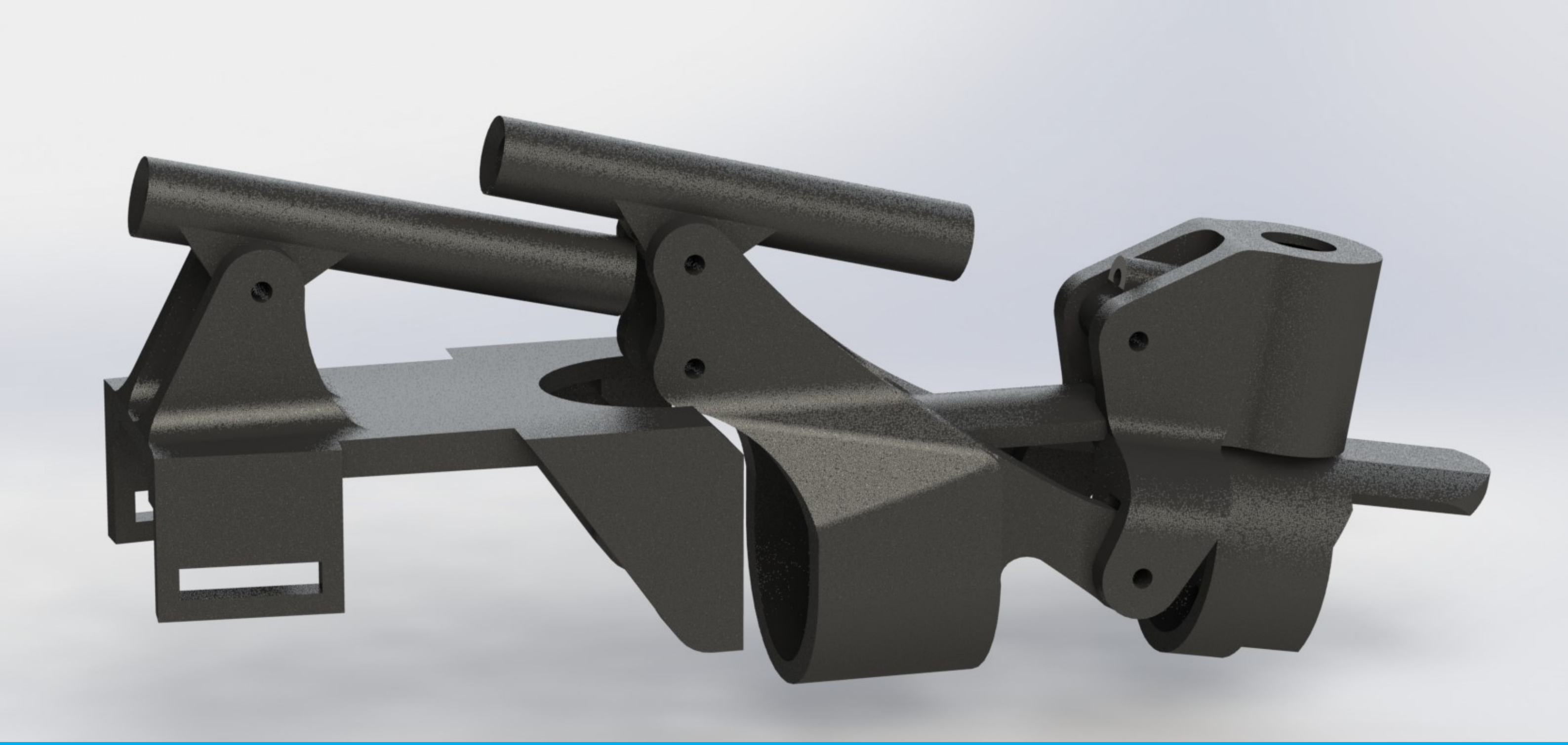
A Dual Actuated Hand Exoskeleton

Improving Force Transmission

Sebas Kracht



TUDelft

A Dual Actuated Hand Exoskeleton

Improving Force Transmission

by

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ABSTRACT

For patients with a hand disability, hand exoskeletons can improve their ability to perform activities of daily living. Its complicating that on the hand little space is available to build an exoskeleton. So, moment arms of actuators must be small. This complicates generating adequate moments. Strong actuators may be a solution, but they add weight, which should be minimized for comfort. The goal of this thesis is to design a proof of concept that improves force output, considering weight and size criteria.

The proof of concept divides the function of the exoskeleton into two phases that work one after the other. In the first phase the fingers flex to encapsulate an object, in the second phase force is applied. Each phase has an actuator that suits its requirements.

Results show that force output equals 5.087 [N], while the system weights 49.9 [g]. This equals a force-to-weight ratio of 102 [N/kg].

Force output was lower than theorized due to a variety of reasons and did not meet the set criteria of 10 [N]. The criteria of size were not met at the dorsal side of the proximal phalanx. The criteria were 20 [mm] extrusion, 27 [mm] was the end result. Both failures are expected to be solvable. It is concluded that with updates, the design can improve force output while maintaining a small and lightweight design.

CONTENTS

INTRODUCTION

There are many causes of hand disability (e.g., rheumatoid arthritis, osteoarthritis, diabetes, stroke, thyroid disease, neck and shoulder pain, gout, history of fracture, and Parkinson's disease, Dahaghin et al., 2005). These limit the number of activities of daily living (ADLs) that patients can perform. They usually have lower force output or range of motion (RoM) than a healthy subject's hand, or these activities are accompanied by pain (Dahaghin et al., 2005).

For people with hand disabilities, hand exoskeletons can offer a solution. They apply force to the hand and so they aim to improve force output or range of motion of the hand and fingers that are needed for normal hand function.

In history, many hand exoskeletons have been made (e.g., Bos et al. (2018), Jo et al. (2017), Popov et al. (2016)). When they are distributed to patients, it is useful to study user satisfaction, because it happens that exoskeletons are abandoned by its user. There are multiple reasons for abandonment. A few of these are bundled into the category 'exoskeleton specific reasons'. It consists of subjects as size, patient needs, orthosis functional abilities, discomfort, fitting and the patient's know-how of proper exoskeleton use. Together, this category makes up 31.8[%] of the total amount of upper limb orthosis abandonment (Sugawara et al., 2018).

Within this master thesis it will not be possible to measure abandonment rates, because a multiple year follow-up study is required to create a robust image of exoskeleton use and satisfaction. However, it is possible to extract some subjects of the exoskeleton specific abandonment and improve these, with the goal of improving the category as a whole.

Design specifications as size, weight and force output are important exoskeleton characteristics. Force output allows the exoskeleton and its user to apply enough force to everyday objects, weight keeping the burden of carrying low and small size makes the design discrete and ensures that the hand can reach without colliding with the environment (Sarac et al., 2019). These three characteristics are also directly related to the exoskeleton specific abandonment reasons mentioned above (size is mentioned directly, weight is linked to discomfort and force output is linked to patient need and functional abilities). So, the idea is that an improvement of these will lower this abandonment category. Besides, in the design of any exoskeleton these three are important factors for exoskeleton functioning as will be specified in the design criteria section.

The design criteria of low weight combined with high force output, wrapped in a small design is difficult to achieve. Firstly, the physical dimensions of the exoskeleton must be as small as possible. A larger design negatively affects handling during ADLs (i.e., bumping or failing to reach into small openings, Sarac et al., 2019). As can be imagined, a small design means that the actuators and its transmission must be packed close to the finger. And since the finger joints are only capable of rotation, the most important measurement of the actuator force over a joint is the moment it produces. A small design means that the actuators have small moment arms over the joints. Therefore, to create large moments, the exoskeleton becomes dependent on strong actuators.

In its turn, an actuator able to produce large forces is heavier and larger than a less powerful alternative. And, the part of the exoskeleton's structure that the actuator forces are transferred to, must also increase in either size or weight.

The actuator force must generally be a multiple of an external force at the fingertip, because the moment arm of the external force to the most proximal finger joint is much larger than the moment arm of the actuator to this joint, see figure 1.

The role that the actuator plays in the impasse of force, weight and size is displayed in figure 1. The actuator force (F_{exo}, in green) must be multiple times larger than the size of the external force (F_{ext}, in black) to allow for a similar joint moment.

To overcome the fact that the actuator force must be a multiple of the external force, the actuator should have a moment arm equal to the external force, this is depicted as the red arrow (F_{direct}). Of course, realizing a force such as F_{direct} brings many problems, such as actuator placement or the size of the exoskeleton's structure.

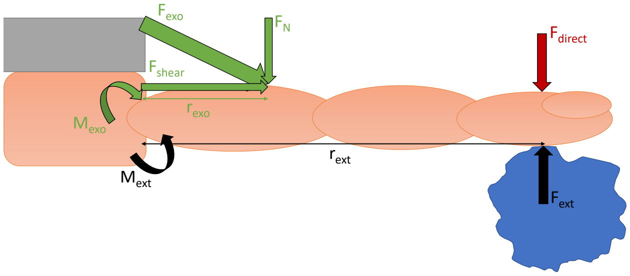

Figure 1. The finger experiences an external force, two ways of reaction forces are displayed. In red, the moment arm around the MCP joint is large, so a small force would suffice. In the case of the green force, the moment arm is smaller, so a larger force is necessary to create an equal moment around the MCP joint.

This master thesis will discuss hand exoskeletons that can be used daily by people with a permanent hand mobility disorder, who can benefit from an exoskeleton for longer periods of time. This type will hereafter be referred to as an assistive exoskeleton. Rehabilitative exoskeletons are not discussed. These are not used in such a diverse environment as an assistive exoskeleton. Therefore, small size might not be equally important. Often, rehabilitative exoskeletons remain in place, even in a holder, in the rehabilitation center during the entirety of a rehabilitative session. The criterion of weight is therefore less important as well (Sarac et al., 2019). Hand exoskeletons used for haptic purposes are not discussed for lack of medical subject-matter.

The goal of this master thesis is to design an exoskeleton proof of concept with improved force output, considering weight and size criteria. The reason for doing so is eventually to improve hand exoskeleton abandonment rates.

This main goal can be dissected into sub questions. Is it possible to increase force output, to decrease the weight or to decrease size without affecting the other two criteria? And afterwards, if it is possible, could the improved force transmission method from the proof of concept be incorporated into an exoskeleton?

The problem is approached by incorporating a new way of actuating the fingers. One that aims to improve moment arms without increasing size or weight.

The available literature is searched through to define design criteria. From the criteria, the problem is approached and a new exoskeleton proof of concept is designed, that has the goal of overcoming this impasse of size, weight and force. The new design is fabricated and validated by scientific experiments and from the results, its potential to proceed from proof of concept to actual exoskeleton will be discussed.

