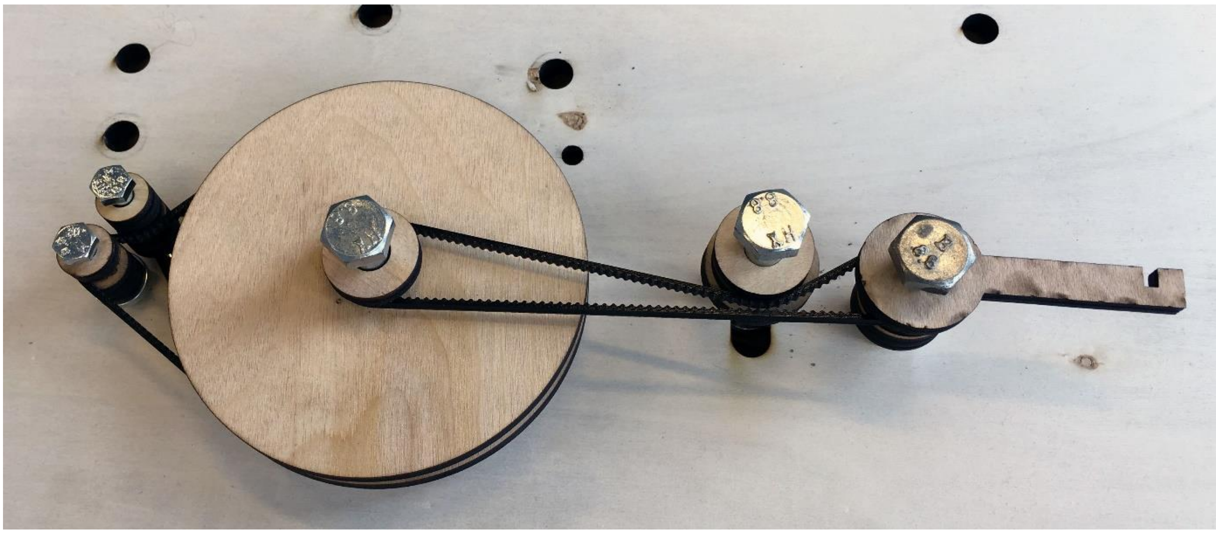


Figure 16-5: The complete test rig with semiflex timing belts.

c) Predictions

These are the predictions set for this system:

- The belts can transfer nearly 8kg of force.
- There will be little slippage/skipping in the system.
- Belts have little to slack.
- The system will create smooth motion from both input and output.
- The system will be slightly compliant.

d) Results

Pulling on the thumb with about 10N of force caused the belts to skip without using the tensioners. Using the tensioners this increased to about 35N, before it started to skip. The belts can transfer more force, but they need to be fastened tighter for it to transfer the necessary amount of force

Since the belts are elastic there was quite a bit of slack in the system. When the belt was tensioned as much as possible the belt as mentioned stopped skipping as much, but the thumb could be bent nearly 90 degrees before the belt started skipping. Leaving nearly a full 90 degrees of slack from the elongation due to the material of the belt.

The motion is smooth from input and choppy from the output, and therefore it does not work well in both directions

The system is much more compliant due to elongation of the belts than anticipated, and would probably handle both slow and quick crashes well.

e) Discussion

The belt needs to be stronger, and allow for less elongation. Therefore, a timing belt was printed using nylon. This broke the entire prototype when trying to tighten the belt up due to it being too strong for the glued MDF prototype. However, the belt gave smooth motion in both directions and seemed capable of transferring larger forces, but this was not tested due to the prototype breaking during the experiment. A stronger prototype using nylon belts may be devised.

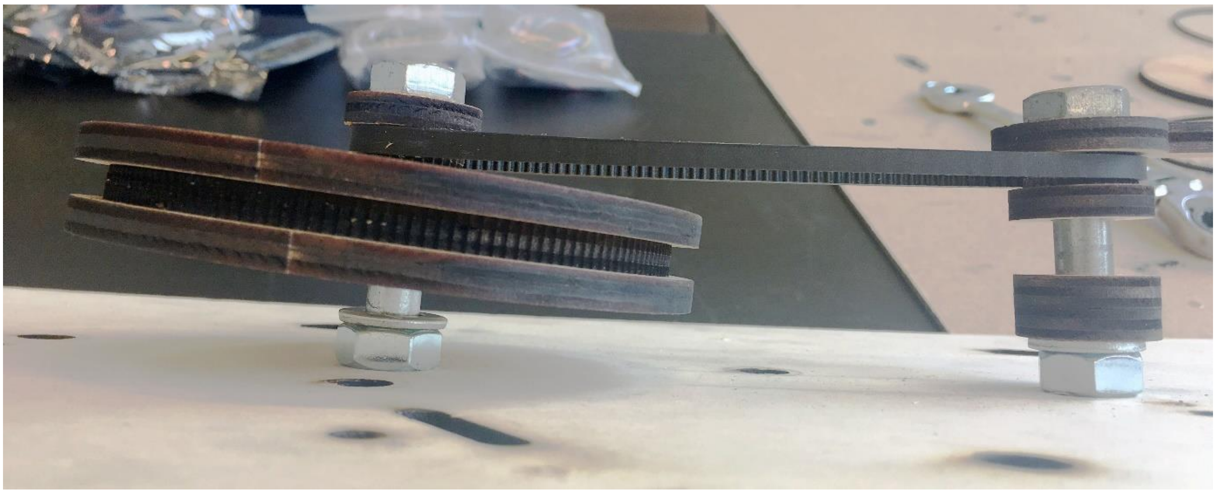


Figure 16-6: The prototype broke when tensioning the nylon timing belt.

