Honours Master 'High Tech Systems and Materials'

Designing of a DIY flexion assisting exoskeleton

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Content

Abstract

Recently, ScienceLinX opened a new exhibition at the University Museum called “Beyond the Lab: the DIY Science Revolution”. It focusses on “do-it-yourself scientists” around the world. These scientists are ordinary people that experiment and invent new products. Without the use of professional labs. These people often use low-cost sensors, apps, and online community forums.

This project investigates the possibilities of designing a DIY powered exoskeleton following the DIY principle. Stroke survivors often suffer from decreased hand strength. Goal of the product is to generate sufficient hand strength or grip force. Only one finger is designed to act as a proof of principle. The project follows the Methodical design process. A system is designed that compensates the loss in hand strength that can be made at home. The system must fulfil the requirements, of which the most important are that the product can be produced at home, and the product restores hand strength. A concept is selected out of five pre-concepts, and elaborated.

The result is a design of a 3D printable exoskeleton system that uses two force sensitive resistors as sensors and a servo motor as actuator. The system is controlled using an Arduino board.

Method

The project will follow the methodical design process by prof. dr. ir. G.J. Verkerke and dr. ir. E.B. van der Houwen. Methodical design is the standard method used for all the design courses for Biomedical Engineering (BME) students. This methodology consists of an analysis phase, three synthesis phases and an use phase.

The analysis phase consists of problem definition, goals, design assignment, list of requirements and wishes, and function analysis. In synthesis 1 wild ideas are created and combined in pre-concepts. During synthesis 2, the best pre-concepts are detailed to concepts. Size, materials, mode of operation, etcetera is specified. Then the best concept is selected. This concept (a workable, realistic solution, will be worked out until all details are known in synthesis 3. Than a prototype can be made which can be tested and improved. In the use phase, the final tests will be performed, transfer to the industry will be performed and series production is prepared. Products that are used will be collected and analysed for failures.[1]

For this project, the methodical design process is slightly trimmed down. Only 5 pre-concepts are created instead of 10 in Synthesis phase 1. Also, synthesis phase 2 is skipped. These alterations are implemented to better fit the 5ECTs workload for the assignment. This project covers up to and including synthesis 3. It results in technical drawings and a prototype of the designed product.

Background information

Finger anatomy

The fingers are the five terminating members of the human hand. These include the thumb, index finger, middle finger, ring finger, and little finger. The thumb has two phalanges: proximal and distal, while the other fingers have three phalanges: proximal, middle, and distal[2]. There is a total of 19 bones and 14 joints distal to the carpals. In total, there are 20 degrees of freedom. [3] There are also a lot of tendons in ligaments in the hand. These include extracapsular ligaments and capsular ligaments such as MCP joint ligaments, and the PIP and DIP joint collateral ligaments[3]

The fingers enable humans to perform daily-life tasks, like grasping, with fine and gross motor functions. Therefore, the correct functioning of finger joints is essential to perform “simple” tasks.

Metacarpal bones

Figure 1: Radiographic visualization of the bones in the hand[2]

The metacarpal (MCP) bones are all in the same plane and run parallel to each other. The five MCP bones are short tubular bones of various lengths, where the first MCP bone corresponds to the MCP of the thumb. The MCPs form the proximal part of the finger joints at the distal end. MCP joints resemble an ovoid joint and therefore permit abduction-adduction along the longitudinal axis, extension-flexion along the transverse axis, and circumdiction. The range of motion of the second to fifth MCP joints is 90° flexion, 40° extension, and 15° abduction and adduction. Ligaments around the MCPs prevent fingers from spreading apart excessively and limits flexion of the middle and ring finger while the other fingers are spread.

Structure and Function of the Proximal Interphalangal Joints (PIP joints)

The proximal interphalangeal joints (PIP joints) are hinge joints. They primarily allow only flexion and extension. However, slight side-to-side and rotation motions are also possible. The PIP joints are, along with the MCP joints, the most important functional unit for grasping, gripping and making a fist. They are also a significant part in the undisturbed motion of the fingers and hands. The second to fifth PIP joints have a range of motion of 130° flexion and 0° extension.

Structure and function of the DIP joints

DIP joints are smaller that PIP joints but similar in build. Supination in the index finger is possible, which is important for precision and fine motor grasping. The DIP joint is more susceptible to hyperextension than the PIP joints. The second to fifth DIP joints have a range of motion of 90° flexion and 30° extension.

Extrinsic muscles of the finger

The extrinsic muscles of the finger exert their influence on the finger joint in interaction with the intrinsic muscles.[2] There are nine extrinsic muscles that contribute to finger flexion, finger extension and thumb abduction. The intrinsic muscles, namely the dorsal interossei and the palmar interossei, are used for flexion of the MCP joints and extension of the PIP and DIP joints.[3] Most muscles that actuate finger movement are located in the lower arm. Therefore, EMG measurement related to finger movement is performed on the lower arm.

Movements and range of motion of the thumb

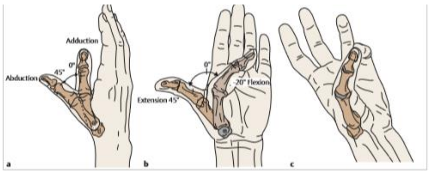
The thumb is the first and strongest digit of the hand. Its oppositional positioning acts as a grasping tool for powerful closing of the fist. Pinch grip force amounts to approximately a quarter that of the force during maximum fist closing. The thumb contributes significantly to optimizing gross and fine motor grasping functions of the hand.[2]

The complexity of the thumb is provided by the carpometacarpal (CMC) joint and nine individual muscles, each having multiple functions. The functional joints of the thumb are the CMC joint, located at the wrist joint, the thumb metacarpophalangeal (MCP joint, and the interphalangeal (IP) joint. The latter two belong to the digit itself.[2]

Movements of the thumb CMC joint

The CMC joint is a saddle joint. The first degree of freedom is abduction and adduction (35° and 25° respectively), and the second degree of freedom is that of flexion and extension (25° and 45° respectively). Rotation is possible to a very limited extent of 10°.[2]

Figure 2: movements of the thumb[2]



Range of motion of the thumb MCP and IP joints

The MCP is an ovoid joint. The movements flexion-extension and abduction-adduction are possible. The range of motion of the MCP joints of the thumb are 80° and 0° for flexion-extension, 12° and 7^0 for abduction-adduction, and 20° and 6^0 for pronation and supination. The IP joints, being pure hinge joints, allow for flexion-extension and opposition. In structure, these joints are nearly identical to that of the DIP joints of the fingers. The range of motion of the IP joints of the thumbs are 90° and 30° for flexion-extension and 10° and 0° for pronation and supination.[2]

Stroke

More than 7 million stroke survivors reside in the USA alone in 2012. Stroke survivors often suffer from impaired motor function in hands and arms, resulting in a reduced (power) grip strength. The loss of hand function leads to dependency on others, like family and health care, to complete daily living activities.[4]

The action of the long finger flexor muscles and the action of the extensor muscles and intrinsic hand muscles are important for controlling force direction and distribution. Stroke related changes could lead to decreased object stability and object dropping. Stable hand grip requires that phalanx forces do not deviate from the direction normal to a gripped object's surface by more than an angle defined as the "cone of friction", calculated as the arctangent of the coefficient of friction between skin and object surface. Phalanx force direction outside this cone leads to finger slippage and dropping of the object. The phalanx force angular deviation is far greater in stroke survivors compared to age-matched controls. This may be explained by altered muscle activation patterns and impaired somatosensation. Also, deviation from the typical grip force distribution of the highest force contraction of the distal phalanx directed to the palm could result in a reduced grip force, discomfort, and/or object rotation out of the hand. There is evidence that stroke survivors develop muscle fatigue earlier in tasks requiring submaximal force. In conclusion, stroke survivors are limited in completing everyday tasks and progressing in rehabilitation by these phenomena's, leading to long-term negative effects on hand function post-stroke.[4]

Clinical problem

Muscle strength is the ability of the skeletal muscle to develop force for the purpose of providing stability and mobility within the musculoskeletal system to enable functional movement to occur. Grip strength is defined as the force applied by the hand to pull on or suspend from objects. It is a specific part of the hand strength. Two types of grip can be defined: power grip and pinch grip. The former is the grip of the entire hand. The latter provides an indication of thumb function and can be further classified in tip pinch (thumb and index finger), tripod pinch (thumb, index-, and middle finger), and lateral pinch (thumb and radial side of the index finger) [6]

Weakness or disappearance of active movement can have several causes. These include failure of the afferent nerve, destruction of muscle tissue, ischaemia, tendon rupture, and tendon adhesions.[6] These causes can on turn be related to a lot of events. Injuries of the hand or surgery can lead to nerve- and muscle damage and tendon- rupture or adhesion. Stroke survivors often have some sort of neural damage as stated before. Spinal cord and other local injuries also lead to nerve damage and partial paralysis.[3] These injuries may all cause long-lasting disabilities, because of a lost fine sensory and motor functions. [5]

Robotic exoskeleton systems

A robotic exoskeleton system is a man-machine intelligent system. It is an orthotic device, with its joints and links corresponding to human joints and links (bones). Torques are transmitted to the human joints from the actuator through its links. Robotic exoskeleton technology developed rapidly in recent years.[7]

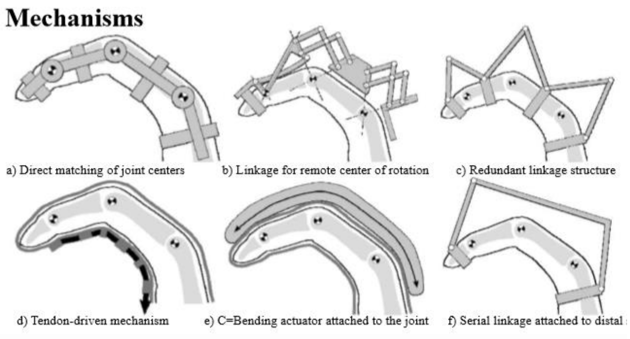
The concept of an exoskeleton is derived from natural exoskeletons. It is an outer cover on a creature to shield support, power enhancement, and/or sensing and data fusing. An example is the shell of a crab. In robotics, exoskeleton systems are often wearable devices consisting of structural mechanisms, actuators and sensors, of which the links and joints correspond to human links and joints. When worn by an user, physical contact between user and exoskeleton allows for the transfer of mechanical power and information signals. In assisting exoskeletons, the user provides control signals for the exoskeleton and the actuators of the exoskeleton provides most of the power for the action.[7]

The main challenge for robotic exoskeletons is the current unavailability of proper accessory devices. Available actuation and power transmission technology are not perfect yet for the perfect robotic exoskeleton. The exoskeleton should not be to heavy and should generate natural motion without vibration, jerk or sudden motion change. Back-drivability is essential if the exoskeleton uses geared electric motors. Power transmission technologies should be highly efficient. Structures of exoskeletons should be flexible with high strength, while still being lightweight.[7]

Since not all injuries can be completely repaired, there is a need for another way to restore function.[9] As stated by Gopura et al: *"It is important to develop exoskeleton systems to assist and/or rehabilitate physically weak people in the present society in which considerable percentage of population is aged and physically weak"[7].* The use of exoskeletons offers an opportunity to restore some of the lost functions in patients that cannot be cured completely. However, most current exoskeletons are expensive.[8] Powered exoskeletons have the potential to reduce the metabolic cost of movement, improve performance, increase movement speed, and/or restore function. However, improper designed exoskeletons can potentially hinder the user in its movement. For example when the exoskeleton is to heavy or when the joints are not located in the right locations. A new challenge is to find populations in which an exoskeleton can significantly improve quality of life.[9]

Potential mechanisms for joint motion can be seen in figure 3. These are: actuators directly matching the joint centers, a linkage system for a remote center of rotation, a redundant linkage structure, a tendon driven actuator mechanism, a C-bending actuator, and serial linkage only attached to the finger tips.[3] Used exoskeleton actuators are: electric motors[3], pneumatic actuator[3], shape memory alloys[3], electroactive polymers[3], and soft robotics[10].