LITERATURE

To design an exoskeleton, the first step is to know what criteria must be set for the exoskeleton. In the next section, a theoretical framework is created that directs design choices. It will assess what requirements are important and makes it possible to evaluate the exoskeleton in the discussion.

Design criteria

The design criteria are based upon an article by Sarac et al., (2019), a manual for designing a 'generic hand exoskeleton'. They describe important characteristics of assistive exoskeletons. In this thesis, the focus will lie on assistive (i.e., daily use for chronically affected patients) exoskeletons. Some criteria will be added based on other articles describing hand exoskeletons.

While the design criteria are important for the proof of concept phase, they are also relevant for the next stage, to see if the proof of concept could be translated to a final design. Weight and force criteria of the proof of concept are given for one finger and can simply be multiplied to account for number of fingers the eventual design will have. Criteria such as comfort and cosmesis are relevant for the final design and are therefore included in this master thesis, but cannot be tested in the proof of concept phase. The design criteria begin with a minimal functionality, this is the baseline. With some criteria a higher goal is defined, the desired features.

The design criteria are inherently linked to choice of actuator, since large parts of e.g., weight and size are dictated by actuators. When the criteria have been defined, they will be used twice. Once to evaluate the finished proof of concept and once to determine method of actuation.

Weight

A weight criterion is necessary to keep the physical strain of carrying and arm movements minimal (Sarac et al., 2019). To roughly match weight requirements of other orthoses we set a limit of 500 [g] of parts that are connected to the hand. Some other orthoses also wish to stay below this border (e.g. (Polygerinos et al., 2015)) or a 450 [g] limit but desired 230 [g] limit by Aubin et al. (2014). However, since lowering weight will always be an improvement, 250 [g] is the desired criterion. The total system weight can be higher if parts are carried elsewhere on the body or mounted to a wheelchair.

Grasp force

Different ADLs require different pinch force levels. According to Pylatiuk et al. (2006) for regular ADLs 20 to 30 [N] force output is adequate. According to Taylor (1954) this is 30 [N]. So, 30 [N] is deemed a minimum and to incorporate a margin of safety, a force output of 35 [N] is desired.

Degrees of freedom

The hand orthosis will actuate the digits of the human hand, which has a total of 21 degrees of freedom (DoFs). In digits two to five these are extension/flexion of the distal and proximal interphalangeal (DIP) joints (8 DoFs) and flexion/extension as well as ab-/adduction of the metacarpophalangeal (MCP) joints (8 DoFs). The thumb has flexion/extension of the interphalangeal (IP) joint (1 DoF), and flexion/extension as well as ab-/adduction of the MCP joint and carpometacarpal (CMC) joint (4 DoFs) (Agur & Lee, 1999). See figure 2 for a figure of the hand joints.

Actuating all 21 DoFs is neither necessary nor desired. An intelligent choice in number of DoFs prevents an overly complex and heavy system. Existing literature can help define a fitting solution, one where the system is not more complex and heavier than needed, but still plenty movement patterns are possible to allow ADLs to be performed. The basis of hand movements defined by object shape has been captured by Cutkosky (1989) and is cited often on the subject of hand grasp taxonomy (e.g., Feix et al., 2009, Feix et al., 2015, Gonzalez et al., 2014). However, grasp taxonomy can also be described more in terms of finger position (Feix et al., 2009). With both studies it can be seen that in many precision grasps

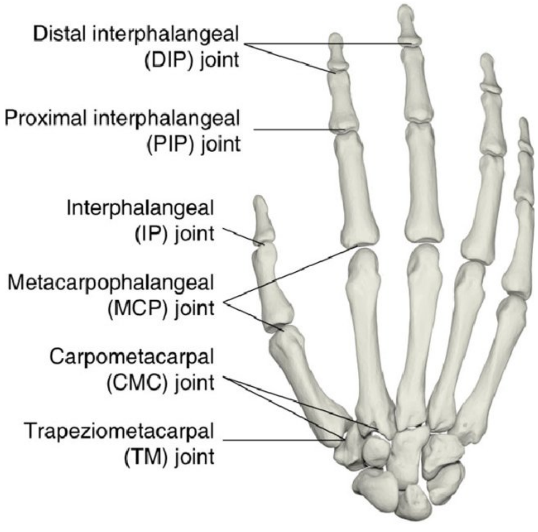

Figure 2. Hand and finger joints. In this thesis, the MCP and PIP joint are actuated.

the first three digits are used and that the fourth and fifth are used for either larger objects or power grasps. Therefore, it is advised not to actuate digit 4 and 5.

Flexion/extension is the most prominent movement for letting fingers grasp an object (Feix et al., 2009). Therefore, only this movement is the minimal functionality. The desired features include some passive MCP joint lateral flexion to allow natural hand functionality.

Joint angles

The fingers must open to near full extension to accommodate normal hand posture and gripping of large objects. To encapsulate small objects, only 90[°] MCP and PIP flexion are able to close the hand relatively far. In robotic hands, two phalanges are sufficient for stable grasping (Kragten et al., 2012). According to (Belter et al., 2013) 0-90[°] or 10-90[°] angles are normal for prostheses, further strengthening the idea that useful grips can be achieved with similar RoM. These angles for two joints per finger are therefore expected to satisfy for human hands as well.

Size

A large orthosis will get in the way of reaching in small spaces and cause accidental hits between mechanism and environment. A small design is also beneficial for cosmesis (Sarac et al., 2019). Boser et al. (2020) interviewed clinicians and patients for their opinion on assistive hand exoskeleton criteria and the majority of clinicians agreed to a limit of 50x50x30 [mm] (l x w x h) on the back of the hand. For this proof of concept only the maximum height requirement of 30 [mm] is taken over. The fingers will be most susceptible to collide with the environment or objects to hold (e.g., trying to stick the hand through the ear of a mug). So, atop the finger 20 [mm] is chosen as a maximum. Yet ideally, both would be 10 [mm] less. Between the fingers, a maximum of 3 [mm] assures that lateral flexion remains possible. At the palm of the hand only some necessary straps to keep the maximal possible amount of tactile sense.

Speed

A too slow orthosis will cause inconvenience and tediousness for the user. Also, a faster orthosis can be used better to react quickly to everyday situations. In the study of Boser et al. (2020), all patients would be satisfied by a closing or opening time of 1 [s].

Otherwise, a too fast exoskeleton might cause controllability issues for users if they are not accustomed to operate at high velocity. This might be the case especially for physically impaired patients. This is likely patient specific, but as a safety measure, faster opening/closing is not desired.

Comfort

The use of comfortable fabrics that do not irritate the skin is important. Hunter & Fan (2015) explain that breathability positively influences comfort, this is because skin friction increases with increased air temperature and relative humidity (Hendriks & Franklin, 2010). Increased coefficient of friction causes higher peak shear forces. Absence of large compressive forces and shear forces cause lower irritation (Wert et al., 2015).

However, it is difficult to determine quantitative values, because factors like skin hydration, thickness of epidermis and some medical conditions require extensive human testing to determine actual limits (for more details, See appendix D for a literature study on reversible attachment methods for hand exoskeletons). So, instead, a requirement for duration of wear without significant discomfort are set. Minimally, a one-hour period of uninterrupted wear is required and a four-hour period is desired. Note that this cannot be validated for the proof of concept.

Cosmesis

Interviewing participants to obtain an understanding of cosmesis scores is out of the scope of this thesis, therefore no further requirements are set. A summary of all criteria can be found in table 1.

METHOD

In the next session, the design criteria will be used to aid in choosing type of actuator. Thereafter, underactuation is discussed. Then, the design of the proof of concept as a whole is elaborated, followed by the designs of all individual parts. Finally, the experimental validation is discussed.

Table 1 The design criteria. In all cases the minimal functionality must be achieved. The desired features are a secondary, more challenging goal.

	Minimal functionality	**Desired features**
Weight	Max. 500 [g].	Max. 250 [g].
Grasp force	30 [N].	35 [N].
DoFs	The MCP and PIP joint are underactuated in flexion/extension.	MCP joint can still abduct/adduct passively.
Joint angles	MCP joint, 10-90[°] flexion, PIP joint, 10-90[°] flexion.	MCP joint, 5[°] passive lateral flexion.
Size	20 [mm] extrusion at dorsal side fingers, 30 [mm] at dorsal side hand, lateral of fingers 3 [mm] and none (except small attachments) at palmar side.	10 [mm] extrusion less at dorsal side hand and fingers.
Speed	1 [s] open or close time.	
Comfort	Possible to wear for 1 hour without significant discomfort.	Possible to wear for 4 hours without significant discomfort.

Actuation

There are multiple methods of actuation possible, some more common than others. In this thesis the following will be discussed: shape memory alloy (SMA) which utilizes its shape changing capabilities upon heating to actuate the finger. A mechanical solution is one that uses electric motors as a power source. Pneumatics is subdivided into soft pneumatics (use of light, flexible/bendable actuators), pneumatic artificial muscles (PAM) or use of pneumatic cylinders. Lastly, hydraulics, all fluid driven systems.

Existing actuation mechanisms have been subjectively reviewed for their estimated performance in the design criteria that were defined in the previous section: weight, force output, size, degrees of freedom (DoF), Comfort and speed, see table 2 for a summary.

Actuator scores

The actuation mechanisms are subjectively graded on a scale of 1 to 5 for their performance in every category. The scores are multiplied by weight factors that determine the relative importance of each category on a scale of 1 to 3.

Because this thesis focuses on the relation between weight, force output and size, these three criteria receive the highest weight factor, a 3. The criteria of DoF are linked to the number of different shapes of objects can be handled, it receives a score of 2. The same goes for the criteria of comfort, because it prevents high abandonment rates. The factor of speed receives a score of 1 because physically impaired patients usually move more slowly and therefore do not care as much for high speeds (Boser et al., 2020).

Weight

Since SMA uses thin wires for its actuation, it is expected to perform well on the weight criteria, it receives a score of five out of five. Also, soft pneumatics has the potential to be lightweight. It often uses light materials like fabrics or soft plastics and receives a score of four.

Hydraulic cylinders, pneumatic cylinders and PAMs generally have a better power-to-weight ratio than electric motors and are therefore rewarded with a score of three. The heaviest systems are generally based on electric motors, the mechanical category therefore receives a score of one.

Force output

With the some more usual actuation mechanisms like electric motors or hydraulic and pneumatic cylinders, producing power is doable with the many market available components. Therefore, they receive a score of five. Hereafter, it is assumed that achieving forces possible with other actuators is to be more difficult.

Soft actuation receives a score of three for some concerns with the ability of soft materials to withstand great pressure. SMA wires receive a score of one because of the rapid heat induced martensite to austenite transformation, which would be the actuation is more difficult to proportion in strength or RoM than it would be with e.g., an electric motor or a cylinder.