The higher belt tension also created noticeably larger friction in the system, but this might be less of a problem if bearings are used.

f) Conclusion

The hypothesis that this gearing system cannot transfer a decent amount of force with little loss is still unclear, but seems to still ring true. Higher belt tension allows for larger forces to be transferred, but also an apparent increase in friction. Another prototype should be made.

iii. Adjustable lock pliers prototype for testing linkages

The idea of this prototype was to see how well a stiff mechanical linkage system might work. By using the design of lock pliers, the arm can be changed allowing for different gearing ratios and a wider range of motions for the thumb.

a) Hypothesis

"A linkage system cannot transfer a decent amount of force."

b) Set up

A simple testing rig was devised, about twice the size of what ideally could be used in the hand. All holes are 8mm in diameter. The parts were laser cut using 5mm thick sheets of MDF.

Table 16-6: Overview of the parts used.

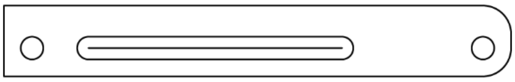
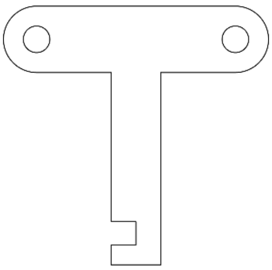
Image	Description
	The upper lever - Distance between the two holes are 180mm - Distance between connecting point for the middle bracket and the front hole is 50mm
	Lower lever - Distance between the two holes are 180mm - Distance between slot and the front hole is 50mm
	Middle bracket - 75mm between the holes
	Thumb bracket - 60mm between the holes - Distance from the holes to middle of the slot is 58mm, slightly longer than the average female thumb. This was not doubled due to concerns with the MDF breaking, and therefore results in the actual mechanism are twice as large.

Figure 16-7: The assembled prototype system.

c) Predictions

These are the predictions set for this system:

- There is room for the system inside the hand, and it will not pose a large problem in placement of the motor to drive it.
- The system will give smooth motion in both directions.

- The gearing ratio will not be that high.
- Friction and inertia will be high.

d) Results

These are the results amassed:

The solution needs quite a lot of space. All the different settings for the slider creates a large possible number of places where the lever can be. This means that the lever probably should be at least 20% smaller than the space of the palm, and all the palm is needed to account for the space needed for both the lever and motor.

As can be seen in Figure 16-8 the test-weight that was used weighed slightly more than 4kg. Setting the slider at the utmost spot on the prototype, as shown in Figure 16-7, the weight showed slightly more than 1kg fastened to the lever arm, as can be seen in Figure 16-9.

This means that the maximum gearing ratio acquired during the experiment was around 4:1, which must be cut in half due to the thumb being the correct size and the rest of the system being doubled in size. That means a maximum gearing ratio of 2:1 is possible to acquire with this form factor. This also means that moving the system in both directions is relatively easy, and it gave smooth motion in both directions

Figure 16-8: Test weight used in the experiment. It weighed sligtly more than 4kg.

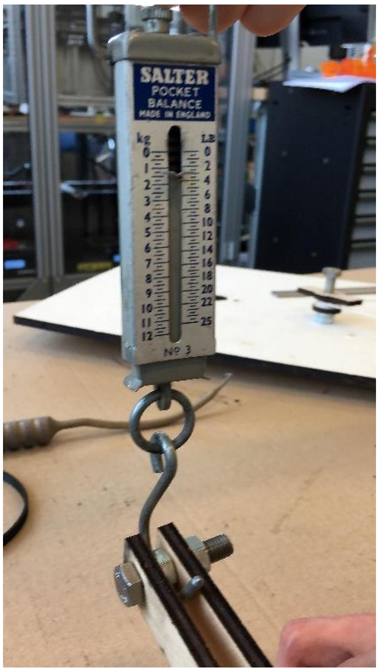


Figure 16-9: Weighed weight during experiment. The weight showed slightly more than 1kg.

The system had quite a bit of friction and inertia. When the weight was used to move the lever in the utmost position as in the previous experiment, the weight showed around 1.5 kg before the system started moving. This means that there was about 5 N of force needed to overcome friction and inertia in the system. Since the test was done moving it slowly, most of this was from friction.

e) Discussion

The test rig worked well as a preliminary examination as to how the system might have worked in the hand.

It needs too much space for how little force multiplication it does. In this system the motor requirements are halved, but that still requires a very powerful motor capable of producing around 40N for it to work optimally. That poses problems in correlation with finding a small enough size for a direct drive motor.

There was also quite a bit of friction and inertia needed to move the system, but this can be reduced by using bearings and grease. Assuming the maximum force is 80N, that means:

$$\frac{5}{80} * 100\% = 6.25\ \%$$

6.25% of the force used in the thumb disappears to friction and inertia, and that is assuming maximum force. During lower forces, which is what the thumb primarily will be used for, the numbers look worse. Since friction isn't linear either, it changes with speed, temperature and other factors, this makes the system more difficult to control.

f) Conclusion

The hypothesis that this system could not transfer high forces falsified in these tests. It could transfer high forces, but the force amplification at 2:1 is too low for it to be used directly in the palm since no motor without gearing will be strong enough at such a small size, and there were a lot of friction.

iv. Oppositely threaded screw gear prototype

The point of this prototype is to check if a screw can work well as a gearing mechanism for the thumb. By using two screws with opposite threads one part will pull on the cable and the other will push the cable. By using this mechanism, the cable will always be tensioned, and can work in both directions without the use of an extra pulley system and an extra motor.