Figure 3: Potential joint motion mechanisms[3]



a) Direct matching of joint centers b) Linkage for remote center of rotation c) Redundant linkage structure

d) Tendon-driven mechanism e) C=Bending actuator attached to the joint f) Serial linkage attached to distal

There is a range of sensors available. These include: force sensing, motion sensing, breath switch, surface Electromyography (sEMG), muscle hardness, mechanomyography, photoplethysmography at the fingernail, finger pad deformation, and force myography.[3]

Analysis phase

Problem definition

The human hand is an important system for interacting with the environment. An average person grasps 1500 times with the hand per day. However, millions of people worldwide suffer from hand function impairment. The most common causes for this loss of function are: spinal cord injuries, degenerative diseases, strokes, motor disabilities, muscle weakness associated with ageing, hand injuries, and hand operations.[6][11]

All problems related to the given problem must be inventoried. This problem is the loss of grip force in fingers. Problems are inventoried asking the five "w"-questions: who, why, when, where, and what. [1]

Who have a problem?:

- Patients with a loss of function in the hand/fingers. This can be due to several causes like strokes, injuries, pathologies, and hand operations for example [6][11]
- Family of the people with a disability [12]
- Home care
- Society
- Employer
- Health insurance companies

What is the problem?:

- Due to a loss of function in the hand or fingers, there is a loss in grip force. Therefore, patients have problems with holding and/or grasping objects [3-6]
- Family have to take care of their family member [12]
- For patients that cannot be helped by their family, home care needs to take care of the patient
- Some patients cannot be completely cured [5]
- Patient could be (partially) incapacitated [5]
- Current devices are mainly restricted to be used in hospital environments [11]

Why is it a problem?:

- Patients can easily drop objects[4]
- Patients can have difficulties getting dressed, etc. [4,12]
- Patients can have difficulties in cleaning their houses[4, 12]
- The loss of self-reliance frustrates the patients, leading to mental issues [12]
- Family members have to take care for their relative, leading to additional stress and workload [12]
- Home care does not have enough employees to help all patients.
- The employer has to continue paying the patient a while, leading to high costs [13]

When does the problem occur?:

- Patients: in their daily life [3-6]
- Family: in their daily lives, especially when taking care of a patient [12]
- Home care: when taking care of a patient
- Employer: from the time of injury until 2 years later [13]

Where does the problem occur?:

- In the affected hand/fingers of the patient
- In the direct surroundings of the patient

Stakeholders

All persons evolved in the problem are considered in the stakeholder analysis.

Table 1: Stakeholder analysis table

Stakeholder	Characteristics	Expectations	Potentials and deficiencies	Implications and conclusions for the project
Patients	Reduced function in the hand, reduced grip force, social and emotional problems	Restored hand function, low costs, increased self-reliance	Potential trial candidates, not all patients are suitable	Wide range of properties makes it difficult to find a common solution, Could participate in trials
Family	High burden since they have to take care of a relative, social and emotional problems	Restored hand function of relative, low costs, decreased workload and stress of taking care of relative	Critical in case of failures, can help patients using new products	Encourage patient to try new product or help in testing, Could be sceptical
Employers	Has to continue paying the employee for two years	Employee resumes its work	Can point to potential trial candidates, might help in financing product for incapacitated employees	Possible funds
Society	Wants a low number of patients, wants low health care costs, demands high quality	Solution for the loss of hand function in patients	Critical in case of failures	Patient groups could participate for easier acceptance
Doctors	Strives for the best treatment, focused on ad-hoc and fast solutions	Optimal improved hand function	Expert in anatomy and necessary functions etc., lacks technical knowledge	Could be conservative, Can help in acquiring testing groups
Home care	Strives for the best care/treatment for a patient	Patients become self-reliant	Can help patient adjust to new device, lacks technical knowledge	Encourage patient to try new product or help in testing

Insurance	Optimal care at low costs	Low costs of treatment	Only interested when cost-effective and low complications	Essential for product acceptance
Industry	Interested in innovative products at low development costs	Profit	Commercialising the product	Knowledge of market potential, manufacturing

Cause-effect order of the problems

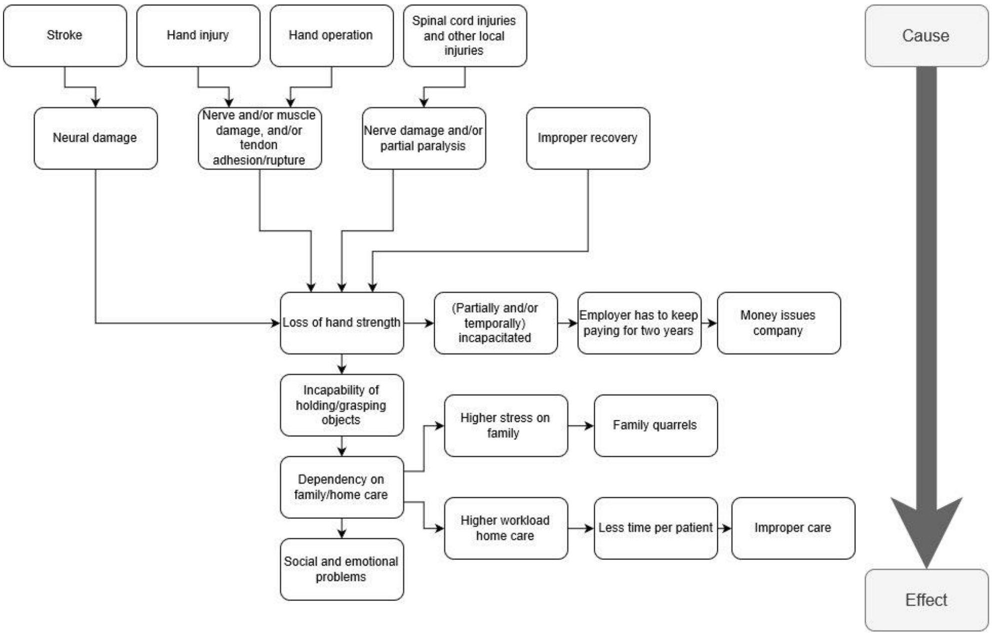
The loss of hand strength and function can have several causes. Injuries of the hand and hand operations can lead to nerve damage, muscle damage, tendon rupture, and/or tendon adhesion[6]. Stroke survivors often have some sort of neural damage. Spinal cord injuries and other local injuries can lead to nerve damage and partial paralysis[3]. All these can lead to a loss of hand strength and function. When the injuries do not recover fully, this loss of hand function and strength can be permanent. [5]

The loss of hand strength leads to an incapability or difficulty in holding and grasping objects[3][5]. This causes the patients difficulties in performing certain tasks themselves, causing a dependence in other people like family and home care. The loss in self-reliance can cause social and emotional problems.

Beside this, patients can become (partially and/or temporarily) incapacitated. Their employers have to keep paying the employees for two years, causing the employer to lose money[13]. The dependence on others causes high stress on the family leading to an unhappy family life and high stress[12]. When family cannot (completely) take care of their relative, a higher workload for home care leads to less time per patient and therefore improper care.

The cause-effect diagram is shown in figure 4.

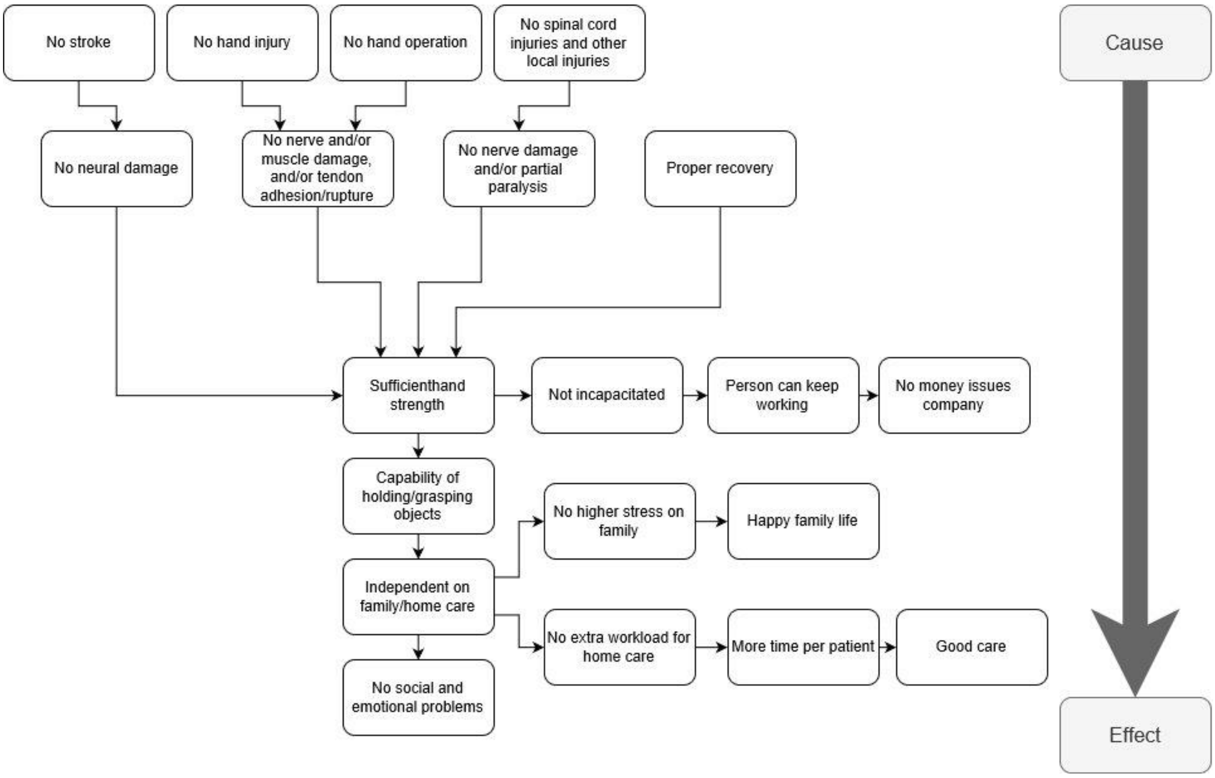
Figure 4: Cause-effect diagram of the problems



Goal

For each problem a goal is formulated. This leads to cause effect diagram of all goals as seen in figure 5. When people do not get strokes, hand injuries, hand operations, or spinal cord or other injuries, there will be no loss of hand function and strength. Also, when there is proper recovery of the damaged tissue when these pathologies do occur, the loss of hand strength and function will not be permanent. Therefore, people will have a normal life in which they can work and take care of themselves.

Figure 5: Cause-effect diagram of the goals



The most fundamental goals are the goals of a proper recovery, and of not getting the conditions that lead to a loss of hand strength. Avoiding all conditions that can lead to a loss of hand function is unachievable. The goal of proper recovery is also out of the scope of the project. Therefore, the most fundamental goal that can be realised is “sufficient hand strength”. If this goal is realised all subsequent goals are also realised.

Design assignment

To reach the goal of the assignment, a method needs to be developed to restore the strength of the hand. This could be done by:

- Developing a method to fully heal hand function
- Developing a system that compensates the loss in hand strength

”Developing a method that fully heals hand function” is very difficult to realise. Moreover, a restriction made by ScienceLinX was to develop a technology that can be made “outside the labs”, meaning that people can create it at home. So the design assignment that was selected, was: “Developing a system that compensates the loss in hand strength”.

To study the feasibility of this assignment, the primary focus is to design a finger prosthesis, because flexion-extension is the only movement that should be realised. This design can be used for multiple fingers. The thumb is not considered, due to its relative complexity. The design is not intended for patients with structural abnormalities of the fingers, such as those in rheumatoid arthritis patients.

The project will result in a prototype of a finger prosthesis.