Size

Electric motors are relatively big compared to their force output (i.e., having a high force/weight and force/size ratio), meaning that they are expected not to fit into the 30 [mm] height criteria and therefore receive a score of two. PAM are relatively small, especially compared to electric motors, yet they receive a score of one because they only pull, meaning palmar placement is necessary for a voluntarily closing device.

Better scores are found with hydraulic and pneumatic cylinders and with soft pneumatics. These categories all possess better power-to-weight ratio’s than electric motors and are thereby expected to achieve the minimal requirements. A score of three is awarded. The highest size score, a five, is awarded for SMA, because it only

Table 2 Six actuation methods are graded for their performance on the criteria (one means worst, five means best). The grades are multiplied with the weight factors. A total is displayed, indicating how well an actuator is suited for a hand exoskeleton. (SMA = shape memory alloy, PAM = pneumatic artificial muscle).

	Weight Factor	SMA	Mechanical	Soft Pneumatic	PAM	Pneumatic cylinder	Hydraulics
Weight	3	5	1	4	3	3	3
Force output	3	1	5	3	5	5	5
Size	3	5	2	3	1	3	3
DoF	2	5	3	3	2	3	3
Comfort	2	3	5	5	5	5	5
Speed	1	1	5	5	5	5	5
Total		**50**	**45**	**51**	**46**	**54**	**54**

Table 3 Material properties.

	Yield strength [MPa]	Density [g/cm^3]	Specific strength [kN·m/kg]	Young's modulus [GPa]	References
Stainless steel 316	290	8	72.5	193	ASM (2021b)
Aluminium 6061 T6	276	2.7	114.8	68.9	ASM (2021a)
MarkForged Onyx	40	1.2	33.3	2.4	MarkForged (2021)

needs small metal wires.

Degrees of Freedom

For mechanical and pneumatic and hydraulic cylinders it is believed that a range of 10-90 [°] underactuated MCP and PIP flexion is possible, but that the passive MCP lateral flexion from the desired criteria will not be possible, a score of three is handed out. The SMA wires are believed to offer more flexibility for passive lateral flexion so it's awarded a score of five. For PAMs it is questioned if the short stroke length is adequate to allow for a range of 80 [°] flexion, it receives a score of two.

Comfort

Comfort scores of SMA is reduced to three, for it is expected that controlling velocity of movement is difficult, which would lead to increased contact forces between the exoskeleton and the hand. Other actuators are not expected to bring these problems and are awarded the highest score of five.

Speed

For this same reason, SMA actuation scores low for the speed criteria. All other actuators are expected to be operable close to 1 [s] opening/closing time. All scores can be found in table 2.

Verdict

The highest scores, namely those of SMA (50), soft pneumatic (51), pneumatic cylinders (54) and hydraulic cylinders (54) are close to each other. Therefore, it has been decided in the first place to eliminate all actuators that score ≤ 2 on weight, force output or size, because these criteria are the key focus of this master thesis and low scores might negatively influence the chance of success. This eliminates SMA and leaves a possibility for either soft pneumatics and pneumatic or hydraulic cylinders. Eventually, because of the large availability of regular hard hydraulic or pneumatic components, these options decided to be best suited. Both systems have one advantage and one disadvantage. For hydraulics, the incompressibility of liquids offers the option to make a system rigid, at the cost of losing compliance, resulting in higher interaction forces between hand and exoskeleton (Sarac et al., 2019). Pneumatic systems allow for compliancy and the compressibility of gas makes the storage and release of energy simpler. A combination of hydraulics and pneumatics that optimizes for good characteristics is therefore investigated.

Underactuation

A mechanism is underactuated when it has fewer actuators than DoFs (Laliberté et al., 2002). Underactuation is a concept that is important in the design of hand exoskeletons, because the fingers and hand have many DoFs in a limited amount of space. Underactuation can simplify physical design and control systems. It also influences the finger's behavior positively. Underactuation allows the finger to follow the shape of an object and apply spread pressure or automatically copy the shape of an object, with only one input signal (i.e., flex the finger) (Laliberté et al., 2002). It thereby surpasses the need for multiple input signals to fit the object at hand.

In return, the controllability of the finger suffers. No direct control of one finger joint is possible, because different joints are coupled. Also, underactuation can make the roll-back phenomenon happen. After contact with an object has been established, the distal joints flex and the proximal joints extend simultaneously. This results in the fingertip sliding along the object instead of gripping (Birglen & Gosselin, 2004). In this thesis, the decision has been made that the advantages outweigh the disadvantages.

Materials

Within this master thesis, budget and therefore the material choice is not unlimited. For this simple reason it will not be possible to use expensive materials such as carbon fiber. Only more common and less expensive materials are considered.

A choice of material is made by inspection of important material properties. The first is high yield strength and because strength will always be in a trade-off with density, specific strength. High stiffness is the third important criteria. Considering this, price and ease of manufacturing, material choice is confined to metals and plastics.

Two commonly used, high grade metals in the biomedical setting are aluminium 6061 T6 and stainless steel 316. There are good alternatives, but for many cases these two have all the important characteristics such as corrosion resistance, good to great fabrication capabilities, stiffness and yield strength. For material properties, see table 3, obtained from Aerospace Specification Metals Inc. (ASM) (2021a & b).

It may be clear that one of the biggest advantages of plastic is the opportunity to 3D print. Within the TU Delft there are printers and different plastics and compounds available for 3D-printing. After internal consultation, it was evident that the best suited material was MarkForged Onyx for its high strength compared to e.g., polylactic acid (PLA). Onyx is a nylon-based compound, reinforced with carbon fiber micro-fibers. The material properties mentioned in table 3 are properties of 3D-printed parts, instead of the solid material. Testing was carried out according to ASTM guidelines, but optimized for fiber direction meaning the results are not representative for every orientation. After consideration of the added benefit of 3D-printing, it was decided that the design will be made from MarkForged Onyx. Even though it has a lower specific strength and Young's modulus than the two metals, it is more suited for precise manufacturing.

Two-phase system

In this section, the schematics of the new design, called the two-phase system, will be discussed, so that the reader can gain an insight in the proof of concept. This section forms the core of the solution for the force, size and weight impasse that has been established in the introduction.

The solution relies of the fact that the function of a hand exoskeleton can be divided into two phases. In the first phase, the fingers must be closed around the object. This is where the most movement takes place. And if the moment arms of the actuators are large, the total amount of distance the actuators need to travel is large. However, there are no external forces on the finger, so the forces during this phase do generally not need to be high. This first phase will be referred to as the motion phase.

During the second phase, the fingers are closed around the object. This means that there does not have to be large movements. If the grip on the object must be firm, then high forces are required during this phase. This is referred to as the force phase.

The idea is to make the system dual actuated, meaning, giving each phase its own actuator. In this way, the actuators can be more specialized in the one task they have. The first phase (the motion phase) must have an actuator that is suited for large movements, this phase can have smaller moment arms to keep system size and actuator stroke low. Then, in the force phase, no large movement is necessary and the actuator is favorably positioned perpendicular to the finger to directly apply force in the direction of the object in the hand. This eliminates moment arms completely for the force phase and, in this matter, the use of two actuators can divert the impasse of small moment arms or high force output.

The previous part has given the general idea of the proposed solution. This can now be used to make an exact design and give a visual representation of the idea. The motion phase, where nearly all of the RoM must be covered, must be able to actuate a large part of the RoM. From the actuation choice it became evident that pneumatic and hydraulic actuators are suited for hand exoskeletons. Stroke length can be chosen according to wish, making them well suited for the first phase.

The two-phase system is shown schematically in figure 3 and can be seen integrated into the final design in figure 4. In the motion phase, there are two cylinders needed (in figure 3, this refers to the slave cylinders 1 & 2), cylinder one to actuate the MCP joint and cylinder two to actuate the PIP joint.

From figure 4 it can be seen that the cylinders span a joint and that actuation would therefore cause flexion. Therefore, the finger would move around the object in the hand.

The second phase consists of the bellows. In figure 3 the system is shown schematically and it can be seen integrated into the final design in figure 4. Note that the bellows would not be visible because it is inside another part (the medial phalanx (MP) part. When actuated, the

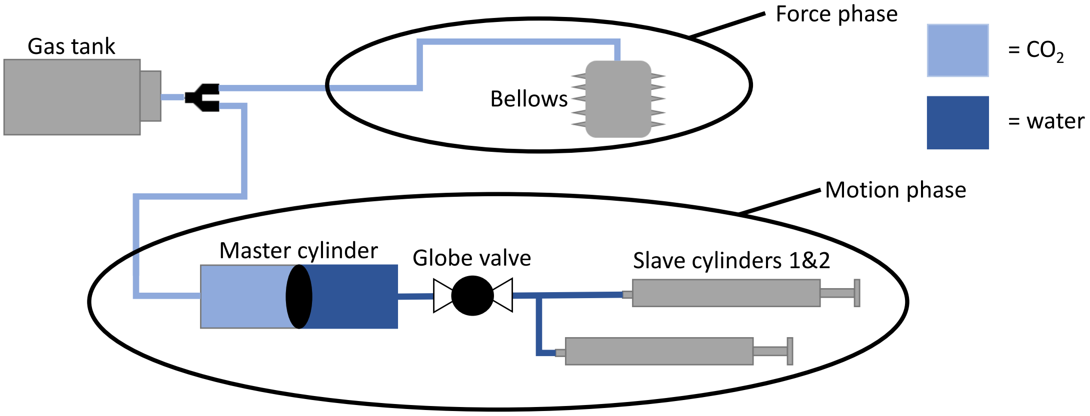

Figure 3. Schematic of the two-phase system. Firstly, the motion system: the gas tank powers the master cylinder, in turn, supplying liquid to the hydraulic slave cylinder. The globe valve is shut to lock the cylinders. Then, the bellows is actuated to apply force directly to the finger in the force phase.