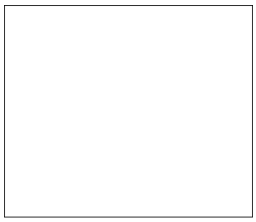
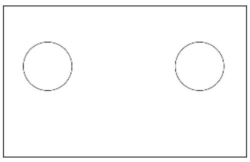
a) Hypothesis

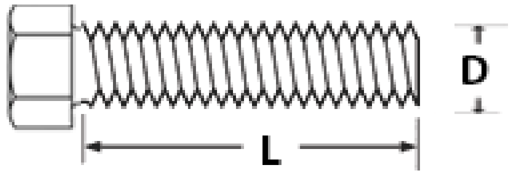
"A screw gear system cannot transfer the needed amount of force, and is not backdriveable."

b) Set up

A simple testing rig was set up to test the validity of the idea. All the parts were laser cut using 6mm sheets of MDF.

Table 16-7: Overview of the parts used.

Image	Description
	Bottom plate - 80mm long and 68mm wide - Two side plates were glued onto the long edge of this bottom plate. - Two 40mm long M16 bolts were used, and the plate was 6mm wide, hence 68mm width.
	Side plate - 80mm long and 50mm tall - Two identical plates were glued onto the bottom plate. - 16mm diameter holes for two 16mm screws, placed 50mm apart.

	Screw - 16mm was used for the preliminary test - L: 40mm - D: 16mm - Used since thread size was large enough for the hemp used as cable

The M16 screws were fastened together using a 16mm nut. Tw screws with different lengths were used so that the cable could be fastened between the two 40mm long M16 screws as shown in Figure 16-10.

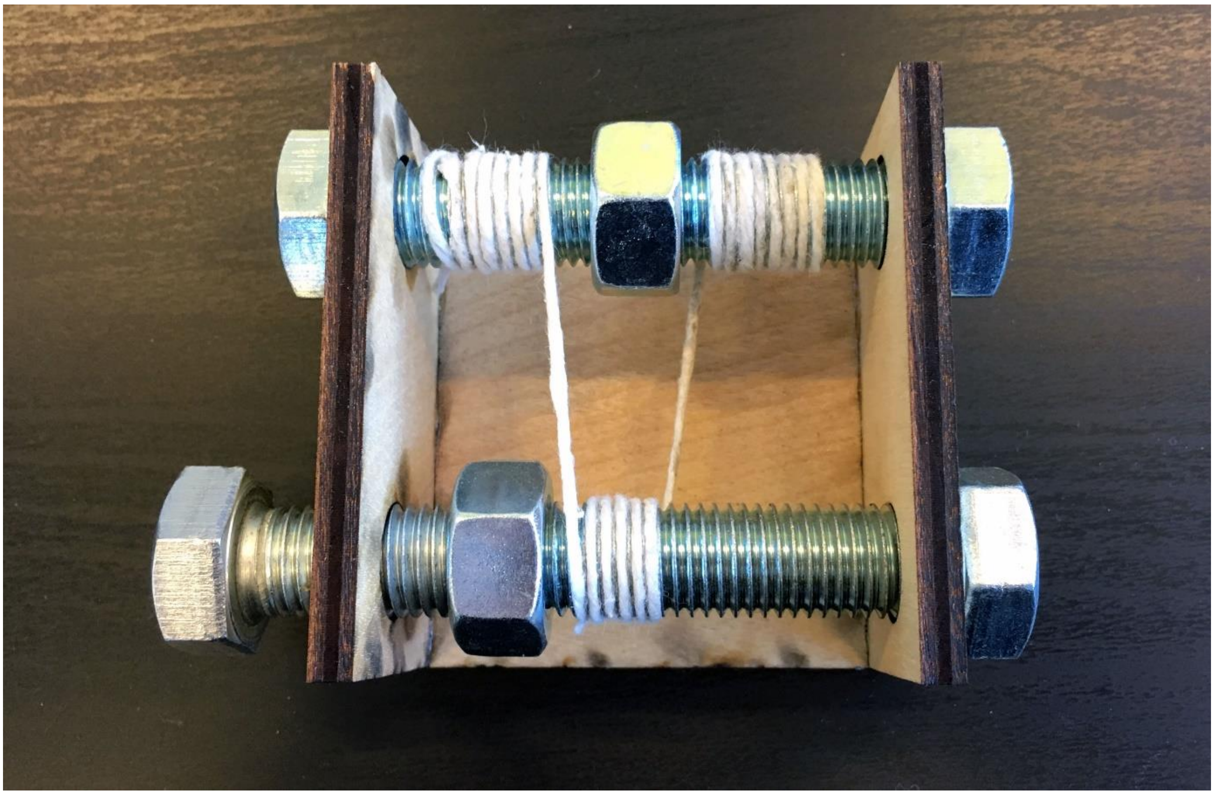


Figure 16-10: The assembled screw gear prototype.

c) Predictions

These are the predictions set for the system:

- The system can transfer up to 8kg of force, dependant on screw diameter and number of windings.
    - A 40mm long screw with a diameter of 16mm will be sufficient.
- The system will be backdriveable using the aforementioned screw.
- There will be a moderate amount of power lost to friction.
- There will be no slippage in the system.
- There will be little slack in the system.
- Motion will be smooth both ways.

d) Results

In the test a 16mm screw to another 16mm screw was used to check the validity of the idea. Thread was wound around the screws and tightened. Smooth motion in both directions was achieved, and it was easy to rotate using both input and output. The thread used wound up and was fed out at an equal ratio, keeping the thread tensioned when moving in both directions. Without any gearing the system is backdriveable.