Requirements and wishes

Table 2: List of requirements and wishes

Type of requirement	Nr	Specification
Use requirements	1	The product responds to (bio) mechanical/electric signals from the user
	2	The product assists in the flexion-extension of the finger[11]
	3	The product can be used by people of 7 year old and older
	4	The product should generate up to 16N power grasping force[11]
	5	The product does not destroy objects
	6	The product can be used without the need of an external power source or an external frame to carry the device
	7	The product should not constrain movement of other joints[9]
Ergonomic requirements	8	The product should fit comfortably around the fingers[9]
	9	The part of the product placed on the hand that is attached to the finger should weigh less than 100 g [11]
	10	The total weight of the product should be less than 2kg [11]
Space requirements	11	The part of the product attached around the finger should not be wider than 3cm [6]
	12	The widest part of the product around the arm should not be wider than 10cm [14]
	13	The product should not be longer than 45cm (length forearm) [14]
	14	The product should not be thicker than 10cm
Safety requirements	15	The product should not cut the user with sharp edges [9]
	16	The product should not produce movements when unwanted [3, 7-11]
	17	The finger does not exceed the natural range of motion (90°, 110°, 90° for DIP, PIP, and MCP joint respectively) [3,12]
	18	If the input control signal is lost, all actuators and motion stops
Time requirements	19	Delay between signal and actuation is no more than 200ms
	20	The product should be attached within 3 minutes
	21	The product can be used for 2 hours of continuous use without recharging
	22	The maximum time between maximum extension and maximum flexion is 1s
Other requirements	23	The device can be created at home
	24	The price should be less than €100,-
Wishes		The product should be as light as possible The product should be as small as possible The product should be as cheap as possible The product looks good

Function analysis

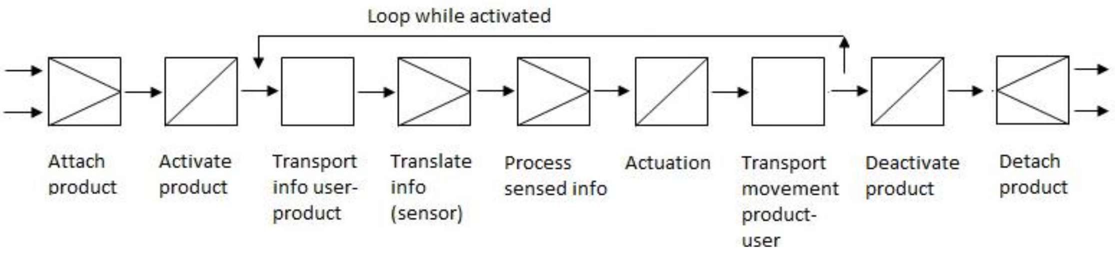
The main function of the product is to assist in achieving sufficient hand strength. The subfunctions the device must be able to perform are:

- Attachment to the finger(s), hand, and/or arm
- Activation of the product

- Transport signal from user to product
- Sensing signals
- Processing of the signals
- Actuation of the finger(s)
- Rotation of the finger joint
- Deactivation of the product
- Detachment from the finger(s), hand, and/or arm

The product must be attached to the individual and activated. Data is transported from the user to the product. When activated, sensors registrate the data which is processed. If the individual wants to flex or extend its finger, the product actuates. Movement of the product is transported to the user. The loop of transport, sensing, processing and actuation continues as long as the system is activated. After use, the product is deactivated and detached. The function analysis scheme is shown in figure 6.

Figure 6: Function analysis scheme



Synthesis phase I

Morphological scheme

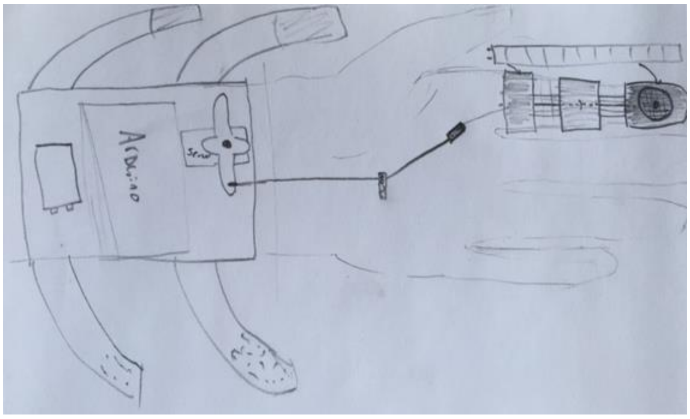
A morphological scheme is used to create the pre-concepts. The morphological scheme is shown in APPENDIX I

Pre-concepts

Pre-concept 1: Tendon-motor glove

The phalanxes are surrounded by a thin tube shaped to the finger. A tendon cable is attached to the fingertip and travels through the phalanx tubes and additional tubes in the palm of the hand to a servo motor located on the lower arm. Actuation of the motor causes flexion of the finger. A flexsensor is mounted on the glove. The initial flexing of the finger by the user triggers the actuation of the motor. A force sensor on the finger sends a signal to stop further actuation and avoid damage to the object. The system is powered by a battery.

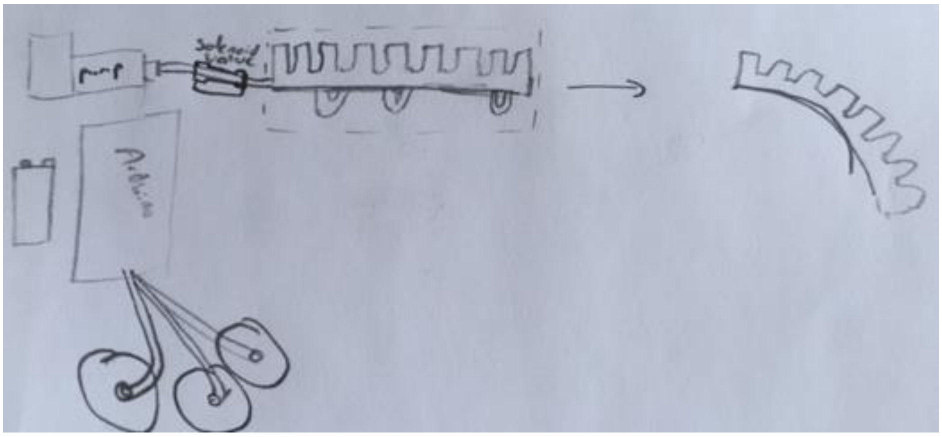
Figure 7: Pre-concept 1 – Tendon-Motor glove



Pre-concept 2: Soft robotic finger

A silicone rubber tube is made that is placed over the length of the finger. A piece of paper or cloth is placed in the side that touches the finger. When the tube inflates, the side with the cloth stays the same size, so the tube bends. A small air pump pumps air through a tube to the silicone finger and causes flexion. A solenoid valve is used to keep the air in the tube and release it when necessary. An EMG sensor is used for the input signal. A soft surface on the fingers is used to avoid object damage. The finger is attached to the surface using elastics.

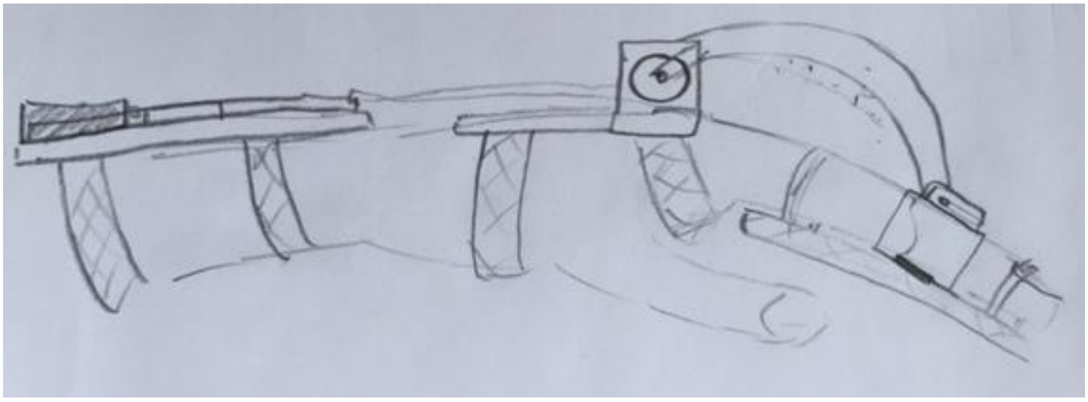
Figure 8: Pre-concept 2 Soft Robotic Finger



Pre-concept 3: Distal end servo motor finger

A 3D printed design is made using a knuckle structure, a fingertip, and a linkage system. The structure on the knuckle is linked to the fingertip with the linkage system. A servo motor in the knuckle structure moves the linkage, causing flexion and extension of the finger. A pressure sensor in the fingertip registrates the initial movement of the finger and triggers the actuation. The same sensor is used to avoid object damage. The structure is secured to the hand using velcro.

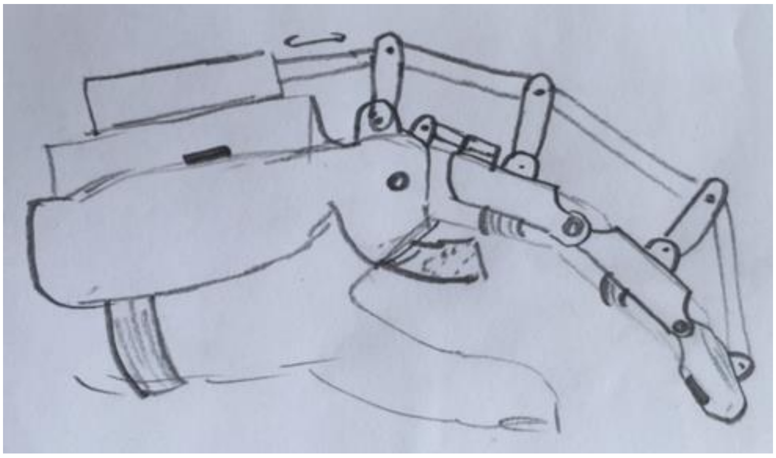
Figure 9: Pre-concept 3 Distal end Servo Motor Finger



Pre-concept 4: Pneumatic finger

A structure is made with joints aligned to the finger joint centres of rotation. Actuation of the pneumatic actuator causes rotation of the three finger joints. There are tilt sensors located in the back of the hand and the finger. When the user starts moving its finger, the resulting (extra) difference between the tilt sensors triggers actuation. Force sensors on the finger tips are used to avoid damage to objects. The structure is attached using velcro.

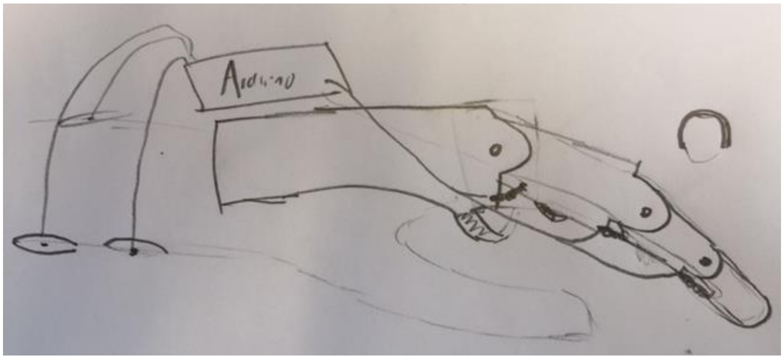
Figure 10: Pre-concept 4: Pneumatic finger



Pre-concept 5: Shape memory alloy finger

A frame is designed consisting of a fingertip, two phalanges, and a hand shell. The fingertip surrounds the fingertip of the user completely. The two phalanges and the hand part are open on the palmar side. These parts are attached to the finger using elastics. Shape memory

Figure 11: Pre-concept 5 Shape Memory Alloy Finger



alloy (SMA) is attached to the two parts of the joints. Actuation causes the SMA to contract, which causes flexion of the joint. An EMG sensor is used to trigger actuation. A deformable surface on the fingers is used to avoid object damage.

Analytic Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) allows to determine weight factors based on the subcategories of the requirements. The requirements are all compared to each other to calculate the grading factors. During the comparison, both requirements are given a grade so that the sum of the two grades equals 10. The most important requirement gets the highest grade. The grading scheme can be seen in APPENDIX II table 1.

Concept selection

The pre-concepts are graded using the requirements and the grading factors. The grading scheme is shown in APPENDIX II table 2 . Pre-concept 1 has the highest total score, meaning that this pre-concept will be further conceptualized in Synthesis phase III. The table with the remarks concerning the grading process is also shown in APPENDIX III table 3.

Synthesis III

Materialization

Phalanges

Three phalanges are designed in Solidworks to fit the index finger. The files can be downloaded from an online forum.

The proximal and middle phalange are tubes around the finger. They are smaller on the palmar side of the hand than on the dorsal side. The palmar side is smaller to enable proper flexion of the finger. Tubes are included in the proximal and middle phalanges. These two phalanges also include a structure on the dorsal side through which the wires from the dorsal FSR are guided towards the hand. The distal phalange surrounds the fingertip completely. Additional space is reserved in the fingertip to place Force Sensing Resistors (FSRs). A structure with a 1mm hole is included on the palmar side to which the tendon can be attached. The designed phalanges are shown in figure 12.

Figure 12: Design of the proximal, middle and distal index finger phalanges

The material used is PolyLactic Acid (PLA). PLA is a material that can be used in 3D printing. It is chosen over Acrylonitrile Butadiene Styrene (ABS) since the latter material should not get into contact with food, has a lower Tensile Strength, and is harder to use. A layer of cloth should be attached to the inside of the phalanges. This ensures a better fit as well as more comfort.