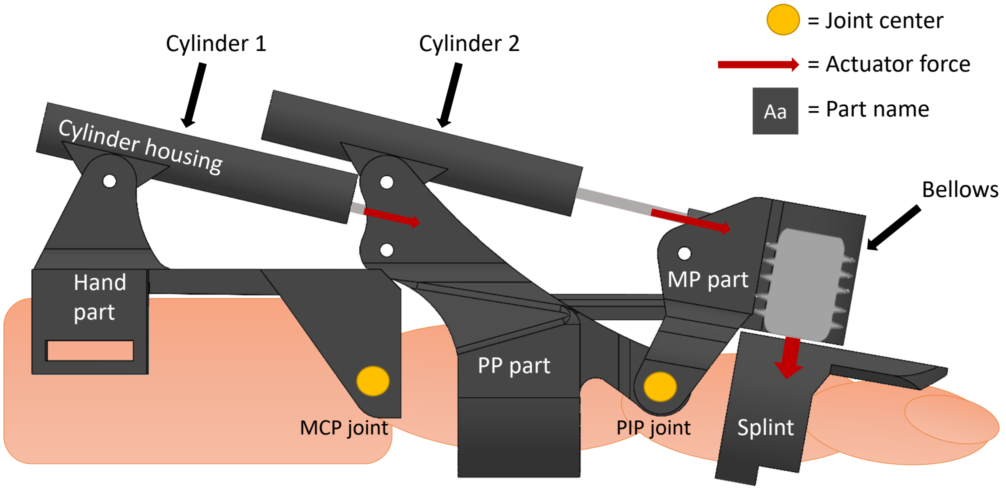

Figure 4. The design assembled on a schematic finger. The cylinders are in the cylinder housings, the rods can be seen sticking out. They stroke to the right, as is made visible with the red arrows and thereby each actuate one joint. The bellows is visible here to indicate its position in the MP part. The MP part holds it in place so it can deliver force against the splint and finger, further actuating the PIP joint.

bellows will expand, which it can only do downwards. It increases the pressure on the splint bellow it, the finger and eventually the object in the hand. The bellows is placed perpendicular to the hand, thus is not dependent on moment arms.

The bellows is encapsulated by the MP part at the top and sides. The MP part is in its turn connected to cylinder two. and via the proximal phalanx (PP) part to cylinder 1. This means that bellows actuation will increase the pressure on the cylinders. As can be seen in figure 3, the slave cylinders are filled with water and can be closed by a valve. This happens before the start of the force phase to prevent the slave or master cylinder to stroke back.

The advantage of a bellows is that it can be extended a multiple of its corrugated length, especially when it is fabricated from flexible materials (e.g., rubber). This is necessary to optimize the size requirement. Downsides of a cylinder would be that it can never increase its length by more than 100 [%]. A bellows also has the advantage of reducing weight and complexity.

Past proof of concept

Both systems need a source of power. For the experimental validation, or the proof of concept phase as a whole, it is not yet relevant how this is achieved. But for a finalized system, low weight is crucial. For size and weight reasons it is beneficial to need only one power source. In this thesis, a system is proposed where both phases are powered by one gas tank, see figure 3. Because the bellows is pneumatically powered, it can be supplied directly from the gas tank. However, the motion phase is a hydraulic system. A master cylinder is needed where the pressurized gas enters and pushes the piston to create the hydraulic pressure that is led to the slave cylinders.

Because it is known that the optimal CO_2 pressure for minimized gas-consumption is found at 12 [bar] (Doedens, 2015), it is considered a good choice to operate the system at this level. If the system consisted only of the first phase, the cylinders must be actuated at high pressure forces. To power this, a small tank to store pressurized gas. Often CO_2, for its ability to be stored as a liquid at room temperature (Doedens, 2015).

The hydraulic system needs to be able to withstand large pressure, Festo cylinders EG-4-20-PK-2 were tested internally within the TU Delft to withstand 40 [bar] before failure, the Legris Polyamide tubing, 1025P03 04 18, 3x1.8mm has been tested to withstand 30 [bar]. To keep the system within the set criteria, a small and lightweight valve is needed to withstand minimally 30 [bar] of pressure. The Lee Company IEP series solenoid valves are small cylindrical valves, of length 28.2 [mm] and diameter of 6.2 [mm] and weigh 4.7 [g]. These are able to withstand pressures up to 55.16 [bar] (The Lee Company, 2021).

Bellows

In this section, bellows design is discussed. The in-house resources available for this master thesis were not adequate to develop one. The decision has been made to purchase. Compared to in-house production, purchasing has the advantage that trial and error can be skipped.

A downside of purchasing is that it was not possible to find a product that matches ideal specifications. The bellow specific design criteria are firstly pressure resistance and maximum deflection and secondly, referring to the general design criteria, size and weight. No specific weight criteria are set because suppliers do not always list weight of parts. Since many companies only produce the bellows in large quantities on demand, choice was limited.

This mainly comes from the fact that bellows suppliers have either rubber (usually NBR) bellows, which were designed for prevention of dirt entering joints and such. These will have limited pressure capacities, but low spring rates and high maximum deflection. They are light and can be pushed into a very flat and corrugated state, reducing size of the housing.

The other option are metal bellows. These are designed to withstand great pressure (around 1.2 [MPa]), but have high spring rates and low maximum deflection. Therefore, their initial length is larger than would otherwise be possible with a rubber bellows.

Due to low maximum pressure of rubber bellows, this study will make use of the metal variant. The larger size, lower deflection and higher pressure resistance led to the decision to move the bellows from the tip of the finger to a more proximal location, roughly above the DIP joint. This is roughly halfway between the fingertip and the PIP joint. This doubles the range of motion achieved at the fingertip but halves force output.

The bellows of choice was A13.2x9,4-13 (Mera Bellows). The bellows is 18.4 [mm] in length, with a maximum deflection of 3.9 [mm] and an outside diameter of 13.2 [mm] (Mera, 2021). The set-up for the pinch force test can be seen in figure 13 (D). For a technical drawing, see appendix C.

The bellows is delivered with an open top end. This allows for a custom made cap. It has been laser cut from a 3 [mm] thick stainless steel plate with an h10 tolerance for the bellows and was glued in place. It must make an airtight seal so that the bellows can be pressurized. A hose that supplies the pressurized air must be connected, so an M3 thread is added. See figure 5.

Figure 5. The bellows. On top the bellows cap is visible with the M3 thread.

SolidWorks

All parts of the exoskeleton are designed in Dassault Systèmes SolidWorks. The 3D designs are made, but not tested using finite element (FE) or similar methods, because the 3D-printed parts do not possess the same material properties as the solid material they have been made of. To increase legibility, basic design elaboration is provided in the thesis and a more detailed one with all decisions elaborated can be found in appendix B. For technical drawings, see appendix C and for an assembly on a mock-up finger of all parts, see figure 4.

Medial Phalanx part

The bellows is held in place by its housing. This part is located atop the medial phalanx (MP), henceforth the name MP part. It has three functions. (1) The housing must secure the bellows in upright position, allowing bellows extrusion at the bottom so that it can actuate the middle and distal phalanx. (2) The cylinder-shaped housing is connected to slave cylinder 2 and (3) the bellows housing has to hinge at the PIP joint. The bellows housing must fit on the medial phalanx of a finger.

Besides the general design criteria, which apply to the design as a whole, and the necessary functionalities described above, high stiffness is required. This is true for all parts of the design, but is mentioned extra for the MP part, because it undergoes high loads during the second phase (i.e., motion phase), when the bellows expands.

To achieve all functions, the part has become a cylinder that houses the bellows, this cylinder is directly connected through two beams of 3 [mm] thick to slave cylinder 2, see figure 6. In this matter, as little flexion between these two actuators is possible. An upside down U-shaped extrusion at the bottom envelopes the finger to ensure a secure fit. At the bottom of this U-shape, the MP part can be connected to the next part. To see how the part is integrated into the design, see figure 4.

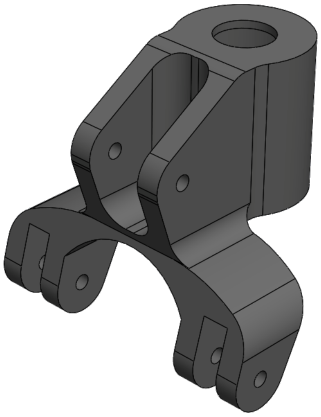

Figure 6. The medial phalanx part.

Proximal Phalanx part

The next part is the proximal phalanx (PP) part. It must be connected to the proximal phalanx for stability. It begins above the MCP joint where it has two cylinder connections, 20 and 30 [mm] vertical from the MCP joint center. The PP part's other end is at the PIP joint, where it forms a hinge with the MP part.

All design criteria apply without special consideration. The design started as a fluent shape from cylinder connections on one end to the joint hinge at the other end. A straight line between these two sides is impossible without going through the finger, so a smooth bend was necessary. This allows forces to flow through the design and lowers its mass. Thereafter, a connection for the finger has been added. See figure 7 and to see how it is integrated into the design, see figure 4.

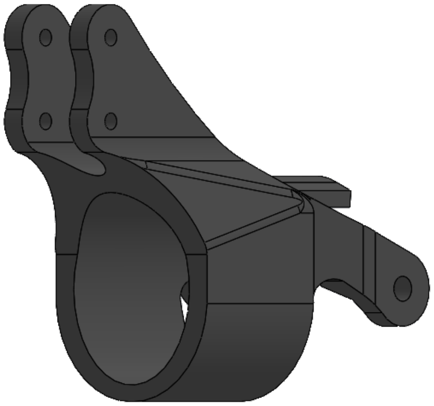

Figure 7. The proximal phalanx part.

Splint

The bellows applies pressure roughly around the DIP joint (roughly the red arrow from figure 1). While, often, the finger is in contact with the external object at the fingertip beyond the DIP joint, causing an extending external DIP moment. Because an internal, muscular flexing moment is (partly) lacking in patients that rely on an orthosis, some external method for preventing DIP hyperextension is necessary to prevent discomfort, pain or injury (Thayer, 1988).

Due to the nature of finger musculature and tendon structure, there is a synergy between the DIP and PIP joint. If the patient has some hand function left and uses this to flex the finger, the DIP joint will flex as a consequence of the PIP joint being flexed. To leave this function free, only DIP hyperextension is prevented normal range flexion of 0-85 [°] (Hume et al., 1990) left unrestricted. Therefore, a splint is attached to the medial phalanx. The distal phalanx and the splint are in contact when DIP joint angle equals 0 [°].

The splint part needs to be connected to the bellows so that the bellows is not a loose part. When the bellows is not pressurized, it folds and pulls the splint back, causing PIP joint extension. When the bellows expand, the part is designed to spread the force out over a larger finger area. The splint has specially been designed for connecting onto the mock-up finger. To see how it is integrated into the design, see figure 4.

Cylinder and rod cap

The hydraulic cylinders do not possess a connection site to attach them to the external world. Therefore, a housing is needed on both sides, called the cylinder cap at the proximal end and the rod cap at the distal end. Both are a hollow tube, closed at one end. The cylinder cap is partially closed. A small hole allows the tubing to be connected to the cylinder. Both have a perpendicular hole that can be connected to an attachment point at either the hand part, proximal phalanx part or the

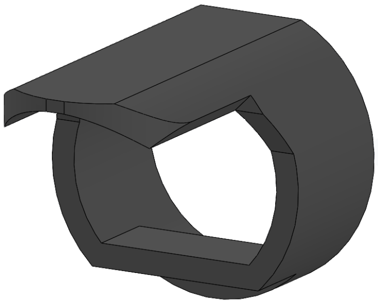

Figure 8. The splint.

bellows housing. See figure 9.