There was no slippage in the system when using the cables were wound tight around the screw five times using hand power.

Little power seems to be lost to friction.

e) Discussion

16mm screws were used because they had threads large enough to accommodate for the cable used. The only cable available when testing was large hemp. A smaller cable will allow for smaller screws and a larger gearing ratio. Backdriveability must be tested using a geared system.

f) Conclusion

When there is no gearing in the system, the hypothesis that the screw gear can transfer the needed amount of force while being backdriveable appears to be false. It is still unknown how it works when geared.

v. Flexible filament using tendons with sheets

This prototype will test if using a flexible filament with cables running through sheets or just holes in the material is a possible solution for a transmission system for the thumb.

a) Hypothesis

“Using flexible filament and cables, the thumb cannot hold a weight of 8kg.”

b) Set up

Table 16-8: Overview of the thumb in flexible material.

Set up for the thumb made with flexible material

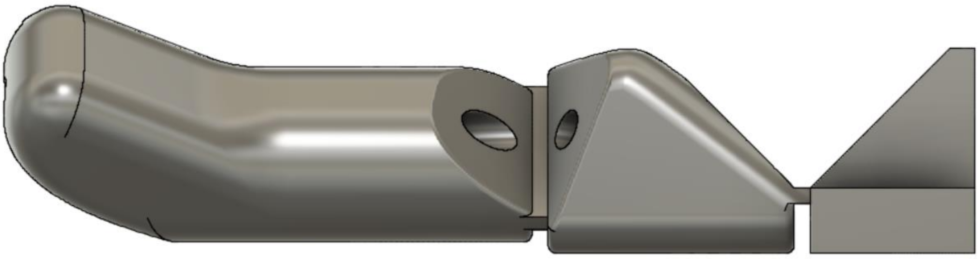



Figure 16-11: Model of the thumb from Fusion 360.

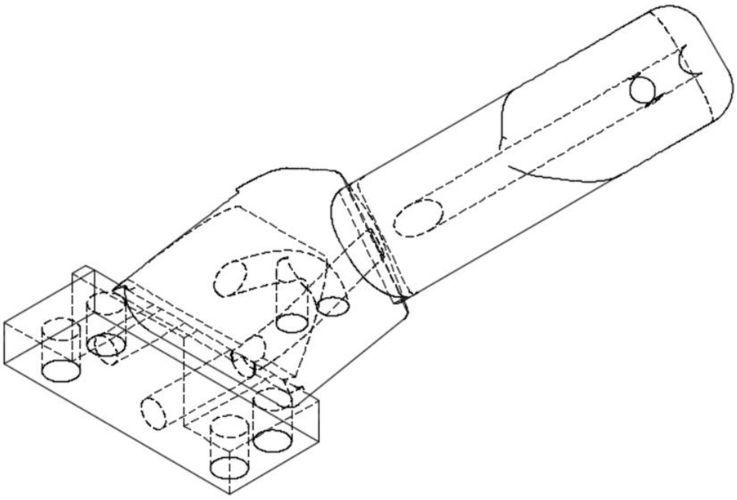



Figure 16-12: Drawing showing the pathways for the cables inside the model.
The thumb is approximately 90mm long, with about 60mm of the length being the thumb, and 30mm the joint residing in the palm. Thickness of the thumb is aproximately 20mm.

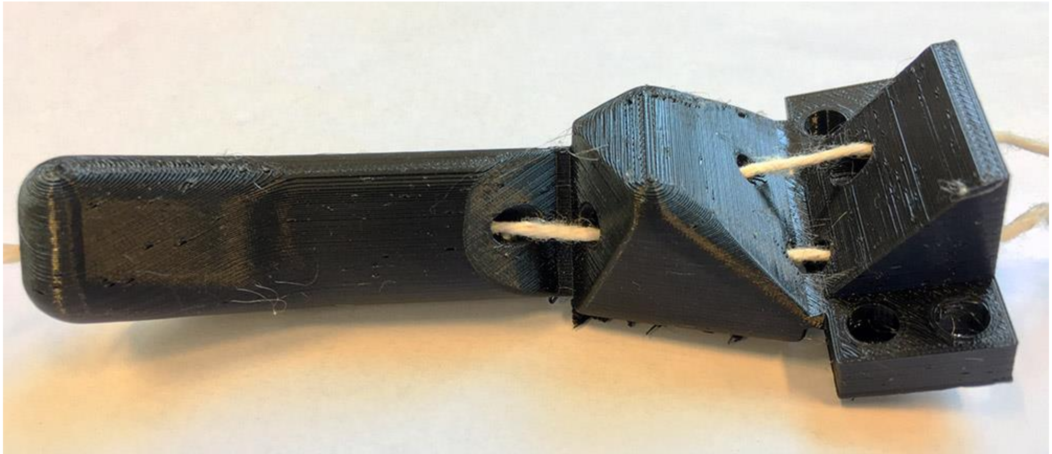


Figure 16-13: The printed thumb prototype in semiflex.

The thumb was printed on a FlashForge Guider 2 using the material SemiFlex. Infill was set to 15%.

c) Predictions

These are the predictions for the system:

- There will be a small amount of force lost from the material in the joints that functions as springs.
- There will be a moderate amount of force lost to friction from the cables.
- The system will be able to hold 8kg.

d) Results

In the inner joint about 0.5kg were lost due to the material in the joint.