TABLE 3: The mechanical properties of ABS and PLA [19]

Properties*	ABS	PLA
Tensile Strength**	27 MPa	37 MPa
Elongation	3.5 - 50%	6%
Flexural Modulus	2.1 - 7.6 GPa	4 GPa
Density	1.0 - 1.4 g/cm^3	1.3 g/cm^3
Melting Point	N/A (amorphous)	173 °C

TABLE 3: The mechanical properties of ABS and PLA [19]

Properties*	ABS	PLA
Glass Transition Temperature	105 °C	60 °C

Arm frame

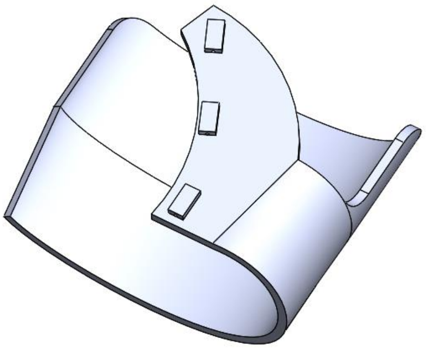
The frame of the exoskeleton consists of two separate parts. A hand shell and an arm shell. Both parts are designed in Solidworks and can be 3D printed using PLA. The files can be downloaded from an online forum.

To design the hand shell, photos were made of the hands from above and from the side. These were imported in Solidworks and scaled to the right size. The photos were used to design the hand shell in the right dimension. The hand shell does not cover the thumb and the inside of the MCP bones. This ensures the free movement of the thumb and fingers.

Three tubes are placed on the palmar side of the hand shell from the wrist to the index finger. These tubes ensure proper guidance of the tendon to the finger. The first tube is located just above the wrist, the second in the middle of the hand, and the third just below the finger.

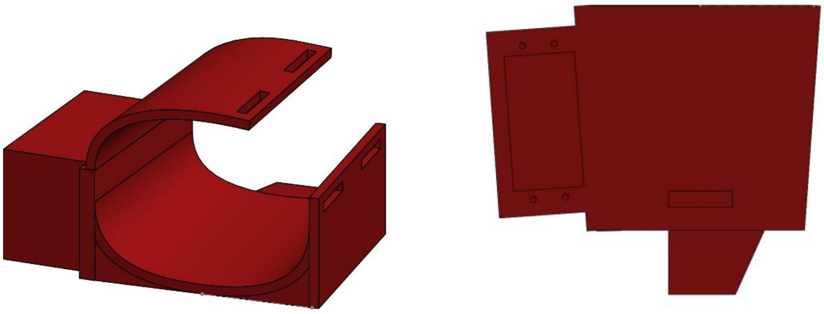
Two strips of Velcro are used. One is located below the thumb and one is located between the thumb and index finger.

Figure 13: design of the shell that is placed on the hand



The arm shell is designed using the dimensions of the lower arm and the sizes of the actuator. The servo can easily be attached to the shell in the designed cavity. This cavity fits the dimensions of the used servo. Two strips of 20mm Velcro are used to attach the shell to the arm. One is located 5mm from the proximal side, while the other is located 5mm from the distal side.

Figure 14: Design of the shell that fits around the arm and holds the servo



A layer of cloth should be attached to the inside of the shells. This ensures a better fit as well as more comfort.

In the case of no 3D printer being accessible, the shells and phalanges can be created using other manufacturing methods. For example, firm cardboard or wood can be used to produce an exoskeleton using the designs as guidelines.

Processor

An Arduino Uno R3 microcontroller is used as it can easily be learned inexperienced people. It is based on a removable DIP ATmega328 AVR controller. It has 20 digital input/output pins, of which 6 can be used as PWM outputs and 6 can be used as analog inputs. The easy to use Arduino computer program is used to create and upload programs.[20]

Wiring

A breadboard is used to easily attach the components. 30 cm Male-male breadboard wires and male-female breadboard wires are used to attach components to the breadboard and Arduino. A 10k ohm and 330 ohm resistor are used for the FSRs.

Sensors

Two Force Sensitive Resistors (FSR) are used as sensors. FSRs are sensors that detect physical pressure, squeezing and weight. It consists of two layers separated by a spacer. Higher pressure makes the resistance go down[21]. It can sense applied force in the range of 100g-10kg.[23]

One is placed on the dorsal side of the fingertip, while the other is placed on the palmar side. When the user starts gripping an object, the palmar FSR senses this and sends a signal to the processor. If the wearer wants to release the object, the finger pushes to the dorsal FSR. A signal is sent to the processor.

Actuator

An analog Servo-HD-6001MG servo motor is used as actuator. It weighs 56g and has dimensions of 40,7x20,5x39,5mm. It has a stall torque of 7 kg.cm or 6kg.cm for 6V and 4,8V respectively. The servo can be easily attached to the arm frame. An arm of 30 mm is mounted on the servo.

It has three cables. The orange cable should be attached to a digital output pin, the red cable to the 5V power output, and the brown cable to the ground.

Using the length of the motor arm and the stall torque the pull force can be calculated. The pull force is 2kg.

Transport movement

Nylon fishing line is used to transport the movement from the servo motor to the finger. This nylon line is attached to the fingertip on one side. The line goes through the tubes in the phalanxes and the tubes on the hand. The other end is attached to an arm on the servo motor.

Using the law of moments:

$$F1 * r1 = F2 * r2 \rightarrow F2 = F1 * \frac{R1}{R2}$$

Where F1 is the desired force of 16N (see requirements), r1 is the distance between the place where the force acts in the vertical direction and the joint in the horizontal direction (approximately 15mm), r2 is the distance between the place where the horizontal force acts and the joint in the vertical direction (approximately 5mm), and F2 is the necessary force through the tendon. This results in a necessary force of 48N.

Mitchel MX3 Clear nylon fishing line is selected. It has a pull force of 8,7 kg, which is sufficient to withstand the desired force.

(De)activation and reset

A simple pushbutton is used to reset the system. Holding down the button makes the servo move to its start position, stopping the assisted flexion. A switch is used to activate and deactivate the system.

Prototyping / proof of principle

The initial design is tested by making a proof of principle. The prototype is created with cardboard, an Arduino set, two FSRs, a servo, nylon thread, and an old nylon glove.

The process started with the Arduino set and a FSR. First step was to get data from the FSR. The guide “using an FSR” from Adafruit was used for this step. The result was a setup to read the analog FSR measurement.[21]

Second step was to use the data from the FSR to control the servo. For this step, first a simple code was used as described in the guide: “Control a Servo with a Force Resistive Sensor on Arduino” retrieved from the Arduino project hub. It reads the FSR sensor data and translates it to a value for the servo. [22].

This code is modified. Instead of translating the sensor data to servo position via mapping, a threshold was created. When the FSR data exceeds this threshold, the servo actuates to a set position. When the FSR data drops below the threshold, the servo moves back.

A second FSR is introduced as well as a second threshold and the code is once again modified. The motor actuates to a set position when the threshold for the first FSR is exceeded. When the threshold for the second FSR is exceeded, the servo moves back to its original position.

A stepsize is introduced to the coding. When the threshold of the first FSR is exceeded, the servo rotates in the positive position with the set stepsize. Exceeding of the threshold of the second FSR leads to the servo rotating in the negative position with the set stepsize. The minimum and maximum limit of 0 and 180° are implemented as the servo cannot exceed these values.

Materials are bought to create a prototype. Contact glue, cardboard, tape, paper straws, nylon line, and a nylon glove are used in the process. These matertials are shown in figure 15.

Figure 15: Materials used for prototyping of the exoskeleton

Cardboard is used to create an exoskeleton. For the proximal and middle phalanges, cardboard pieces are cut in the right size. These pieces are placed around the finger while the glove is worn and the cardboard is glued to form a tube around the finger. These tubes are cut to fit the phalange while the finger is flexed. Cardboard is cut in shape to fit the palmar side of the hand and the dorsal side of the hand. These parts are glued directly to the glove. Another piece of cardboard is glued to both the dorsal side and the palmar side to connect them.

A piece of cardboard is glued to the lower arm part of the glove. Another piece of cardboard is cut and formed to hold the servo. This part is glued to the other piece of cardboard on the lower arm and extra secured using tape.

Four pieces of straw are cut and glued to small pieces of cardboard. Tape is used to extra secure the straws. Three parts are then glued on the palm of the hand of the exoskeleton and the other is glued at the lower arm part near the wrist.

The nylon thread is tied to a piece of cardboard. This piece of cardboard is glued to the fingertip of the glove. Tape is placed on the FSRs. A small piece of cardboard the size of the measurement area is glued at the FSRs to improve the force measurement. One FSR is glued to a piece of cardboard that is glued to the dorsal side of the fingertip, while the other is glued to the palmar side. A piece of rubber is placed on the fingertip, covering the dorsal side, palmar side and fingertip. This ensures force measurement of the dorsal FSR. The nylon thread is placed through the phalanges and the straw parts and tied to the arm of the servo.

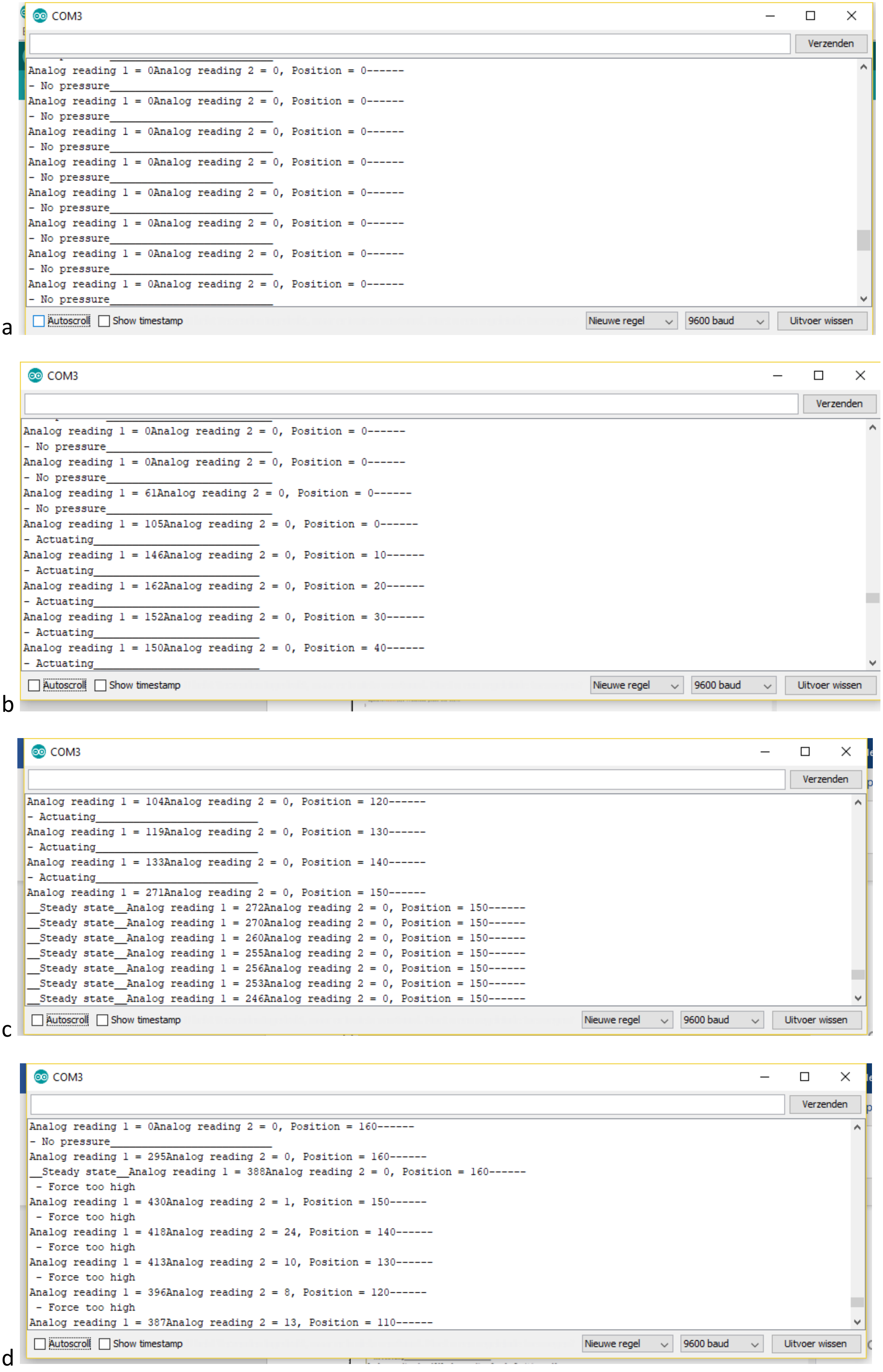
The resulting first version of the prototype including servo and FSRs is shown in figure 16.

Figure 16: the first version of the prototype: finger and complete exoskeleton

The code is further elaborated leading to the final code. Extra thresholds are added leading to thresholds for triggering actuation, reaching the desired gripforce, reaching the maximum desired grip force, and deactuation. Different combinations of sensor data and current position lead to different command. The code is described in “Functioning”.