Figure 9. The cylinder cap.

The space between proximal and distal attachments of the cylinder is 41 [mm] while the length of the cylinder is 59 [mm]. The cylinders must extrude at the ends to compensate the overshoot. The two cylinder caps are slightly different from one another. This has two reasons. Firstly, the MCP and PIP joint of the mock-up finger do not have the same RoM (45 [°] and 70 [°], respectively) and secondly, the bellows adds 13 [°] of movement over the PIP joint. To see bellows extrusion at the design and the difference between the two cylinder housings, see figure 4. For the cylinder cap design, see figure 10.

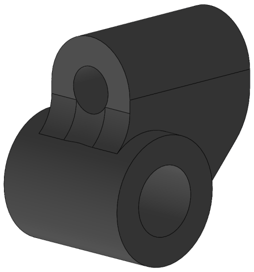

Figure 10. The rod cap.

Hand part

The hand part is designed to fit onto the mock-up finger and is a piece of equipment that holds the cylinder cap of the first cylinder and is easily but rigidly connected to the mock-up finger. It is part of the proof of concept phase and cannot fit onto an actual human hand. Therefore, the design criteria of size or comfort do not apply to it. Note that the attachment of the cylinders in its current shape, size and location is representable for actual placement past a proof of concept.

The mock-up finger has small cut outs at the MCP joint. The distal end of the hand part can use this to lock itself into place in. On the proximal end this is done with a small ridge that falls just over the sides of the mock-up and connected to the hand with a Velcro band, see figure 11. To see how it is integrated into the design, see figure 4.

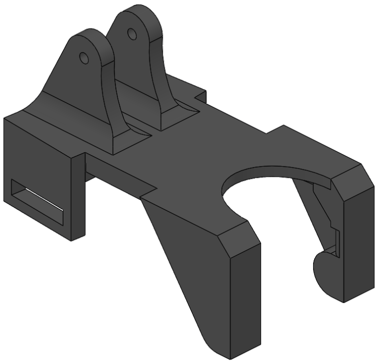

Figure 11. The hand part.

Force estimation

A theoretical maximum output force, at the tip of the finger, will be derived from this model. In practice, the maximum force will be lower, due to friction and elastic deformation of the parts. Therefore, this calculation can only be seen as an indication.

The underactuation of the slave cylinders result in that the angles of the MCP and PIP joint (angle α and β, respectively) are not to be controlled. The stroke of the master cylinder only dictates total stroke of slave cylinders 1 and 2 combined. Thereafter, the angles α and β are dependent on external factors such as object shape and whether roll-back phenomenon occurred, which is linked to skin-to-object friction and finger kinetics.

This is solved by finding a theoretical balance in angles α and β. It is important to understand that there are four moment arms important to find this equilibrium position. Firstly, the slave cylinders have a moment arm over the joint they actuate. Cylinder 1 and moment arm (r_1) and cylinder 2 and moment arm (r_2). These moment arms shortens when the fingers move towards flexed position. Secondly, the external force F_{ext} (here simulated at the fingertip) has a moment arm over both actuated joints. The moment arm of F_{ext} over the PIP joint (r_{PIP}) stays equal. On the other hand, the moment arm of F_{ext} over the MCP joint (r_{MCP}) decreases if the PIP joint flexes. In formula form, the equilibrium can be found if:

$$\frac{r_1}{r_{MCP}} = \frac{r_2}{r_{PIP}}$$

Only if the effect of the four moment arms on the cylinder force cancel each other out, can there be equal moments around the MCP and PIP joints. Only in this case (if fingertip friction is ignored) can the finger remain static.

This over a range of α and β angles. One example where this equation can be solved is for $\alpha = 15$ [°] and $\beta = 64$ [°]. For this specific case, the cylinders can achieve a fingertip force of 6.1 [N] at a pressure of 12 [bar], see appendix A for complete calculation. After the motion system is locked by the valve. The bellows maximum theoretical force output, at a pressure of 12 [bar] and an effective area of 1.01 [cm^2] amounts to 121.2 [N]. Because the bellows is not located at the outer tip of the finger but at 42 [%] of the PIP to fingertip length, a lever applies and force output drops to 50.6 [N]. The motion and force system together can apply 56.7 [N]. Note that this would increase slave cylinder pressure to 99.8 [bar], well above the pressure limit of the hydraulic cylinders. At the limit of the tubing (30 [bar]), force output would equal 15.2 [N].

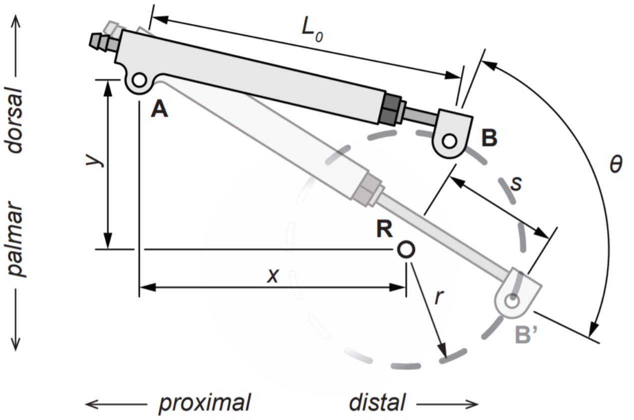

Figure 12. Moment arm of a cylinder (distance from R to cylinder) during part of the range of motion. Note that the moment arm decreases as the joint angle increases. Adopted from Bos et al. (2018).

Experimental validation

Data for this study were collected using three qualitative tests. In these tests the following variables were measured: weight [g], hydraulic and pneumatic pressure [bar], force [N], displacement [mm] (differing between tests, this can be displacement of MP part atop the finger (test 2) expansion of the bellows, or master cylinder stroke (test 3a & b)). The data is collected via an analog transmitter and directed to the Data Acquisition (DAQ) system. A LabView script reads the data and saves it in a text file.

The variables are used in test 1 to measure weight and size of the parts, in test 2 to measure the fingertip force of the exoskeleton. The results of test 1 and 2 are also used for the force-to-weight ratio. Test 3 results to measure the hysteresis of the hydraulic system (test 3a) and of the pneumatic system (test 3b) by plotting the pressure against master cylinder stroke or bellows expansion, respectively. See table 4 for the sensor specifications.

Test 1 - weight and size measurement

Test one used the scale seen in table 4. All parts were measured separately and once together to check for rounding errors. The size of the system was measured with a ruler.

Test 2 - Force output

Test 2 was performed by setting up the load cell in the path of the fingertip, at an MCP and PIP angle of 45 [°] contact takes place. This happens during the motion phase: the hydraulic pressure was increased by manual placement of a weight on the piston of the master cylinder (figure 13A). The piston moved, displacing the water towards the hydraulic system and consequentially the slave cylinders were actuated (D). After contact with the load cell (E), the finger stopped its movement. The globe valve (B) was closed to lock the water inside the system and prevented the finger to extend (i.e., prevented the slave cylinders to return stroke) when the pneumatic system was activated.

During the second phase, the force phase, air is pumped into the pneumatic system to actuate the bellows. Pressurized air was supplied by a system present in the lab and could be turned on by a lever and supplied air between 0.5 and 7 [bar]. Upon bellows expansion, on one end, the bellows presses against the finger, increasing force output. On the other end, the bellows touches the MP part. The MP part is connected to the second cylinder and via the PP part to the first cylinder. So, the pneumatic system causes an increase in hydraulic pressure. Hence, the need for a valve to prevent hydraulic backflow during the pinch phase. Deformation of the PP part by bellows expansion is measured by a laser distance sensor (F). The hydraulic pressure in measured by pressure sensor (A) and the force by load cell (E). Note that the pneumatic pressure is measured by a pressure sensor (not visible in figure 13).

Investigation for leaks, as standard practice when working with hydraulics, was done by keeping the weights on the master cylinder for longer time or by loading and then closing the valve. It was discovered that the master cylinder leaked from pressurized chamber to non-pressurized chamber. Test 2 was not disturbed by the leak, because it did not alter hydraulic pressure. Also, after loading the master cylinder, the valve is closed to keep pressure on the slave cylinders constant. After, the master cylinder is deloaded, this prevents chamber to chamber leakage.

Then, there appeared another issue. A drop in pres-

Table 4 Information of sensor used for the experimental validation.

Instrument	**Model**
Scale	Ohaus Emerald hand-held jewelry scale
Load cell	FUTEK LSB200
Pressure sensor (hydraulic)	AE sensors 0-100 bar ATM
Pressure sensor (hydraulic)	Gems 0-40 bar
Laser distance sensor	Micro-Epsilon optoNCDT 1420
DAQ	National Instruments NI USB-6008
Analog transmitter	Scaime CPJ

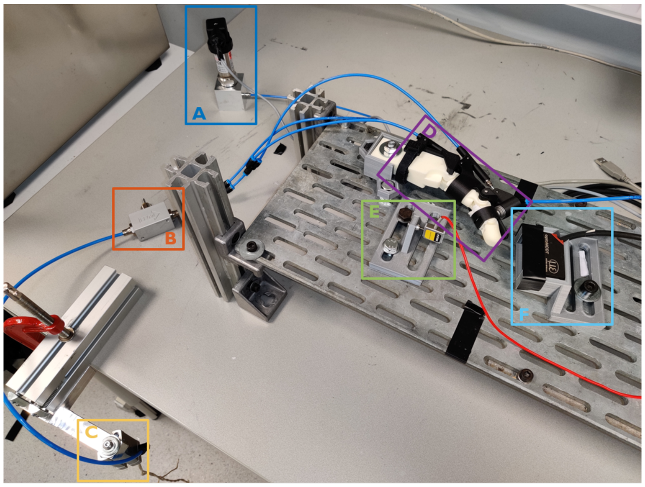

Figure 13. Experimental set-up of test 2 (force measurements). A is the hydraulic pressure sensor, B is the globe valve, C the master cylinder, D the design including bellows, E the pressure sensor and F the displacement sensor.