On the outer joint about 1kg were lost due to material in the joint, and some of this resistance also stems from the inner joint.

If the cables could travel along the opening, and not rub along one of the edges of the holes the friction was minimal. When the cable started rubbing along the edges friction became excessive and the cable started fraying from the forces and friction. Friction in the inner joint was about 0.5kg due to these issues, and much higher in the outer joint. Approximately 3 to 4kg of force was lost in the outer joint.

Lifting a 1kg weight resulted in not being able to control any of the joints freely due to excessive resistance in the system. Especially the outer joint was incontrollable, some movement was still allowed on the inner joint. The structure of the thumb also starts to deform at around 4kg of force exerted on the tip of the thumb.

e) Discussion

Movement worked relatively well for an early prototype, but the pathways and opening for the cable were placed incorrectly and/or were too small. Fixing this can remove part of the issue with excessive friction, but controlling the thumb will still be difficult due to the length of the thumb and the cables increasing the force needed to use it.

f) Conclusion

The transmission system is not capable of functioning with 8kg of forces in its present state, and the hypothesis is correct.

III. Programs used

An overview of the programs used in the thesis.

Table 16-9: A table showing the different programs used and the program version.

Logo	Program
	Microsoft Word 2013, version 15.0.4981.1001
	SolidWorks 2016-2017 Student Edition
	Fusion360 Ultimate, build 2.0.3706. Have been used to model the hand and for FEM-calculations.
	Adobe Photoshop CC 2018
	Microsoft ExCel 2013, version 15.0.4981.1001
	Granta Design CES EduPack 2017, build 17,2,0,0
	OneDrive 2018 version 18.044.0301.006

IV. Project plan with milestones

GANT scheme showing when the different aspect of the thesis is planned to be done, and how for how long certain aspects are to be worked on.

Table 16-10: Simple GANT table showing approximate planned time usage.

Milestones Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Theory	■	■	■	■	■	■												
Competitor research					■	■	■											
Project plan and method						■	■											
Metric hand specifications						■	■											
Concept generation							■	■	■									
Prototyping and testing								■	■	■	■	■						
Concept design, CAD									■	■	■	■	■	■				
FEM									■	■	■	■	■	■	■			
Finishing writing															■	■	■	■
Deliver thesis																		■

V. Process

A schematic overview of the process that was to be used in the thesis.

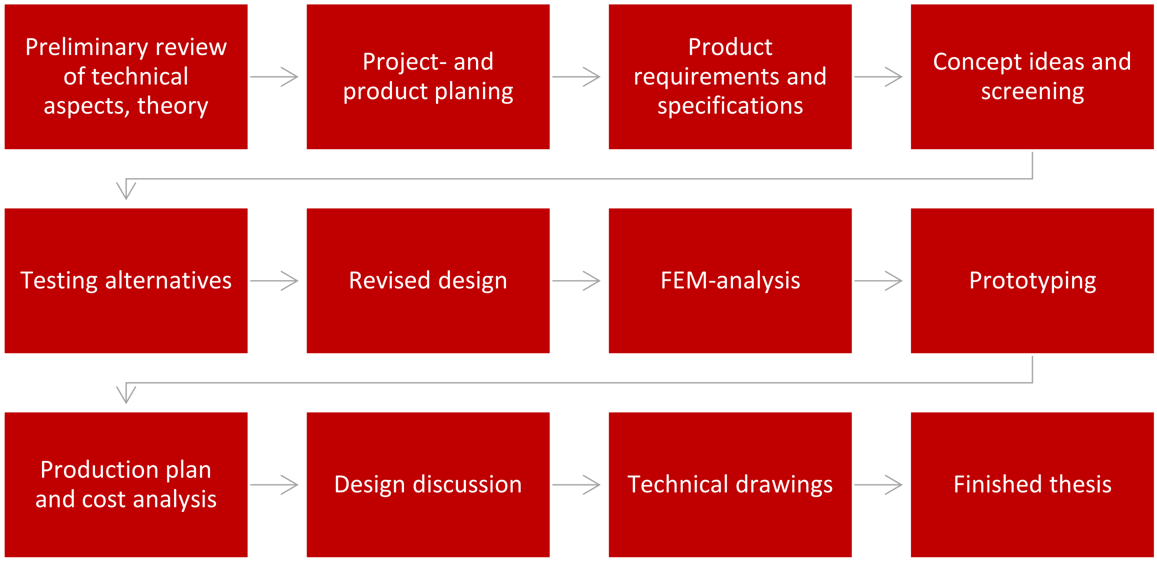


Figure 16-14: Process for the thesis

VI. Calculated scores for concept screening

How the scores and sums were calculated for the concept screening.

Calculated scores for thumb actuation:

Table 16-11: Calculated scores for actuation of the thumb.

Criteria	Backdriveable	Power to weight	Price	Sum
Importance	6	7	7	20
Weight	0,3	0,35	0,35	1
Solenoid actuator	0	0	0	
Rotary DC	1	0	1	
SMA	-1	1	-1	
Ultrasonic	-1	1	-1	
Weighted scores:				
Linear actuator	0	0	0	0
Rotary DC	0,3	0	0,35	0,65
SMA	-0,3	0,35	-0,35	-0,3
Ultrasonic	-0,3	0,35	-0,35	-0,3

Calculated score for trapeziometacarpal thumb transmission:

Table 16-12: Calculated scores for transmission to the trapeziometacarpal thumb joint.