The prototype is first tested without the servo. The thumb and index finger are squeezed together to simulate gripping. The resulting output is given in figure 17. The figure shows that the program works as intended: a force that is too low is considered as “no pressure” (a), a force above the actuation threshold triggers actuation (b), a force between the desired minimum grip force and the maximum force keeps the system at its current position (c), and a force higher than the desired maximum force makes the servo move back (d).

Figure 17: Responses from the system to no pressure, light pressure, medium pressure, and hard pressure



```
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
```

a

```
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 0Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 61Analog reading 2 = 0, Position = 0------
- No pressure__________________________
Analog reading 1 = 105Analog reading 2 = 0, Position = 0------
- Actuating__________________________
Analog reading 1 = 146Analog reading 2 = 0, Position = 10------
- Actuating__________________________
Analog reading 1 = 162Analog reading 2 = 0, Position = 20------
- Actuating__________________________
Analog reading 1 = 152Analog reading 2 = 0, Position = 30------
- Actuating__________________________
Analog reading 1 = 150Analog reading 2 = 0, Position = 40------
- Actuating__________________________
```

b

```
Analog reading 1 = 104Analog reading 2 = 0, Position = 120------
- Actuating__________________________
Analog reading 1 = 119Analog reading 2 = 0, Position = 130------
- Actuating__________________________
Analog reading 1 = 133Analog reading 2 = 0, Position = 140------
- Actuating__________________________
Analog reading 1 = 271Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 272Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 270Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 260Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 255Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 256Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 253Analog reading 2 = 0, Position = 150------
__Steady state__Analog reading 1 = 246Analog reading 2 = 0, Position = 150------
```

c

```
Analog reading 1 = 0Analog reading 2 = 0, Position = 160------
- No pressure__________________________
Analog reading 1 = 295Analog reading 2 = 0, Position = 160------
__Steady state__Analog reading 1 = 388Analog reading 2 = 0, Position = 160------
 - Force too high
Analog reading 1 = 430Analog reading 2 = 1, Position = 150------
 - Force too high
Analog reading 1 = 418Analog reading 2 = 24, Position = 140------
 - Force too high
Analog reading 1 = 413Analog reading 2 = 10, Position = 130------
 - Force too high
Analog reading 1 = 396Analog reading 2 = 8, Position = 120------
 - Force too high
Analog reading 1 = 387Analog reading 2 = 13, Position = 110------
```

d

Flaws and improvements

After using the prototype with the servo attached, some flaws were discovered.

- The palmar FSR does not always give a reliable measurement of the force. Sometimes the applied force was not registered.
- The arm of the servo does not give steady movement
- The servo does not produce enough movement
- Actuation of the servo causes movement of the arm shell towards the hand.
- Actuation of the servo causes unwanted wrist flexion.

The prototype was slightly altered to improve the results.

- The FSR is placed under an angle on the fingertip using a piece of wood:
  It is assumed that the forces acting more perpendicular to the FSR improves the output from the sensor.
- Using cardboard and glue, a wheel is made that is placed over the arm:
  Using a wheel, every angular displacement step of the servo leads to the same length of pulled nylon line. Also, a higher displacement of nylon line is possible, since the amount of displacement is now equal to half of the circumference instead of twice the arm length.
- The arm shell and hand shell are connected using cardboard and glue:
  The connection between arm and shell avoids unwanted wrist flexion, and movement of the arm shell towards hand. However, a big disadvantage is that this solution disables active wrist movement from the user.

The design alterations are seen in figure 18. The prototype is tested again by pressing tips of the thumb and index finger together, and by trying to grip some objects. The detection of applied force is improved due to the angle of the FSR. The wheel attached to the servo makes the movement more gradual and increases the amount of possible movement. The connection between the arm- and hand shell cancel the wrist flexion and movement of the arm shell. This increases the finger flexion possibilities and comfort.

Figure 18: Second version of the exoskeleton prototype

However, in some cases an applied force still is not detected. Especially in the case of soft materials, like water bottles, and small objects. Also, the hard surface and the distance from the finger make it more difficult to hold small objects. Therefore, a new improvement is proposed. The FSR is placed on a flat structure on the fingertip. A hinge mechanism is placed on the fingertip with a tip located over the FSR. On the hinge mechanism is a structure that creates a small angle. Pressure applied to the fingertip presses the tip on the hinge mechanism against the FSR. This way, the force during gripping is always applied to the FSR, thus improving the force detection. Unfortunately, due to time constraints there is no possibility to test this system.

Functionality

The code uses the data of two FSRs. One is located on the palmar side of the fingertip and the other one is located on the dorsal side. These FSRs send signals to the Arduino UNO. The palmar and dorsal FSR are named FSR1 and FSR2 respectively.

The code contains a number of set thresholds regarding actuation and deactuation:

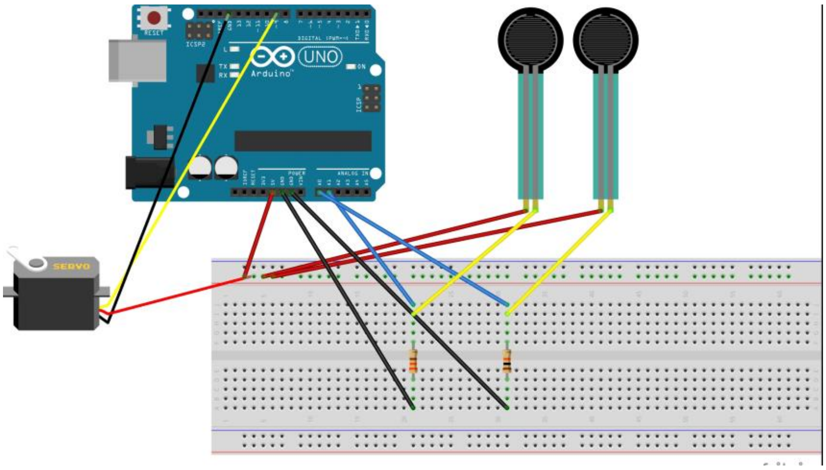
- F_des: The value of FSR1 corresponding to the desired grip force
- F_trig: The threshold of FSR1 corresponding to triggering of actuation.
- F_max; The value of FSR1 corresponding to the maximum desired value. This is used to avoid object damage and discomfort
- F_deac: The threshold of FSR2 corresponding to deactuation of the system.
- Pos: the integer used to move the servo to its desired position
- Stepsize: the integer that sets the movement of the servo per cycle
- Delaytime: the integer that sets the waiting time after each cycle of the loop
- Pos_max: the maximum set value the servo can reach

The system can only actuate if the value from the dorsal FSR is below F_deac. When this is the case there are some different possible situations regarding actuation.

- FSR1 < F_trig:
  The system does not actuate.
- F_trig < FSR1 < F_des+20 & pos <= pos_max-stepsize:
  pos increases with the set stepsize. The new desired position is sent to the servo which moves to its new position. F_des+20 is used to improve stability of the system.
- F_des <= FSR1 <= F_max:
  The system is in its desired range of grip force.
- F_max < FSR1 & pos >= stepsize:
  The current force on the fingertips is too high. The value of stepsize is deducted from pos and the servo turns to its new desired rotation to avoid damage to objects and/or the finger
- Other possibilities:
  For example, the servo has reached its maximum position and the grip force is still too low, or the servo has reached its minimum position and the grip force is still too high. In these cases, the servo cannot improve the situation, so it should stay in its current position.

The complete code is shown in APPENDIX III. A schematic view of the Arduino circuit is shown in figure 19.

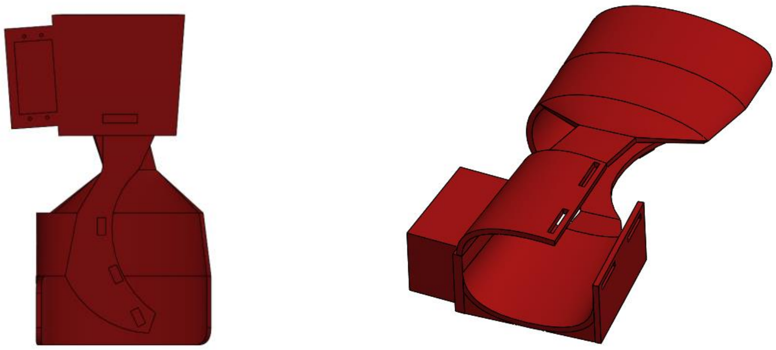
Figure 19: Schematic view of the Arduino circuit with a breadboard two FSRs and a servo



Final 3D design

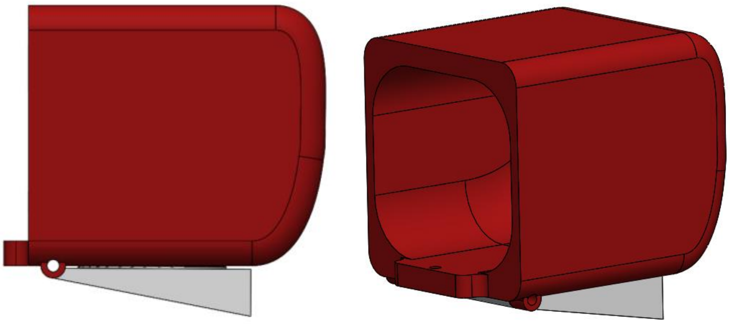
The findings from the prototyping process are included in the final design. The proximal and final design are not adjusted. The hand and arm shells are merged by making a connection on both the palmar and distal side. Openings are designed in the part to which Velcro can be attached. The arm frame is designed so that the servo, processor and breadboard can be easily attached. Three tubes on the hand and one tube on the wrist guide the tendon towards the servo motor. The frame does not interfere with movement of the fingers. The new design can be seen in figure 20.

Figure 20: bottom view and trimetric view of the newly designed shell that covers the hand and lower arm of the user



A hinge mechanism is added to the distal phalange. The new design is shown in figure 21. One FSR is placed on the inside of the shell on the dorsal side, while the other is placed under the hinge mechanism. Under the hinge mechanism is a part that is located on the FSR. Therefore, grip forces applied on the hinge mechanism should be transferred to the FSR.

Figure 21: Side view and diagonal view of the new distal phalange with a hinge mechanism



The assembled exoskeleton is shown in figure 22 It shows the bottom view, right side view, top view, and diagonal view of all designed parts of the exoskeleton. A rendered image is shown in figure 23. A technical drawing of the exoskeleton can be seen in APPENDIX IV.

Figure 22: Bottom view, right side view, top view, and trimetric view of the assembly of the exoskeleton parts

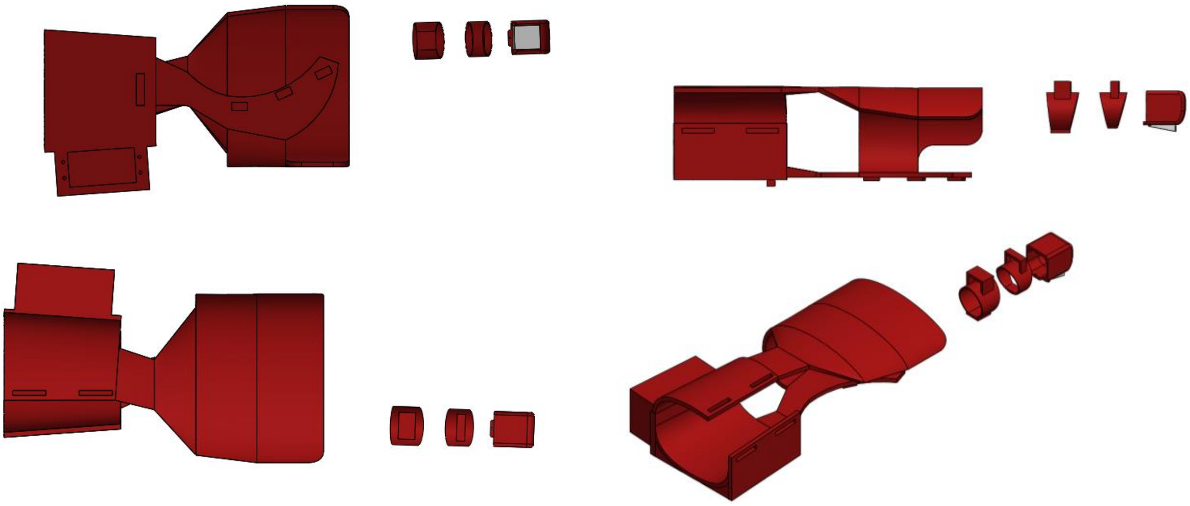
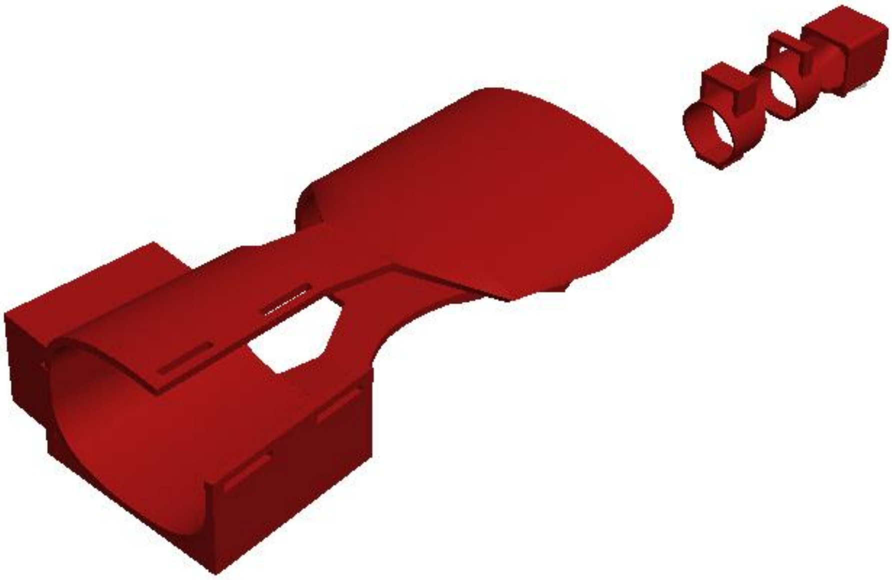