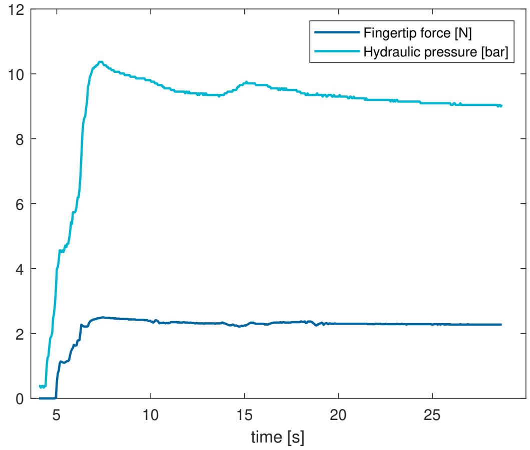

Figure 14. A finite drop in hydraulic pressure and consequently fingertip force occurred during all force tests.

sure, and consequentially force, was measured. Due to closing of the globe valve, this could not be the master cylinder. This pressure drop can be seen in figure 14. Multiple tests were done, all show a finite decline in pressure similar to the one displayed in figure 14. In this particular, but representative case the pressure drops 1.376 [bar] (13.3 [%]) and the force drops 2.274 [N] (8.9 [%]). Note that the increase in pressure and force around 14 [s] is caused by closing the valve.

Test 3 - Hysteresis

For test 3, hysteresis, the set-up is altered. There is no need for the valve (B) or the load cell (E) and the laser distance sensor is used to measure displacement (i.e., stroke of the master cylinder (C) or bellows expansion). The hydraulic or pneumatic pressure is repeatedly increased and decreased, which causes the slave cylinders or the bellows to displace. The hysteresis cycle is obtained by plotting the pressure as a function of displacement. From this the amount of hysteresis is defined as the integral of pressure as a function of displacement during upstroke minus the return stroke. In other words, the integral of pressure difference between the forward and the return stroke:

$$H = \int \delta P \, dx \tag{0.1}$$

The test was inconvenienced by the leak in the master cylinder. Over the loading cycles, due to the moving of fluid from the fluid-filled chamber to the air-filled chamber, the hysteresis cycle shifts. See figure 15 for the shift in stroke. The shift is corrected for by subtraction of the average leakage per cycle.

RESULTS

This section will discuss the results of test 1 through 3. In test 1 the parts are weighted and their protrusion from the finger is investigated. In test 2, fingertip pinch force and pneumatic and hydraulic pressure are measured to determine maximum pinch force, its relation with system pressure and force-to-weight ratio. Test 3 measures hysteresis of the hydraulic and pneumatic systems.

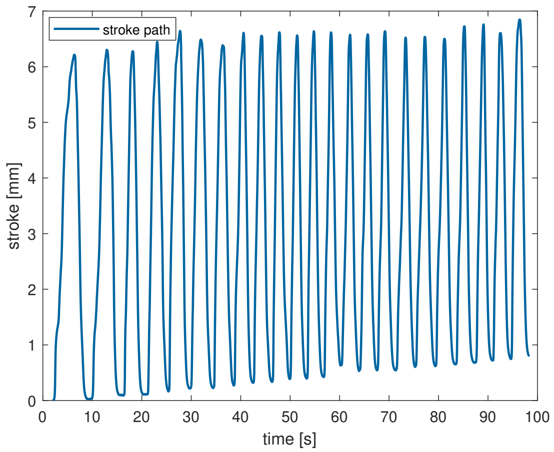

Figure 15. Cylinder leakage during the hysteresis tests causes a stroke shift, especially at the bottom it is visible that the cylinder's down positions shifts upwards.

Test 1 - Weight and size

The weight of the final products can be seen in table 5. The second column indicates how many units of said part are used per actuated finger.

Table 5 Parts weight results.

	# per finger	**Weight [g]**
Hand part	1	6.6
PP Part	1	7.0
Cylinder	2	5.7
MP part	1	3.9
Splint	1	2.0
Cylinder cap	2	1.2
Rod cap	2	0.2
Bellows & cap	1	3.8
Axes	1	1.7
Hoses & plugs	1	10.8
Total		**50.0**

The weight of the skeleton of the design (all 3D-printed parts without the cylinders, coupling pieces, hoses or axes) is 22.3 [g]. Two cylinders add 5.7 [g], the bellows adds 3.8 and the axes that act as hinges and connect the parts together weight 1.7 [g]. The hoses and coupling pieces weight 10.8 [g] per finger, adding up to 50.0 [g]. After weighing the complete system, it turned out that this 50.0 [g] contained a small rounding error caused by the precision of the scale. Total weight of the finger actually equals 49.9 [g] per finger. The weight on hand for the suggested three finger design would be 149.7 [g]. Note that these numbers are based on the assumption that all fingers weight an equal amount and that the weight of the hand part is equal in weight when the orthosis is mounted on a hand.

The cylinders proximal end can achieve a height of 43 [mm] above the hand and fingers. Towards the fingertips, the height decreases. The proximal end of the cylinder protrudes 22 [mm] and the bellows housing 19.4 [mm]. Towards the fingertip the protrusion keeps decreasing. The splint has a protrusion of 1 [mm] above the finger. Aside the finger can be found one joint between the MP and PP part. This extrudes 9 [mm] out to the sides. At the palmar side, only some small straps protrude with a maximum thickness of 2 [mm].

Test 2 - Force output

The experimental set-up for testing fingertip force and pressure can be seen in figure 13. In test 2a, solely the hydraulic system actuated the exoskeleton. The master cylinder is loaded, thus pressure inclines. The MCP and PIP joint flex from a 5 [°] to a 45 [°] angle towards the load cell and after contact is made, fingertip force inclines linearly with pressure. The system's maximum tested hydraulic pressure equals 10.369 [bar] and results in a fingertip force of 2.495 [N].

The second, pneumatic, phase of the design increases the maximum force of the design to a maximum of 5.087 [N] under a hydraulic pressure of 10.624 [bar] and pneumatic pressure of 6.133 [bar], See figure 16. The exoskeleton weights 49.9 [g] per finger and can deliver 5.087 [N] fingertip force. This equals a force-to-weight ratio of 102 [N/kg].

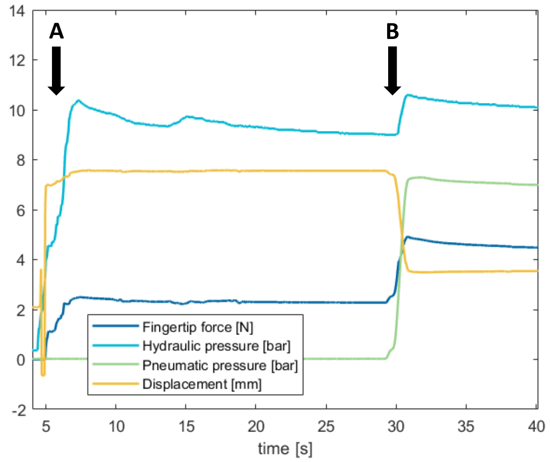

Figure 16. The results of the force test. At time A the motion system is activated, the hydraulic pressure increases and as the finger touches the force sensor, force increases. The shift in displacement is the MP part moving in range of the laser distance sensor. This is the start value of the displacement. At time B, the force phase is activated. The pneumatic pressure increases and the pressure of the bellows increases the fingertip force, it makes the MP part move (visible in the displacement line) and makes the hydraulic pressure increase further.

Test 3 - Hysteresis

the resulting hysteresis plot can be seen in figure 17. The return phase (lower line) is significantly lower than the go phase (upper line). This indicates that some of the energy is lost to friction. Over twenty three cycles the average hydraulic hysteresis equals 33.59 ± 0.46 [%].

The pneumatic system was also tested for hysteresis. This can be seen in figure 17. The go phase and return phase almost overlap, indicating very minimal hysteresis occurs. Calculation turns out this is only 3.39 ± 6.88 [%]. The confidence interval is large because sample size [n] equals 5. The highest hysteresis cycle only amounted to 4.24 [%].

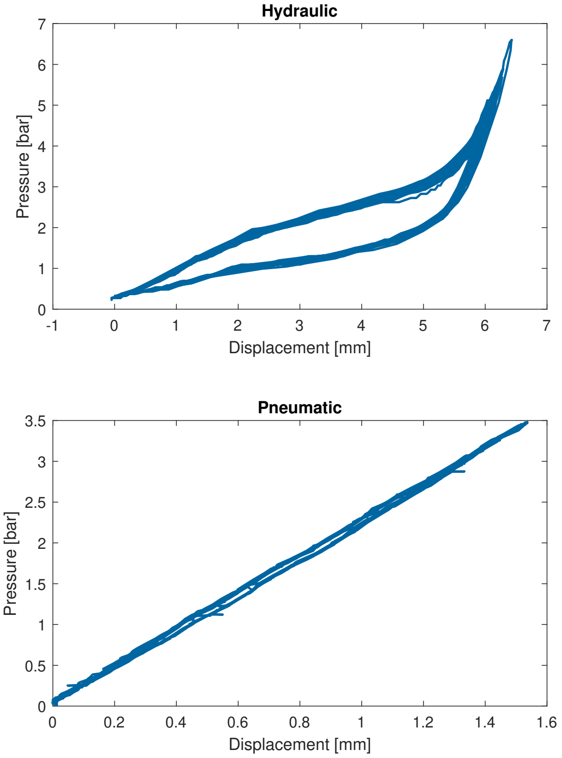

Figure 17. Hydraulic and pneumatic hysteresis loops. The surface inside the loop is larger for the hydraulic plot, therefore, hydraulic hysteresis is higher.

The bellows was tested to pressures as low as 0.5 [bar] because it was not possible to decrease pressure further without shutting air supply off. The maximum pressure equaled 4 [bar], because the bellows can elastically deform in a range of 3.9 [mm]. The spring rate equals 19 [N/mm], meaning that a force of 74.1 [N] is proficient to reach the elastic limit. The bellows has an effective area of 1.01 [cm^2], requiring a pressure of 7.34 [bar]. However, upon inspection it was discovered that 4 bar was enough to reach plastic deformation. A limit of 3.5 [bar] was chosen as safe measure. Since this 3.5 [bar] window can be located, as desired, by a onetime plastic deformation, it was placed between 0.5 and 4 [bar]. This was not a problem during the force tests, as the bellows was shielded from overstretching by the finger on one side and exoskeleton on the other.

DISCUSSION

The tests for weight, fingertip force and hysteresis were carried out successfully. All three test base itself directly on sensor in- and output. Before testing, sensors were either calibrated or checked to give logical output. One faulty pressure sensor was replaced and all test carried out according to the method section. Therefore, all test results are assumed to be reliable.

Not all criteria were achieved. This goes for force output, size and partly the DoF criteria. The minimal output force criterion for one hand exoskeleton was 30 [N], for a three fingered design this equals 10 [N] per finger, nearly twice the 5.087 [N] achieved in the force test.

The size criteria were not achieved at the dorsal side of the finger, the cylinders extrude 27 [mm] above the proximal phalanx of the finger, here, only 20 [mm] is allowed. Above the medial phalanx the protrusion is maximally 20 [mm] and above the distal phalanx this is 1 [mm].