Criteria	Prehensile	Backdriveable	Robustness	Low friction	Small size	Sum
Importance	7	6	6	4	6	29
Weight	0,241	0,207	0,207	0,138	0,207	1
Tendons w/sheats	1	-1	0	-1	1	
Tendons w/pulleys	0	0	0	1	1	
Timing belts w/pulleys	1	1	0	0	1	
Linkages	1	1	1	-1	-1	
Gears	1	-1	1	-1	-1	
Screw gear	1	1	0	0	0	
Weighted scores:						
Tendons w/sheats	0,241	-0,207	0,000	-0,138	0,207	0,10
Tendons w/pulleys	0,000	0,000	0,000	0,138	0,207	0,34
Timing belts w/pulleys	0,241	0,207	0,000	0,000	0,207	0,66
Linkages	0,241	0,207	0,207	-0,138	-0,207	0,31
Gears	0,241	-0,207	0,207	-0,138	-0,207	-0,10
Screw gear	0,241	0,207	0,000	0,000	0,000	0,45

Calculated score for outer thumb transmission:

Table 16-13: Calculated scores for the transmission for the outer thumb joint.

Criteria	Prehensile	Backdriveable	Low friction	Small size	Bending	Sum
Importance	7	6	4	6	7	30
Weight	0,233	0,200	0,133	0,200	0,233	1
Tendons w/sheats	1	-1	-1	1	1	
Tendons w/pulleys	0	0	1	1	0	
Timing belts w/pulley and screw	1	1	0	1	1	
Screw gear	1	1	0	0	1	
Weighted scores:						
Tendons w/sheats	0,233	-0,200	-0,133	0,200	0,233	0,10
Tendons w/pulleys	0,000	0,000	0,133	0,200	0,000	0,33
Timing belts w/pulley and screw	0,233	0,200	0,000	0,200	0,233	0,63
Screw gear	0,233	0,200	0,000	0,000	0,233	0,43

Calculated score for trapeziometacarpal thumb joint type:

Table 16-14: Calculated scores for the trapeziometacarpal thumb joint type.

Criteria	Low friction	Creates push and pull	Low weight	Price	Sum
Importance	4	7	7	7	25
Weight	0,241	0,207	0,207	0,138	1
Shaft	-1	-1	1	1	
Bearings	1	-1	0	-1	
Flexible material	-1	1	0	0	
Bushings	1	-1	1	-1	
Bearings with springs	1	1	0	-1	
Weighted scores:					
Shaft	-0,16	-0,28	0,28	0,28	0,12
Bearings	0,16	-0,28	0	-0,28	-0,4
Flexible material	-0,16	0,28	0	0	0,12
Bushings	0,16	-0,28	0,28	-0,28	-0,12
Bearings with springs	0,16	0,28	0	-0,28	0,16

Calculated scores for metacarpophalangeal thumb joint type:

Table 16-15. Calculated scores for the metacarpophalangeal thumb joint type.

Criteria	Low friction	Robustness	Low weight	Price	Sum
Importance	4	6	7	7	24
Weight	0,167	0,250	0,292	0,292	1
Shaft	-1	-1	1	1	
Bearings	1	1	0	-1	
Flexible material	-1	0	0	0	
Bushings	1	1	1	-1	
Weighted scores:					
Shaft	-0,167	-0,167	0,167	0,167	0,000
Bearings	0,167	0,167	0,000	-0,167	0,167
Flexible material	-0,167	0,000	0,000	0,000	-0,167
Bushings	0,167	0,167	0,167	-0,167	0,333

VII. External testing done in TIP300

Questionnaire for robotic hand

Name	ELLING DIESEN
Occupation	ELECTRONICS DESIGN ENG
Education	MASTER MICRO ELECTRONICS

Rate the following features on a scale from 1 to 8, where 1 is the most important to have.

Feature	Important							Not important
An IP67-rating. This means that the hand has no dust ingress, and is water-proof down to 1m.	1	2	3	4	5	6	7	8
Modular.	1	2	3	4	5	6	7	8
Lift a payload of 8kg or more	1	2	3	4	5	6	7	8
As many DOF as DOA, to have the possibility to create a kinematic steering algorithm.	1	2	3	4	5	6	7	8
Low weight	1	2	3	4	5	6	7	8
Cheap	1	2	3	4	5	6	7	8
Quiet	1	2	3	4	5	6	7	8
Back-driveability	1	2	3	4	5	6	7	8

Note which engine you belive would be best, and why

Motor:	Linear actuator	Linear servo	Rotating servo	Other
Why (if other; type)?				
COST, SPACE, FORCE				

Write the answer (ONE HAND) (TO CUSTOMER)

	Min	Max
Acceptable price (kr):	0	1500
Acceptable weight(g):	0	
Acceptable strength(kg):	USEFUL	SAFE

What kind of, and how many sensors do you believe is necessary for the hand to function properly?
ONE CURRENT SENS PER FINGER ONE TOUCH SENS PER FINGER

Questions about the aesthetic of the hand:

Question:	Answer
How should it look?	PLEASING, SLIM (NOT BULKY)
Should it have fingers, how many?	3, 4 OR 5 (SIZE, COST, FUNCT. IS MORE IMPORTANT THAN MANY FINGERS)
What materials should be used?	LIGHT AND CHEAP

Thank you for your help!

Figure 16-15: Answers from Elling Diesen.

Questionnaire for robotic hand

Name	Przemyslaw Dominik GACIA
Occupation	Design Eng.
Education	PhD

Rate the following features on a scale from 1 to 8, where 1 is the most important to have.