Figure 23: rendered view of the exoskeleton



Cost estimation

Table 4: Cost estimation

COMPONENT	SUPPLIER	QUANTITY	PRICE PER COMPONENT	PRICE
ARDUINO UNO REV3 ATMEGA 328	Kiwi Electronics	1	23,95	23,95
SERVO-HD-6001MG	Model Aircraft Company	1	17,95	17,95
ROUND FORCE SENSITIVE RESISTOR (FSR)	SOS Solutions	2	10,-	20,-
400 PIN BREADBOARD	KIWI Electronics	1	4,95	4,95
PREMIUM JUMPERWIRES STRIP - 40 STUKS - M/M - 20CM	Kiwi Electronics	1	4,95	4,95
PREMIUM JUMPERWIRES STRIP - 40 STUKS - M/F - 20CM	Kiwi Electronics	1	4,95	4,95
VELCRO DOUBLESIDED	Alle kabels	1	5,95 per roll	5,95
ESUN 3D-PRINTER FILAMENT WHITE 1.75MM PLA 1KG ROLL	Hobbyking	1	17,15 per kg	17,95

MITCHEL MX3 CLEAR NYLON LINE 0,35MM	Tackleshop	1	5,95 per 300m	5,95
TOTAL COSTS				106,-

Table 4 shows the total costs for acquiring all components. The total costs were determined using the current prices of the necessary components in webshops. This leads to a total cost of €106,-, which is slightly above the desired price. However, many of the components need to be bought in a certain quantity, like fishing line, printer filament, and jumper wires. Therefore, there are more components than needed. This is an advantage when someone wants to build a version with multiple fingers. For each additional finger, only an extra servo motor and two extra force sensors have to be bought. This brings the price of an additional finger to €37,95.

No labour costs are included in the calculation, since it is assumed that users create the exoskeleton themselves in their spare time or that they are assisted by acquaintances.

The current cost estimate is based on Dutch webshops since these have faster delivery[25-30]. Other sites, like Sparkfun and Aliexpress have lower prices. If the delivery time is not an issue, components can be ordered from these sites to save money, bringing the total costs below the requirement of €100,-

Risk analysis

Risk identification[1]

The first step of the risk analysis for the product is identification of the potential risks. The Failure Mode and Effect Analysis (FMEA) is used for this. This analysis analyses the most occurring risks. If the risks are too great, the design of the product can be altered to make the risks acceptable. A risk is defined as an event that reduces the functioning and/or the result of the prototype.

The risks are divided in the following categories:

- Production: errors that originate from manufacturing.
- Montage: all risks that originate while the product is assembled.
- Functioning: all risks during use of the product.
- Use: all risks caused by incorrect use of the user
- Maintenance: risks that reduce the quality of the product

Risk quantification[1]

The risks of the powered exoskeleton are prioritized according to likelihood and impact rating. The likelihood and impact are rated as described in table 5 and table 6. The Priority is calculated as the average of the likelihood and impact scores.

Table 5: Risk likelihood rating score and description[1]

Title	Score	Description
Very Low	20	Highly unlikely to occur; however, still needs to be monitored as certain circumstances could result in this risk becoming more likely to occur during the project
Low	40	Unlikely to occur, based on current information, as the circumstances likely to trigger the risk are also unlikely to occur
Medium	60	Likely to occur as it is clear that the risk will probably eventuate
High	80	Very likely to occur, based on the circumstances of the project

Very High	100	Highly likely to occur as the circumstances which will cause this risk to eventuate are also very likely to be created

Table 6: Risk impact rating score and description[1]

Title	Score	Description
Very Low	20	Insignificant impact on the project. It is not possible to measure the impact on the project as it is minimal
Low	40	Minor impact on the project, e.g. < 5% deviation in scope, scheduled end-date or project budget
Medium	60	Measurable impact on the project, e.g. 5-10% deviation in scope, scheduled end-date or project budget
High	80	Significant impact on the project, e.g. 10-25% deviation in scope, scheduled end-date or project budget
Very High	100	Major impact on the project, e.g. >25%% deviation in scope, scheduled end-date or project budget

A priority score below 20 is considered as very low, between 21 and 40 as low, between 41 and 60 as medium, between 61 and 80 as high, and higher than 80 as very high. A risk plan is written for the risks that are rated as high or very high.[1]

Table 7: Risk quantification

				Rating			
Nr	**Categorie**	**Risk**	**Consequence**	Likelihood	Impact	Priority	
1	**Production**						
1.1		No 3D printer present or accessible elsewhere	The exoskeleton cannot be fabricated using a 3D printer or a 3D printer has to be bought	80	80	80	Very high
1.2		User and acquaintances cannot adjust drawings to dimensions of its own hands	The exoskeleton cannot be fabricated using a 3D printer or a 3D printer has to be bought	80	80	80	Very high
1.3		Flaws occur during production of the exoskeleton	The exoskeleton has parts that are thinner than designed, the product does not fit the user, or components do not fit	80	60	70	High
2	**Montage**						

2.1		Components do not fit on the exoskeleton	The device cannot be finished	60	20	40	Medium
2.2		Tendon line is tied too long	The finger cannot be flexed	40	40	40	Medium
2.3		Tendon line is too short	The finger cannot be extended	40	40	40	Medium
2.4		Tendon line is not tied properly	The tendon can loosen, so the finger cannot be flexed	40	40	40	Medium
2.5		Electronics components are not correctly wired	The system does not function	60	40	50	Medium
3	**Functioning**						
3.1		Connection between components broken	Product does not work	40	40	40	Medium
3.2		Motor is not powerful enough	No proper assisted flexion	20	60	40	Medium
3.3		The device causes unwanted wrist flexion	The wanted movement cannot be performed properly	20	60	40	Medium
3.4		Force is not applied to the FSRs	The FSRs do not measure the right force or do not measure force at all, potentially leading to too much actuation or no actuation at all	60	80	70	High
3.5		The cable is not strong enough	The cable breaks, so the device cannot support flexion	40	20	30	Low
3.6		Lifetime of the product is less than expected	New parts have to be made	60	40	50	Medium
4	**Use**						

4.1		Variables in the program are given the wrong value	The device does not work properly	80	60	70	High
4.2		Device is placed wrongly on the hand/fingers	The device potentially causes injury and/or does not work properly	20	60	40	Medium
4.3		Device hits something in the surroundings	The device can break	40	40	40	Medium
4.4		The wheel on the motor is not secured	The wheel can detach from the motor	40	40	40	Medium
4.5		A sudden high force on the fingers during assisted flexion	The motor breaks down	60	80	70	High
4.6		The system is accidentally reset or deactivated	The device stops working (momentarily)	60	20	40	Medium
4.7		Using the product without assistance is impossible	User needs help with attaching the product	40	40	40	Medium
4.8		Product hinders movement of other joints	Product will not be used	100	60	80	Very high
4.9		The exoskeleton breaks down	Product cannot be used anymore	60	40	50	Medium
5	**Maintenance**						
5.1		Surface of the finger exoskeleton is greasy	Objects can slip from the hand	20	20	20	Low

Risk plan

Measures needs to be taken to prevent the risks. The preventive measures for the risks along with the person responsible for the measure can be seen in table 8.[1] Since the project is intended to be accessible to all users, the project community is the action resource for all preventive actions.

Table 8: Preventative actions and action resources of the high risks

Rating	Operation	Preventative actions	Action Resource
Very high	1.1 No 3D printer present or accessible elsewhere	Present an alternative method to fabricate the exoskeleton	Project community
Very high	1.2 User and acquaintances cannot adjust drawings to dimensions of its own hands	Present an alternative method to fabricate the exoskeleton	Project community
High	1.3 Flaws occur during production of the exoskeleton	Alter the design so that small deviations created by flaws do not impact the overall quality of the product too much	Project community
High	3.4 Force is not applied to the FSRs	Design a mechanism so that the applied force is redirected to the FSR. Otherwise, another sensing mechanism should be investigated	Project community
High	4.1 Variables in the program are given the wrong value	Write clear guidelines how to properly determine the values of the variables	Project community
Very high	4.8 Product hinders movement of other joints	Develop a new wrist part that ensures movement of the wrist while preventing forced wrist flexion due to actuation	Project community

Discussion

During this project, a DIY powered exoskeleton system is designed using the Methodical Design process as described by G.J. Verkerke and E.B. van der Houwen. The project resulted in a 3D design of the index finger assisted flexion exoskeleton, a prototype of the code for Arduino, and a proof of principle. Also, the possible risks are identified and a cost estimation is made.

The final prototype differs slightly from the initially proposed design:

- The palmar FSR is placed under an angle on the fingertip
- A wheel is mounted on the Servo instead of an arm
- The arm shell and hand shell are connected

These alterations improved the functionality of the device. Force detection of the palmar FSR is improved, pulling of the line by the servo is more gradual, forced wrist flexion is minimalized and the shell around the hand and lower arm stays at its desired location.

However, the exoskeleton still does not function optimally. Some of the current flaws of the prototype are:

- The FSRs sometimes do not detect applied forces. Especially for plastic bottles and small objects.
- Active wrist flexion by the user is very limited. This limits the user during daily life activity where wrist movement is normally used like eating and drinking.
- The prototype is still powered via the USB port of a computer

For the first flaw, a new distal phalange is designed that uses a hinge mechanism to redirect the forces to the FSRs. Unfortunately, due to time constraints this could not be tested. Potentially, the same mechanism could be added to the dorsal FSR too.

The second and third flaw are also not resolved due to time constraints. The third flaw could be solved by powering the Arduino using a battery pack. The second flaw is harder to solve. A new mechanism should be found for this if the limited wrist flexion proves to be too hindering.

Overall, the concept is proven too work. When a force is applied correctly, the FSRs are able to detect it. The output of the FSRs increases as the force input increases, so the system is able to differentiate a sufficient grip force from an insufficient grip force. The servo motor can be controlled based on the output of the FSRs. Theoretically, the force resulting from the servo is sufficient to reach the desired grip force. However, the actual resulting grip forces still have to be tested quantitively.

Initially, a FEM analysis was planned. However, due to constant crashing of the software the test could not be performed. FEM analysis should be performed to ensure the design can withstand the intended forces.

The designed exoskeleton can be created at home by future users. The shell can be produced using 3D printing or other methods. Using the Arduino board can easily be learned by inexperienced people and the thresholds in the code can easily be adjusted to another person. There is the possibility to use online forums to share the designs and code to further improve the system.

The exoskeleton is designed to be 3D printable. This limits the production costs since 3D printable filaments are not expensive. However, not everyone has access to a 3D printer. Purchasing a 3D printer is rather expensive, so an alternative production method should be available. Luckily, there is a wide variety of materials that can potentially be used. Depending on the skill of the user and availability of the material, parts can be made of cardboard, wood, thermoplastic foams, and glass fibre for example.