The MCP and PIP joint could not reach a 10-90 [°] angle. This would not have been possible due to limited mock-up finger mobility, but the cylinders, with current moment arms around the joint would collide with the knuckles at 70 [°]. Also, no consideration went into passive MCP joint lateral flexion.

As explained in the method section, the master cylinder displayed some leakage. See figure 15 for the effect this had on the master cylinder. Attempts to stop this leakage were not successful. But it is hypothesized that this did not significantly influence hysteresis or force measurement results and it was therefore ignored.

Thereafter, there was the issue of hydraulic pressure drop that is visible in figure 14. Note that this could not have been caused by the master cylinder leak, because the globe valve was closed when the pressure drop occurred. No other leaks were found that could be the cause of it.

This pressure drop always seemed to follow a stress relaxation like curve. Initially, the pressure dropped quickly, but later on more slowly and it eventually stopped. This makes the belief that the plastic PA tubing displayed viscoelastic properties, slowly relaxing under the pressure towards an equilibrium. Note that PA material is known for displaying viscoelastic properties (Ishisaka & Kawagoe, 2004).

The laser distance sensor recorded a 3.403 [mm] displacement of the top of the MP part during activation of the hydraulics. The bellows applies pressure to the roof of its housing, the MP part. This leads to the laser sensor detecting displacement (i.e., the roof rising). One cause can be the deformation of the MP part. Other explanations are deformation of the PP part, caused by the forces that are passed along via the second slave cylinder, or deformation of the hand part, because the forces are passed along further through the first slave cylinder. It is also possible that residues of air in the hydraulic system are being compressed, allowing the cylinders to stroke back, even when the valve is closed. This can be linked to the viscoelastic properties of the tubes. Expansion of the PA tubing allowing water to flow out of the slave cylinders.

Upon inspection, this above mentioned cylinder return stroke appeared to be present at the first cylinder, it moved 1 [mm]. Considering the ratio of moment arms of the cylinder over the MCP joint to the moment arm of the fingertip to the MCP joint equals 1:2.5, the fingertip moves 2.5 [mm] because of this cylinder stroke. Whether this is caused by residual air or tube expansion is not known. Although, the stress relaxation-like course of the hydraulic pressure, and the fact that there have been multiple attempts to remove all air from the system did not alter PP part displacement, it is assumed that creep relaxation of the PA tubes causes said pressure drop. The fact that only the first cylinder moved back, while the second remained in position is linked to small friction differences.

Of the total 3.4 [mm] of displacement 0.9 [mm] is still unaccounted for, it is assumed that this is caused material flexion of one or more of the following parts: the PP, MP or hand part.

The displacement affects maximum potential force. MP part displacement increases the length of the bellows. This significantly impacts output force, because the bellows has a spring rate of 19 [N/mm]. A PP part displacement of 3.403 [mm] therefore equals a spring force of 64.657 [N]. The bellows has an active area of 1.01 [cm^2] the maximum air pressure achieved in the lab was 7.295 [bar]. This creates an expanding force of 73.680 [N]. After the expanding force overcomes spring force, 9.023 [N] remains as the maximum achievable output force. As the bellows connects to the finger not above the fingertip but at 14 [mm] from the PIP joint, whereas the fingertip is at 34 [mm] from the fingertip, the force that is present at the fingertip equals $9.023/34 * 14 = 3.715[N]$

The size criterion was not met. The cylinder placement.

Placing the cylinders close to the hand is not always desirable, because the moment arm of the cylinder around the actuated joint decreases. In this thesis it was not possible to place the cylinders closer, because the cylinder will come into contact with the knuckle during flexion. Bringing the points where the cylinders are connected to the MP and PP part more proximal can offer a solution, both for the size criteria, RoM and moment arms. But this will put more stress on the MP and PP part. This improved orientation would not have been beneficial in the current proof of concept phase, because the mock-up hand has very limited RoM.

Recommendations

From the results and the discussion, a set of recommendations is formulated to further research and develop the proof of concept.

The first recommendation will be to further investigate increasing force output by increasing the system's ability to withstand the hydraulic pressure while displaying less (visco)elastic deformation. Then it can be truly seen if it is possible to increase the force transmission. I recommend using aluminium 6061-T6 for its higher specific strength for the part of the design between the bellows and the slave cylinders. Note that it would be beneficial to relieve pressure on the motion system (i.e., slave cylinders) during the force phase. Ideally, the cylinders are locked or blocked directly to prevent a spike in hydraulic pressure.

As said, the resources and time available for this master thesis were not adequate to develop a bellows. From external sources it was possible to find a metal bellows from Mera Bellows. Because of this, length and outer diameter were larger than desired. An ideal bellows would exist of rubber for its elastic properties, even though the possibilities of pressurizing will be low. If the bellows is developed in-house, size can be optimized for individual patients and the bellows can be moved more to the tip of the finger to reduce its force requirement.

CONCLUSION

The research question of this master thesis is, if it is possible to design an exoskeleton proof of concept with improved force output, considering weight and size criteria and if this proof of concept can be used in a final hand exoskeleton.

It is is concluded that the proof of concept shows that it is possible to use a two-phase system to power a hand orthosis:

- Criteria state a minimum of 30 [N] at a maximum of 500 [g], equalling a force-to-weight ratio of 60 [N/kg]. Current design achieves 15.261 [N] at 149.7 [g], or a force-to-weight ratio of 102 [N/kg].
- Though the force requirement is not met, the low weight leaves room for increasing stiffness. Theoretically, the system allows for 46.8 [N] for a three-fingered design.
- Size criteria are not achieved, doing so can be done by relocating cylinder attachment sites, but this likely requires the use of higher stiffness material.

- The current two-phase system allows for one power source and lowers pressure inside part of the system, decreasing required weight and improving efficiency, if the optimum pressure of 12 [bar] is maintained.

The design shows potential for two-phase systems as a way to increase force transmission while keeping weight and size low and can benefit future hand exoskeletons.

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A MATLAB SCRIPT

```
%Cylinder pressure per external force
%By Sebas Kracht for the master thesis

clear all; close all; clc;

%% joint angles and cylinder begin and end coordinates
%F_limit1 = zeros(53,1);
%F_limit2 = zeros(53,1);

%For the cylinder coordinates/orientation
PC1x = -40; %(always negative) x position of proximal attachment cylinder 1.
h_prox = 30; %prox cylinder hight
h_dist = 20; %dist cylinder hight

%MCP angle (between 5 and 45 [deg] for mock-up finger)
%PIP angle (between 5 and 57 [deg] for mock-up finger)
alpha = 15;
beta  = 67.5; %angles of 15 and 67.5 degrees give a finger equilibrium.



%MCP joint is the origin of the coordinate system
PC1 = [PC1x, h_prox]; %proximal end of cylinder 1
% (PC1 coordinates are fixed because we use a local coord. system which is fixed to the hand)
DC1 = [h_dist*-sind(-alpha), h_dist*cosd(-alpha)]; %distal coord cylinder 1
PC2 = [h_prox*-sind(-alpha), h_prox*cosd(-alpha)]; %proximal coord cylinder 2
PIP = [40.5*-sind(-90-alpha), 40.5*cosd(-90-alpha)]; %coord of the PIP joint
DC2 = PIP + [h_dist*-sind(-alpha-beta), h_dist*cosd(-alpha-beta)]; %distal end cylinder 2

%% Moment arm cylinders
%y1 = a1x + b1 represents the orientation of the cylinder
%y2 = a2x + b2 represents the moment arm of cylinder over joint

%%%%%%%%cylinder 1
dx1 = DC1(1) - PC1(1);
dy1 = DC1(2) - PC1(2);
a1 = dy1/dx1;
b1 = DC1(2) - a1*DC1(1); %b = y - ax

alpha1 = atand(a1); %angle of moment arm
beta1 = alpha1 + 90; %make perpendicular vector

a2 = tand(beta1); %a of moment arm

%shortest line (begin = origin, end = perpendicular crossing cylinder)
%a1x+b = a2*x
rx1 = -b1/(a1-a2); %a1x+b = -1/a2*x
ry1 = a1*rx1+b1;
r1 = sqrt(rx1^2 + ry1^2); %r1 is momentarm cylinder 1

%%%%%%%%cylinder 2
dx2 = DC2(1) - PC2(1);
dy2 = DC2(2) - PC2(2);
a1 = dy2/dx2;
b1 = DC2(2) - a1*DC2(1); %b = y - ax

alpha2 = atand(a1); %angle of moment arm
beta2 = alpha2 + 90; %make perpendicular vector
a2 = tand(beta2);

%find b (you know line runs through PIP joint)
b2 = -a2*PIP(1) + PIP(2);

%shortest line
%a1x+b = -1/a2*x +b2
rx2 = (b2-b1)/(a1-a2); %a1x+b1 = a2*x+b2
```

```
ry2 = a2*rx2+b2;
% r is length momentarm PIP joint to cylinder 2
r2 = sqrt((PIP(1)-rx2)^2 + (PIP(2)-ry2)^2);
%r2 = r2 + 5;%cylinder centres are rougly 5 mm above the cyl and rod cap axes.

%% moment and force equations
%Moment needed to resist external force
F_ext = 0.01:0.01:50.6;

%moment arm F_ext to joints
r_PIP = 33.8; % [mm] from PIP joint to normal place on fingertip to hold an object
r_MCP = r_PIP + 40.5 * cosd(-beta); %moment arm to MCP joint

%External moment:
M_ext_MCP = F_ext * r_MCP;
M_ext_PIP = F_ext * r_PIP;

%cylinder force = M/r
F_cyl1 = M_ext_MCP / r1;
F_cyl2 = M_ext_PIP / r2;

%% Cylinder data
% cylinder 4mm
P_spring = 6e5; %[Pa] used for spring force
F_theor = 4.9; %[N] theoretical force at 6 bar
spring = -2.6; %spring return force
F_incl = F_theor - spring; % [N] actual pressure force = netto - spring
A = F_incl/P_spring; %[m2] cylinder area

P_max = 30e5; %[Pa] estimated maximum system pressure
P_opt = 12e5; %optimum pressure [Pa] (Doedens, 2015)

%Cylinder pressure = F/A
P_cyl1 = F_cyl1 / A;
P_cyl2 = F_cyl2 / A;

%force where [P] reaches P_max
F_limit1 = F_ext(find(P_cyl1 ≥ P_max, 1));
F_limit2 = F_ext(find(P_cyl2 ≥ P_max, 1));

%force where [P] reaches P_opt
F_opt1 = F_ext(find(P_cyl1 ≥ P_opt, 1));
F_opt2 = F_ext(find(P_cyl2 ≥ P_opt, 1));


figure
plot(F_ext,P_cyl1); hold on
plot(F_ext,P_cyl2); hold on
plot(F_limit1,P_max,'o'); hold on
plot(F_limit2,P_max,'o')
plot(F_opt1,P_opt,'o')
plot(F_opt2,P_opt,'o'); hold off
title('Cylinder pressure over external force')
legend('cylinder 1','cylinder 2','P max1','P max2','P opt1','P opt2')
xlabel('external force')
ylabel('pressure in Pa')
```

B DESIGN ELABORATION

Medial Phalanx part

The bellows is held in place by its housing. This part is located atop the medial phalanx (MP), henceforth the name MP part. It has three functions. (1) The housing must secure the bellows in upright position, allowing bellows extrusion at the bottom so that it can actuate the middle and distal phalanx. (2) The cylinder-shaped housing is connected to the distal cylinder (in this case, cylinder means the hydraulic actuator), and (3) the bellows housing has to hinge at the PIP joint. The bellows housing must fit on the medial phalanx (and possibly distal phalanx) of a finger.