Feature	Important							Not important
An IP67-rating. This means that the hand has no dust ingress, and is water-proof down to 1m.	1	2	3	4	5	6	7	8
Modular.	1	2	3	4	5	6	7	8
Lift a payload of 8kg or more	1	2	3	4	5	6	7	8
As many DOF as DOA, to have the possibility to create a kinematic steering algorithm.	1	2	3	4	5	6	7	8
Low weight	1	2	3	4	5	6	7	8
Cheap	1	2	3	4	5	6	7	8
Quiet	1	2	3	4	5	6	7	8
Back-driveability	1	2	3	4	5	6	7	8

Note which engine you belive would be best, and why

Motor:	Solenoid Linear actuator	Linear servo	Rotating servo	Other
Why (if other; type)?				
Good balance between mass and force on output.				

Write the answer per 1 hand

	Min	Max
Acceptable price (kr):	?	?
Acceptable weight(g):	600	700
Acceptable strength(kg): ~~payload~~ grip	30N	50N

What kind of, and how many sensors do you believe is necessary for the hand to function properly?
- pressure sensors (for 3 fingers min.) - accelerometer - additional pressure sensor in wrist joint as overload indicator

Questions about the aesthetic of the hand:

Question:	Answer
How should it look?	nice
Should it have fingers, how many?	min 3, 5 is estetic, avoid 4 due to cultural implications
What materials should be used?	plastics, fabrics + elastomers, composites included

Thank you for your help!

Figure 16-16: Answers from Przemyslaw Dominik Gacia.

Questionnaire for robotic hand

Name	PHUONG NGUYEN
Occupation	CSO Halodi
Education	PhD in Robotics

Rate the following features on a scale from 1 to 8, where 1 is the most important to have.

Feature	Important				Not important			
An IP67-rating. This means that the hand has no dust ingress, and is water-proof down to 1m.	1	2	3	4	5	6	7	8
Modular.	1	2	3	4	5	6	7	8
Lift a payload of 8kg or more	1	2	3	4	5	6	7	8
As many DOF as DOA, to have the possibility to create a kinematic steering algorithm.	1	2	3	4	5	6	7	8
Low weight	1	2	3	4	5	6	7	8
Cheap	1	2	3	4	5	6	7	8
Quiet	1	2	3	4	5	6	7	8
Back-driveability	1	2	3	4	5	6	7	8

Note which engine you belive would be best, and why

Motor:	Linear actuator	Linear servo	Rotating servo	Other
Why (if other; type)?		✓	✓	

Write the answer (Per hand, production cost)

	Min	Max
Acceptable price (kr):	100	1000
Acceptable weight(g):	500	1000
Acceptable strength(kg):	3	15

(200)

What kind of, and how many sensors do you believe is necessary for the hand to function properly?
- Encoder (?7) for a hand - Force load cell (4)

Questions about the aesthetic of the hand:

Question:	Answer
How should it look?	Human hand like
Should it have fingers, how many?	5 (4+1)
What materials should be used?	Alluminium / Titanium

Thank you for your help!

Figure 16-17: Answers from Phuong Nguyen.