Future recommendations

- Improve force detection by the FSRs, for example by using the hinge mechanism
- Make the system battery powered
- Add a new wrist mechanism
- Add additional fingers to actuate
- Add an on/off switch and/or reset button
- Finetune the code to make it more efficient
- Use a motor that can freely rotate and therefore is not limited to a range of motion
- Write clear guidelines that describes how to alter the Solidworks file to the dimensions of the user, how to 3D print the object, how to determine the right variables in the code, and how to attach the exoskeleton
- Describe an alternative method to produce the method

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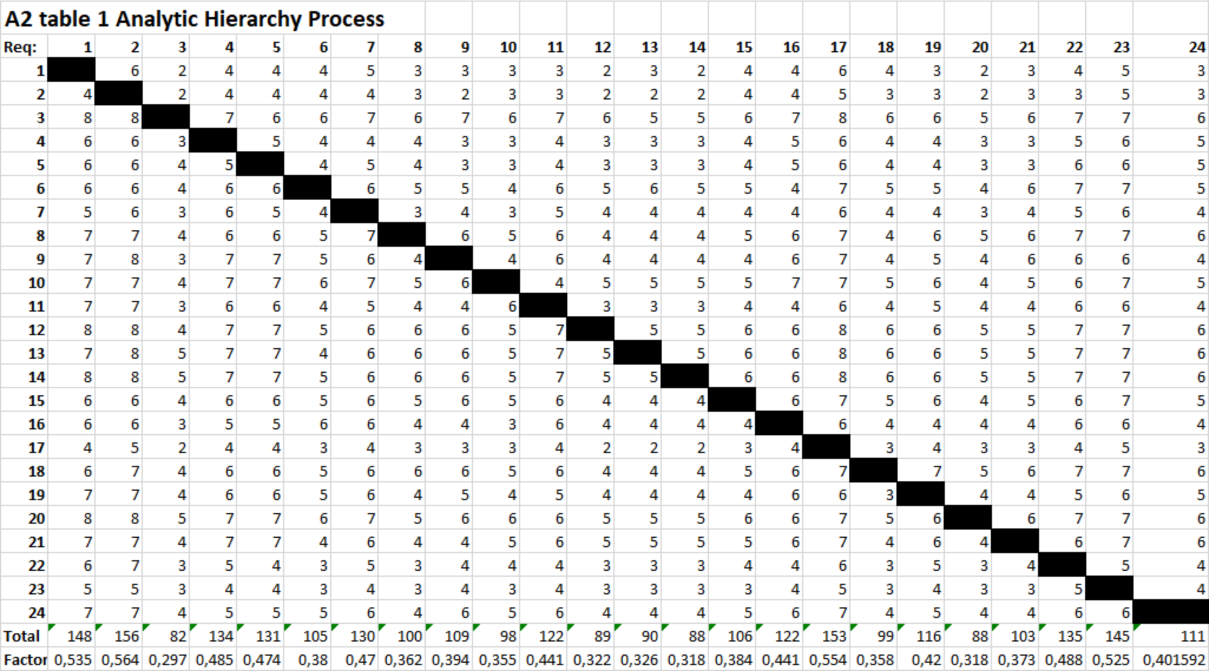
Appendix I: Morphological Scheme[3, 7-11, 15-23]

Function					
Material	EVA foam	Worbla	3D printed	Cloth	Wood
	Cardboard	Silicone rubber	Foam	Metal	PUR
Attachment	Velcro	Elastics	Tape	Glove	Staples
	Glue	Clamp	Sutures	Sticking	
Acticvation	Power button/switch				
Transport user-product	Electrodes	Wires	Frame		
Sensors	Force sensor	Accelerometers	Gyroscope	IMU	Potentiometer
	Mechanomyography	Finger pad deformation	Force myography	Photo-plethysmography	Muscle Hardness
	End switch	Rotary encoder	Force sensitive ink	Touch sensor	ECG
	Tiltsensor	Flexsensors	sEMG		
Processing	Arduino	Manual	Gnomes		
Actuation	Soft robotics	Shape Memory Alloys	Dielectric elastomer	Hydraulics	Electric motors
	Linear actuator	Pneumatics			
Transmission actuator-joint COR	Rods	Tendons	Cords	Elastics	Springs
	Worm gear	Slide bearing	Tube	Direct attachment	Gears
Joint movement	flexibe joint (cloth/elastics)	COR matching joints	Remote COR linkage system	Base to distal end linkage	Circuitous joints
Object destruction prevention	Force sensor	Springs	Elastics	Deformable surface	
Power source	Battery	Mains electricity	USB port	Solar panel	Dynamo
	Compressed air	Fluid tank			

Appendix II: Concept selection



A2 table 1 Analytic Hierarchy Process

Req:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1		6	2	4	4	4	5	3	3	3	3	2	3	2	4	4	6	4	3	2	3	4	5	3
2	4		2	4	4	4	4	3	2	3	3	2	2	2	4	4	5	3	3	2	3	3	5	3
3	8	8		7	6	6	7	6	7	6	7	6	5	5	6	7	8	6	6	5	6	7	7	6
4	6	6	3		5	4	4	4	3	3	4	3	3	3	4	5	6	4	4	3	3	5	6	5
5	6	6	4	5		4	5	4	3	3	4	3	3	3	4	5	6	4	4	3	3	6	6	5
6	6	6	4	6	6		6	5	5	4	6	5	6	5	5	4	7	5	5	4	6	7	7	5
7	5	6	3	6	5	4		3	4	3	5	4	4	4	4	4	6	4	4	3	4	5	6	4
8	7	7	4	6	6	5	7		6	5	6	4	4	4	5	6	7	4	6	5	6	7	7	6
9	7	8	3	7	7	5	6	4		4	6	4	4	4	4	6	7	4	5	4	6	6	6	4
10	7	7	4	7	7	6	7	5	6		4	5	5	5	5	7	7	5	6	4	5	6	7	5
11	7	7	3	6	6	4	5	4	4	6		3	3	3	4	4	6	4	5	4	4	6	6	4
12	8	8	4	7	7	5	6	6	6	5	7		5	5	6	6	8	6	6	5	5	7	7	6
13	7	8	5	7	7	4	6	6	6	5	7	5		5	6	6	8	6	6	5	5	7	7	6
14	8	8	5	7	7	5	6	6	6	5	7	5	5		6	6	8	6	6	5	5	7	7	6
15	6	6	4	6	6	5	6	5	6	5	6	4	4	4		6	7	5	6	4	5	6	7	5
16	6	6	3	5	5	6	6	4	4	3	6	4	4	4	4		6	4	4	4	4	6	6	4
17	4	5	2	4	4	3	4	3	3	3	4	2	2	2	3	4		3	4	3	3	4	5	3
18	6	7	4	6	6	5	6	6	6	5	6	4	4	4	5	6	7		7	5	6	7	7	6
19	7	7	4	6	6	5	6	4	5	4	5	4	4	4	4	6	6	3		4	4	5	6	5
20	8	8	5	7	7	6	7	5	6	6	6	5	5	5	6	6	7	5	6		6	7	7	6
21	7	7	4	7	7	4	6	4	4	5	6	5	5	5	5	6	7	4	6	4		6	7	6
22	6	7	3	5	4	3	5	3	4	4	4	3	3	3	4	4	6	3	5	3	4		5	4
23	5	5	3	4	4	3	4	3	4	3	4	3	3	3	3	4	5	3	4	3	3	5		4
24	7	7	4	5	5	5	6	4	6	5	6	4	4	4	5	6	7	4	5	4	4	6	6	
Total	148	156	82	134	131	105	130	100	109	98	122	89	90	88	106	122	153	99	116	88	103	135	145	111
Factor	0,535	0,564	0,297	0,485	0,474	0,38	0,47	0,362	0,394	0,355	0,441	0,322	0,326	0,318	0,384	0,441	0,554	0,358	0,42	0,318	0,373	0,488	0,525	0,401592

A2 Table 2: Pre-concept grading scheme

Requirement	Factor	1	2	3	4	5	Score 1	Score 2	Score 3	Score 4	Score 5
1	0,5354559	6	7	7	7	7	3,2127352	3,748191	3,748191	3,748191	3,748191
2	0,5643994	8	7	6	7	8	4,5151954	3,9507959	3,3863965	3,9507959	4,5151954
3	0,2966715	8	7	8	8	6	2,3733719	2,0767004	2,3733719	2,3733719	1,7800289
4	0,4848046	8	7	5	8	7	3,878437	3,3936324	2,4240232	3,878437	3,3936324
5	0,4739508	8	6	8	8	6	3,7916064	2,8437048	3,7916064	3,7916064	2,8437048
6	0,3798842	8	8	8	8	7	3,0390738	3,0390738	3,0390738	3,0390738	2,6591896
7	0,4703329	8	8	7	6	6	3,7626628	3,7626628	3,29233	2,8219971	2,8219971
8	0,3617945	7	8	7	6	7	2,5325615	2,894356	2,5325615	2,170767	2,5325615
9	0,394356	9	9	7	6	7	3,5492041	3,5492041	2,760492	2,366136	2,760492
10	0,3545586	7	7	7	6	8	2,4819103	2,4819103	2,4819103	2,1273517	2,8364689
11	0,4413893	7	6	7	6	6	3,089725	2,6483357	3,089725	2,6483357	2,6483357
12	0,3219971	7	7	7	7	7	2,2539797	2,2539797	2,2539797	2,2539797	2,2539797
13	0,3256151	7	7	8	8	8	2,2793054	2,2793054	2,6049204	2,6049204	2,6049204
14	0,3183792	7	7	6	6	8	2,2286541	2,2286541	1,910275	1,910275	2,5470333
15	0,3835022	6	9	6	6	6	2,301013	3,4515195	2,301013	2,301013	2,301013
16	0,4413893	7	9	7	7	9	3,089725	3,9725036	3,089725	3,089725	3,9725036
17	0,5535456	7	7	7	9	9	3,8748191	3,8748191	3,8748191	4,9819103	4,9819103
18	0,3581766	8	8	8	8	8	2,8654124	2,8654124	2,8654124	2,8654124	2,8654124
19	0,4196816	8	7	8	8	7	3,357453	2,9377713	3,357453	3,357453	2,9377713
20	0,3183792	9	9	7	7	8	2,8654124	2,8654124	2,2286541	2,2286541	2,5470333
21	0,3726483	8	6	8	8	7	2,9811867	2,23589	2,9811867	2,9811867	2,6085384
22	0,4884226	8	7	8	8	8	3,9073806	3,418958	3,9073806	3,9073806	3,9073806
23	0,524602	9	7	8	7	8	4,7214182	3,6722142	4,1968162	3,6722142	4,1968162
24	0,4015919	7	8	7	7	7	2,8111433	3,2127352	2,8111433	2,8111433	2,8111433
Total							**75,763386**	73,657742	71,30246	71,881331	73,075253

A2 table 3:Requirement grading remarks table	
Requirement	**Remarks**
1	All concepts respond to signals from the user (force, EMG, or bending) However, all are imperfect. Force sensors require a force input from the user and EMG

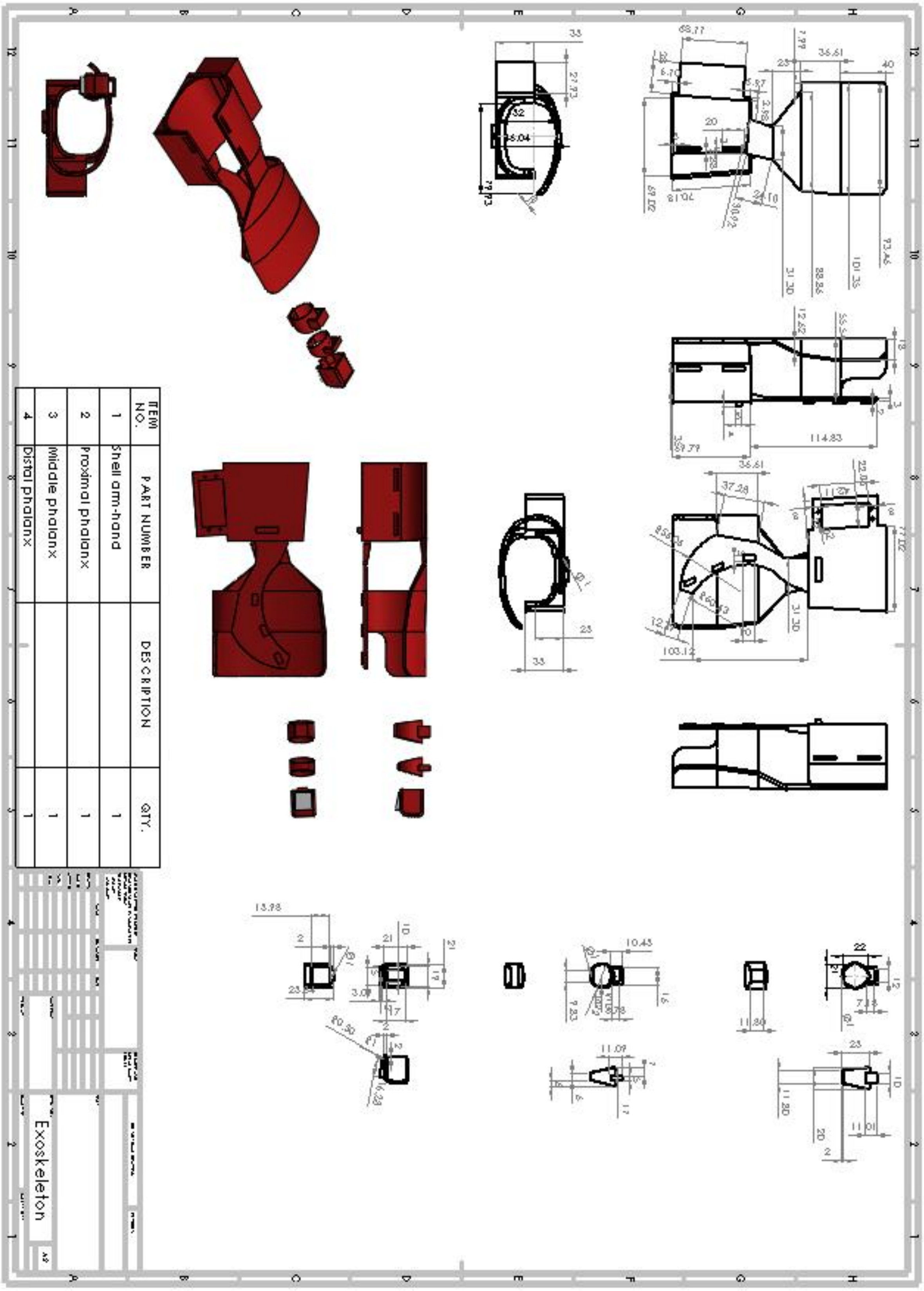
	requires sufficient muscle activity. Both are reduced in stroke patients[4]. Bending sensors do not tell anything about the force.
2	Concept 3 does not assist flexion/extension of the distal joint
3	The EMG sensors might be difficult to place for inexperienced people. SMA has complex motion control[17]
4	Pre-concept 3 does not actuate the fingertip, which significantly reduces the effectivity. Also, the long arm decreases the force the system can produce at the fingers [2-4]
5	The soft surface on the finger should be thick to properly avoid damage
6	SMA has low energy efficiency[17]
7	Concepts 1 and 2 are the narrowest around the fingers, concept 4 is the widest
8	Most concepts are not especially comfortable due to the need for an exoskeleton
9	Concept 1 is the most minimalistic, concept 2 is made of a lightweight rubber
10	The need for a pump and valve increases the weight of concept 2 in comparison to the last requirement[18]
11	More sturdy exoskeletons are needed for the actuation of concept 4 and 5. The soft robotics should be wide to ensure sufficient force generation.
12	The part around the lower arm is approximately the same in size for the pre-concepts
13	Pre-concepts 1 and 2 have more parts located at the lower arm region and therefore need a larger area to place them. All concepts stay within the limit
14	The large structures decrease the scores of pre-concepts 3 and 4. The servo and pump decrease the score for pre-concepts 1 and 2 respectively.
15	Concept 2 is made of rubber. The parts of the external frames of the other concepts introduces the risk of pinching and/or sharp edges
16	The EMG based concepts are more reliable, since the EMG sensor is based on the actual muscle activity[15]
17	In concepts 4 and 5 movement is introduced to the joints directly. Therefore, it is more easily to rotate the joints in the desired positions.
18	This requirement is incorporated in the code
19	Data from EMG sensors needs more complex coding to process.
20	Concepts 1 and 2 are gloves that are easily attached. Concepts 3 and 4 are more complicated structures that are harder to attach
21	The need for an air pump in concept 2 and the SMA wires in 5 consume more energy[16][17]
22	In concept 2, the pump needs to start pumping and fill the structure. SMA in concept 5 is relatively slow[16][17]
23	Due to the relative complexity of the structures of 2 and 4, these concepts are harder to fabricate
24	SMA is relatively expensive[17]. Strong enough servo motors are also expensive[18]

Appendix III: Arduino code

```
 #include <Servo.h>
 #include <Console.h>
 Servo myservo;

 int fsrPin1 = A1; // Sets the pin connected to the palmar force sensor as
analog 1
 int fsrPin2 = A0; // Sets the pin connected to the back of the finger
force sensor as analog 0
 int fsr1;         // Creates fsr1 to read the data from FSR 1 (palmar
side)
 int fsr2;         // Creates fsr2 to read the data from FSR 2 (back side)

 int F_des = 180;  // Set the FSR1 data for the desired grip force
 int F_trig = 100; // This is the threshold for FSR1 to trigger actuation
 int F_max = 350;  // Threshold to avoid object damage
 int F_deac = 450;  // Threshold for FSR2 to deactuate the system

 int pos = 0;      // Sets the initial position of the servo (The servo can
travel from 0 to 180)
 int pos_max=180;  // Sets the maximum angular displacement of the servo
 int stepsize=10;  // Sets the angular displacement for the servo for each
(de)actuation cycle step
 int delaytime = 200; // Sets the delaytime after movement. A lower
delaytime means a faster response

void setup(void) {
  // put your setup code here, to run once:
  Serial.begin(9600);
  myservo.attach(9); //servo at digital pin 9
  myservo.write(0); //initial point for servo
}

void loop(void) {
  // put your main code here, to run repeatedly:
  fsr1=analogRead(fsrPin1);             //Reads the data from fsrPin1 (A1)
  fsr2=analogRead(fsrPin2);             //Reads the data from fsrPin2 (A2)

//// The following prints the Sensor data and position on the monitor
  Serial.print("Analog reading 1 = ");
  Serial.print(fsr1);
  Serial.print("Analog reading 2 = ");
  Serial.print(fsr2);
  Serial.print(", Position = ");
  Serial.print(pos);

  if (fsr2 < F_deac) {         // System can only actuate if the force from
the finger to the back FSR is lower than the set deactivation force
    Serial.println("-------");

    if (fsr1 < F_trig) {
      Serial.println("- No pressure__________________________");

    } else if (fsr1 > F_trig & fsr1 <= F_max & fsr1<F_des+20 & fsr2 <
F_deac & pos <= pos_max - stepsize) {
      Serial.println("- Actuating__________________________");
      pos+=stepsize;         // The desired position increases with the set
stepsize
      myservo.write(pos);    // The servo travels to the new position
```

```
      delay(delaytime);             // Delay for stability

    } else if (fsr1 > F_max & pos >= stepsize) {
      Serial.println(" - Force too high");
      pos-=stepsize;
      myservo.write(pos);
      delay(delaytime);

    } else if (fsr1 >= F_des & fsr1 <= F_max){
      Serial.print("__Steady state__");

    } else {
      Serial.println("Desired Grip force cannot be reached");
      delay(delaytime);
    }
    delay(delaytime);

  } else {
    Serial.println("---Deactuate---");
    pos=0;
    myservo.write(pos);
    delay(delaytime);
  }
}
```

APPENDIX IV: Technical drawing



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Shell arm-hand		1
2	Proximal phalanx		1
3	Middle phalanx		1
4	Distal phalanx		1

APPENDIX V: Beyond the Lab description

In the Netherlands, 43.000 people suffer a stoke per year. That are approximately 117 every day. More than 320.000 people live with the effects of strokes. One of the possible effects of a stroke is the loss of hand strength. This causes stroke survivors to have very limited use of one hand. They still have some strength left, however they sometime lack the strength to grip objects.

A design is made to assist the user in grabbing objects. Force sensors on the finger detect the initial grabbing of an object. A servo motor pulls the wire that runs over the hand and finger to the fingertip. The force of the motor assists the movement of the finger and compensates the lost grip force.

The current design is only a proof of principle with one finger. Figure 1 shows the 3D design and figure 2 shows the proof of principle. The proof of principle is created with an old glove, cardboard, glue, tape, Force sensors, a servo motor, an Arduino board, and a breadboard. A simple code measures the forces at back and front of the fingertip.

Figure 1: Design of the exoskeleton

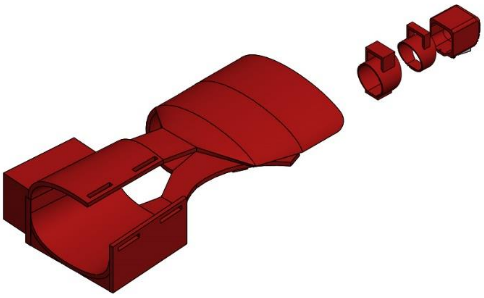
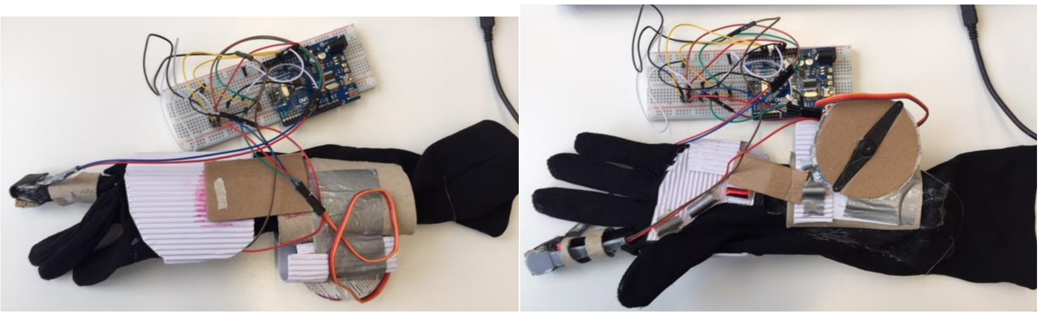


Figure 2: Pictures of the proof of principle of the design



Dimensions

The dimensions of the glove and Arduino + breadboard next to each other is approximately 40x18x6cm

APPENDIX VI: Reflection report

This Master work project has contributed to achieving the learning outcomes of the HTSM masterwork.

Knowledge and understanding

During the project I had to find a wide array of solutions for each aspect surrounding the main problem. Using a morphological scheme, I was able to get a clear overview of: the possible solutions to problems, the possible materials, the possible sensors and actuators, etc. Different pre-concepts were created using different combinations of solutions from the morphological scheme. Selecting the best concept using the list of requirements made me look into the potential advantages and disadvantages of every component and material even more.

The design process made me consider all underlying problems around the project, giving me a clear view of the objectives and possible pitfalls. Considering the problem from the perspectives of multiple stakeholders made the requirements more clear.

Since the final design should be possible to create at home, I particularly had to consider the production method, limiting me in the possible solutions. Using the Arduino board for prototyping gave me a better understanding of programming such devices. Also, the prototyping itself gave me a better feeling for potential design flaws as well as improving the design after a flaw has been detected

Applying knowledge and understanding

This project resulted in a proposal of a design for a DIY flexion assisting exoskeleton. This design is an improvement on other exoskeletons, since it can be produced at home. If the exoskeleton breaks due to an unexpected collision for example, that specific part can simply be produced again. There is no need for expensive replacement of the entire device. Different users probably have different remaining grip forces, so the fact that the thresholds in the Arduino code can easily be adjusted, is a huge advantage. In short, the designed product adds to the current market.

During prototyping, I was able to improve the design after a flaw was detected

Making judgements

The project started with a background research. During this research I had to judge the quality of the research and information I found. During the design process, I had to judge material, sensors, actuators, etc. for their advantages and disadvantages. Especially the grading of the pre-concepts made me judge the available information of all components.

During the analysis phase, all stakeholders were analysed. This lead to a list of requirements originating from multiple aspects. Also, during rating of the pre-concepts and components, I had to judge from multiple disciplines and aspects, including biomechanics, materials science, and the user/producer of the exoskeleton.

Communication

At the start of the project, I had to find a project and a mentor. After some mailing to different people within the university, prof. Katja Loos came with the idea to contact ScienceLinX. This is where the idea of doing a project for the "'Beyond the Lab" expo originated. Prof. Bart Verkerke agreed to be my mentor during the project. During a skype call we decided to trim the design assignment to better fit the workload of the master project. In the beginning weeks of the project, I visited Ingeborg and Renske from ScienceLinX to determine the final topic of the assignment.

Ingeborg guided me through the “Beyond the Lab” expo to give me a better understanding of the exposition

Communication is something I need to improve on. Especially due to my independent nature, I tend to try to do everything by myself. Therefore, I might overlook certain things. Beside this, advice on a subject is always helpful. In hindsight, I think that I should have consulted my mentor more often.

Attitudes

During the project I worked independently. I had to critically look at components and create a creative new design. Signing up for the HTSM honours course shows that I am interested in doing research beyond the regular education programmes. Also, since this project started with a background research and resulted in a design and proof of principle shows that I am interested in a wide aspect of scientific research. This project has shown that I am able to work in a theoretical as well as a practical setting.