VIII. Technical drawings

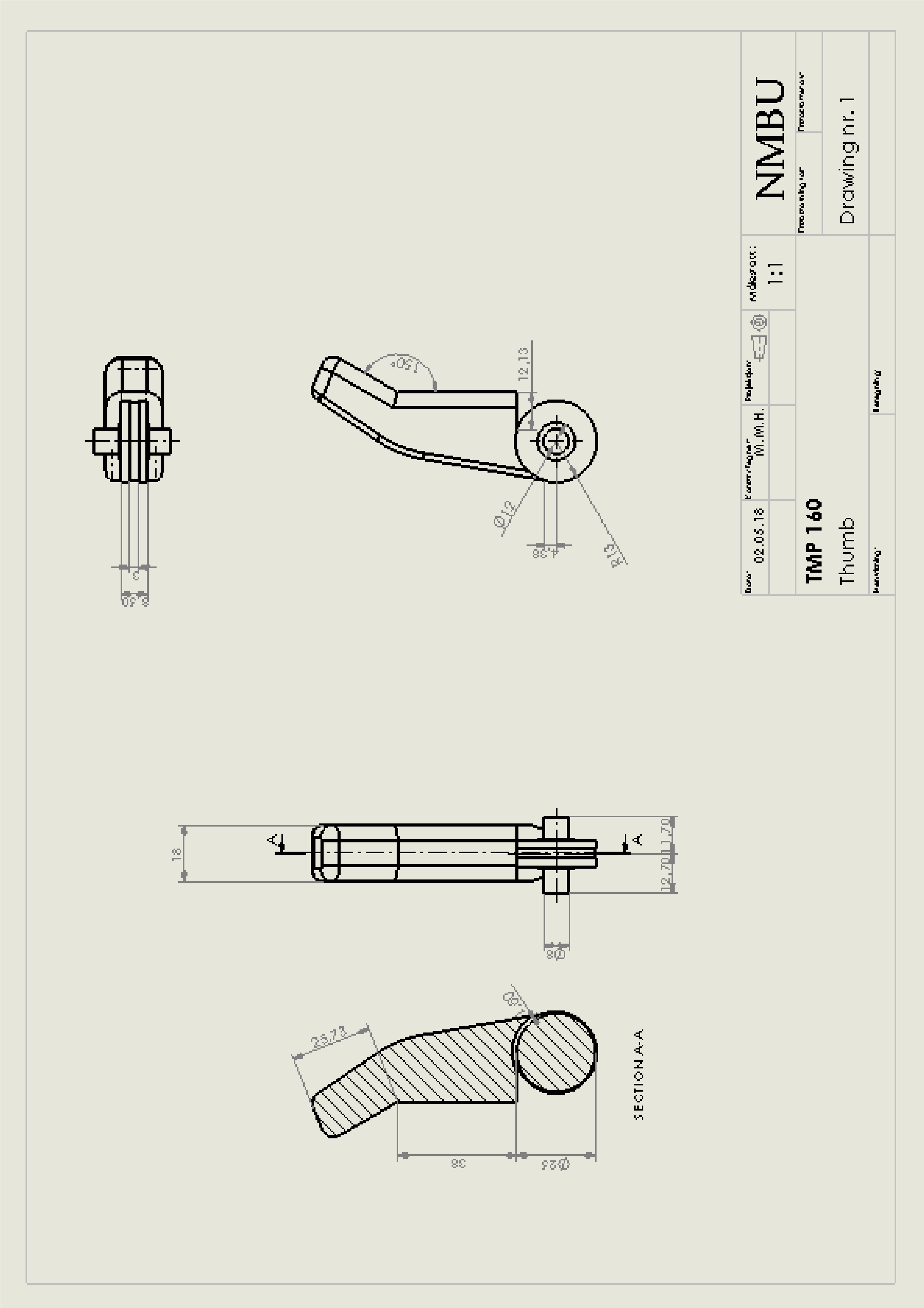


Figure 16-18: Techincal drawing of the thumb.

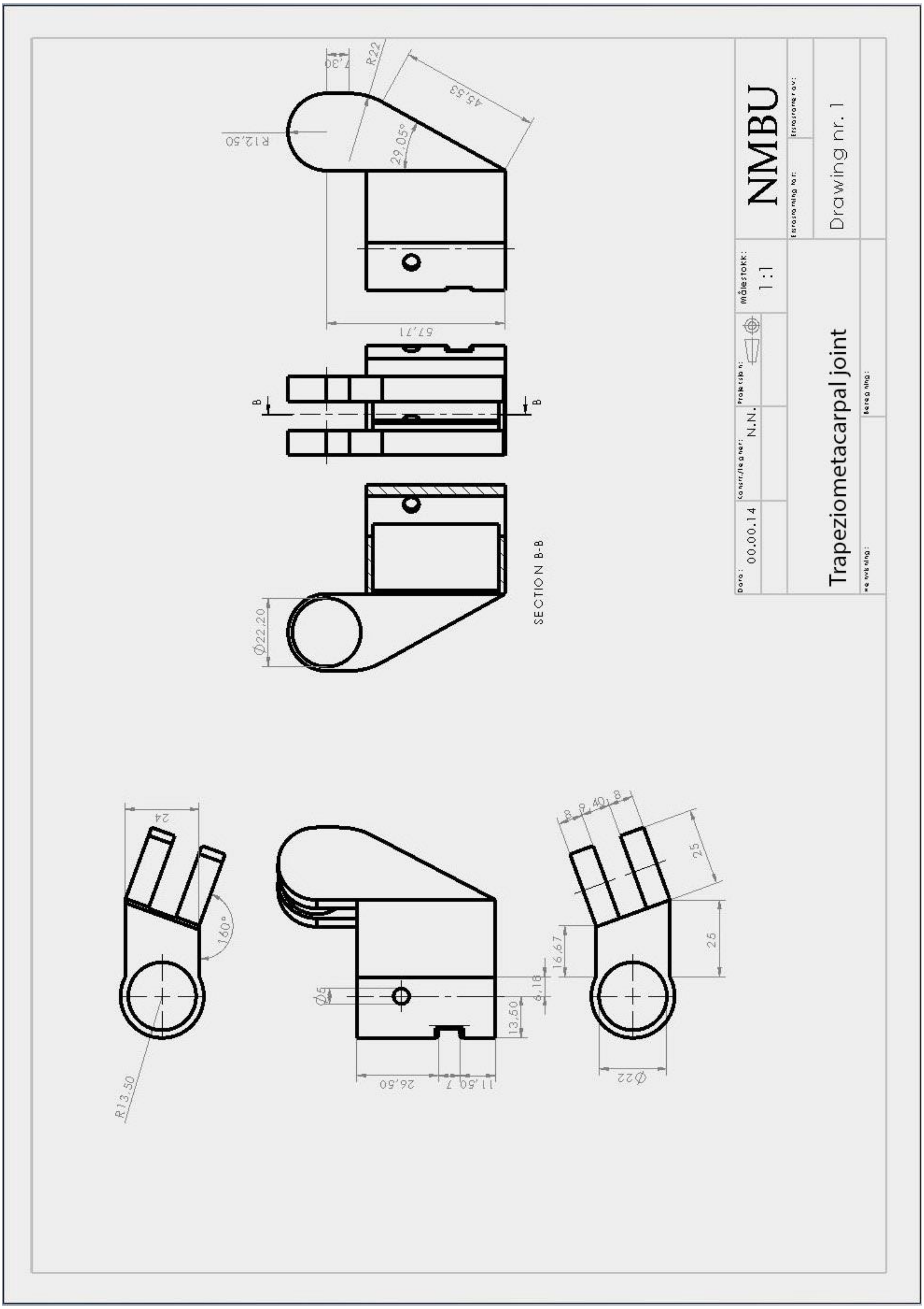


Figure 16-19: Trapeziometacarpal joint technical drawing

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