Besides the general design criteria, which apply to the design as a whole, and the necessary functionalities described above, high stiffness is required. This is true for all parts of the design, but is mentioned extra for the MP part, because it undergoes high loads during the second phase (i.e. motion phase), when the bellows expands.

With all relevant considerations in mind, (achieving the general design criteria, the part specific necessary functionalities and high stiffness) the part can be designed in detail. To start the bellows, which is a cylindrical object, is enveloped in the most simple way by a cylindrical shell, open at the bottom to allow bellows extrusion. A thickness of 1 mm was chosen as a starting point and deemed sufficiently rigid. At the top, a small hole lets through the coupling plug and hose that supplies the bellows of pressurized air (see figure 6). The diameter of the shell is 1 [mm] larger than the bellows to allow free bellows movement.

The small, circular holes are the axes of rotation where the MP part is connected to other parts. All parts will be connected with 2 [mm] diameter stainless steel pins, relying on friction to stay in place. The upper axis attaches the bellows housing to the hydraulic cylinder, and the bottom axis hinges around the PIP joint and attaches the bellows housing to the to the proximal phalanx part.

The housing redirects the force generated by the bellows mostly to the distal cylinder, and from there to the proximal cylinder. It is for this reason that a direct line of material connects the bellows to the cylinder axis. These two support structures are both 3 [mm] thick to prevent buckling. Also, the 3D-printer did not always print smaller thicknesses well. There is 7.5 [mm] space between the two support structures for the pneumatic cylinder and its housing. The cylinder housing will be a 3D printed cap on both the proximal as distal end, which function as a way of connecting the cylinders to the design, since the cylinder itself has no attachments.

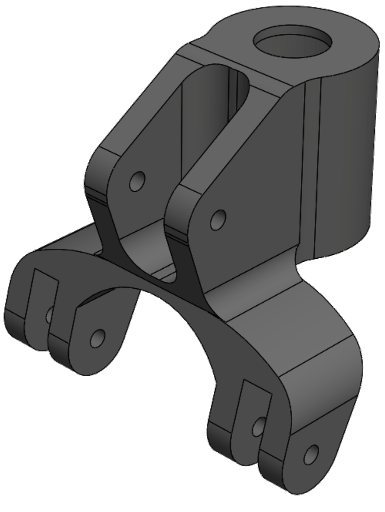


Figure 18. The medial phalanx part.

In the bottom part of the design, there are two support structures going around the finger to the PIP hinge. It has to fit on the finger and will need to be customized for finger size, like a ring. The PIP joint is a hinge joint. The bottom (PIP) axis hinges with the proximal phalanx part at the PIP joint. In this proof of concept, this is done simple and robust. As can be seen in the posterior view of figure 6, the PIP axes (both left and right) have a gap in between. The other part (in this case the proximal phalanx part) has one extrusion which fits in between. The benefit of two extrusions enveloping one over one extrusion being connected to one extrusion is that the latter creates a shear force in the axis. Besides, this method is easy to fabricate. The current scale is as thin as possible given this type of hinge, material and printer (note that the extrusions are 3 [mm] wide), the whole mechanism extrudes 9.5 [mm] lateral of the finger.

Proximal Phalanx part

The next part is the proximal phalanx (PP) part. It must be connected to the proximal phalanx for stability. It begins above the MCP joint where it has two cylinder connections, 20 and 30 [mm] vertical from the MCP joint center. The PP part's other end is at the PIP joint, where it forms a hinge with the MP part.

All design criteria apply without special consideration. The design started as a fluent shape from cylinder connections on one end to the joint hinge at the other end. A straight line between these two sides is impossible without going through the finger, so a smooth bend was necessary. This allows forces to flow through the design and lowers its mass. Thereafter, a connection for the finger has been added.

At the finger joint, the design is made wide enough to fit into the slots created at the MP part. The MP slot is 3.5 [mm] in diameter, the PP part is 3 [mm] wide, because 3D-printing inaccuracies began to appear when dimensions go bellow this level and to fit tightly but not cause excessive friction forces. See figure 7.

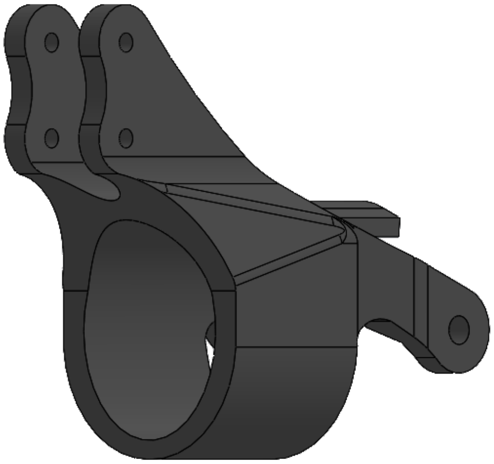


Figure 19. The proximal phalanx part.

Splint

The bellows applies pressure roughly around the DIP joint (roughly the red arrow from figure 1). While, often, the finger is in contact with the external object at the finger tip beyond the DIP joint, causing an extending external DIP moment. Because an internal, muscular flexing moment is (partly) lacking in patients that rely on an orthosis, some external method for preventing DIP hyperextension is necessary to prevent discomfort, pain or injury (Thayer, 1988).

Due to the nature of finger musculature and tendon structure, there is a synergy between the DIP and PIP joint. If the patient has some hand function left and uses this to flex the finger, the DIP joint will flex as a consequence of the PIP joint being flexed. To leave this function free, only DIP hyperextension is prevented normal range flexion of 0-85 [°] (Hume et al., 1990) left unrestricted. Therefore a splint is attached to the medial phalanx. The distal phalanx and the splint are in contact when DIP joint angle equals 0 [°].

The splint part needs to be connected to the bellows so that the bellows is not a loose part. When the bellows is not pressurized, it folds and pulls the splint back, causing PIP joint extension. When the bellows expand, the part is designed to spread the force out over a larger finger area.

The splint has specially been designed for use on the mock-up finger. The mock-up is made up of high stiffness, low friction plastic which is not ideal for firm attachments, where friction or material indentation would prevent unwanted moving around of the parts. The bottom flat part visible in figure 8 is specially made for the mock-up finger to reduce the amount of movement. The mock-up finger has a notch there where the flat spot can cling to. Further, the splint is flat at the top as well, to connect the splint to (figure and number). When testing on human hands or softer mock-up finger material the a hard plastic loop can be used as well (without the flat spot) or a Velcro strap.

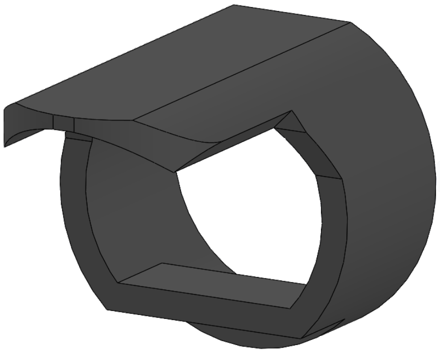


Figure 20. The splint.

Cylinder and rod cap

The hydraulic cylinders do not posses a connection site to attach them to the external world. Therefore a housing is needed on both sides, called the cylinder cap at the proximal end and the rod cap at the distal end. Both are a hollow tube, closed at one end. The cylinder cap is partially closed. A small hole allows the tubing to be connected to the cylinder. Both have a perpendicular hole that can be connected to an attachment point at either the hand part, proximal phalanx part or the bellows housing. See figure 9.

Figure 21. The cylinder cap.

The space between proximal and distal attachments of the cylinder is 41 [mm] while the length of the cylinder is 59 [mm]. The cylinders must extrude at the ends to compensate the overshoot. The two cylinder caps are slightly different from one another. This has two reasons. Firstly, the MCP and PIP joint of the mock-up finger do not have the same RoM (45 [°] and 70 [°], respectively) and secondly, the bellows adds 13 [°] of movement over the PIP joint. The attachment point for the first cylinder housing is 11.5 [mm] from the proximal end, for the second cylinder this is 19.6 [mm].

The fact that the second cylinders proximal housing has a longer extruding segment means that it could potentially pull the PIP joint into hyperextension. This is prevented by the mechanical limit of the PP part that makes contact with the MP part at a 5[°] PIP joint angle. See figure 10 & 9.

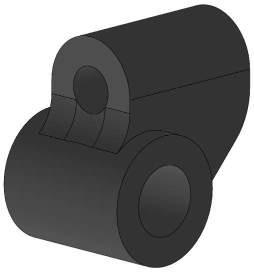


Figure 22. The rod cap.

Hand part

The hand part is designed to fit onto the mock-up finger and is a piece of equipment that holds the cylinder cap of the first cylinder and is easily but rigidly connected to the mock-up finger. It is part of the proof of concept phase and cannot fit onto an actual human hand. Therefore, the design criteria of size or comfort do not apply to it. N.b., the attachment of the cylinders in its current shape, size and location is representable for actual placement past a proof of concept.

The mock-up finger has small cut outs at the MCP joint. The distal end of the hand part can use this to lock itself into place in. On the proximal end this is done with a small ridge that falls just over the sides of the mock-up and connected to the hand with a Velcro band. The small ridge prevents sliding forward because of the mock-ups increasing width and lateral sliding of the hand part, see figure 11.

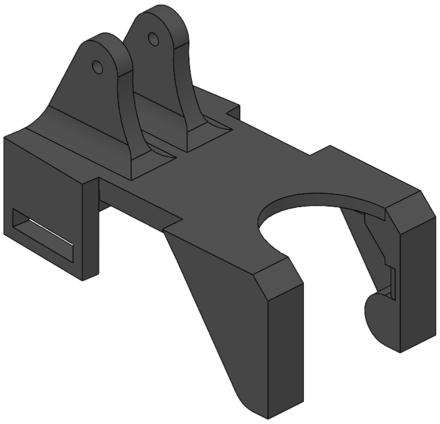
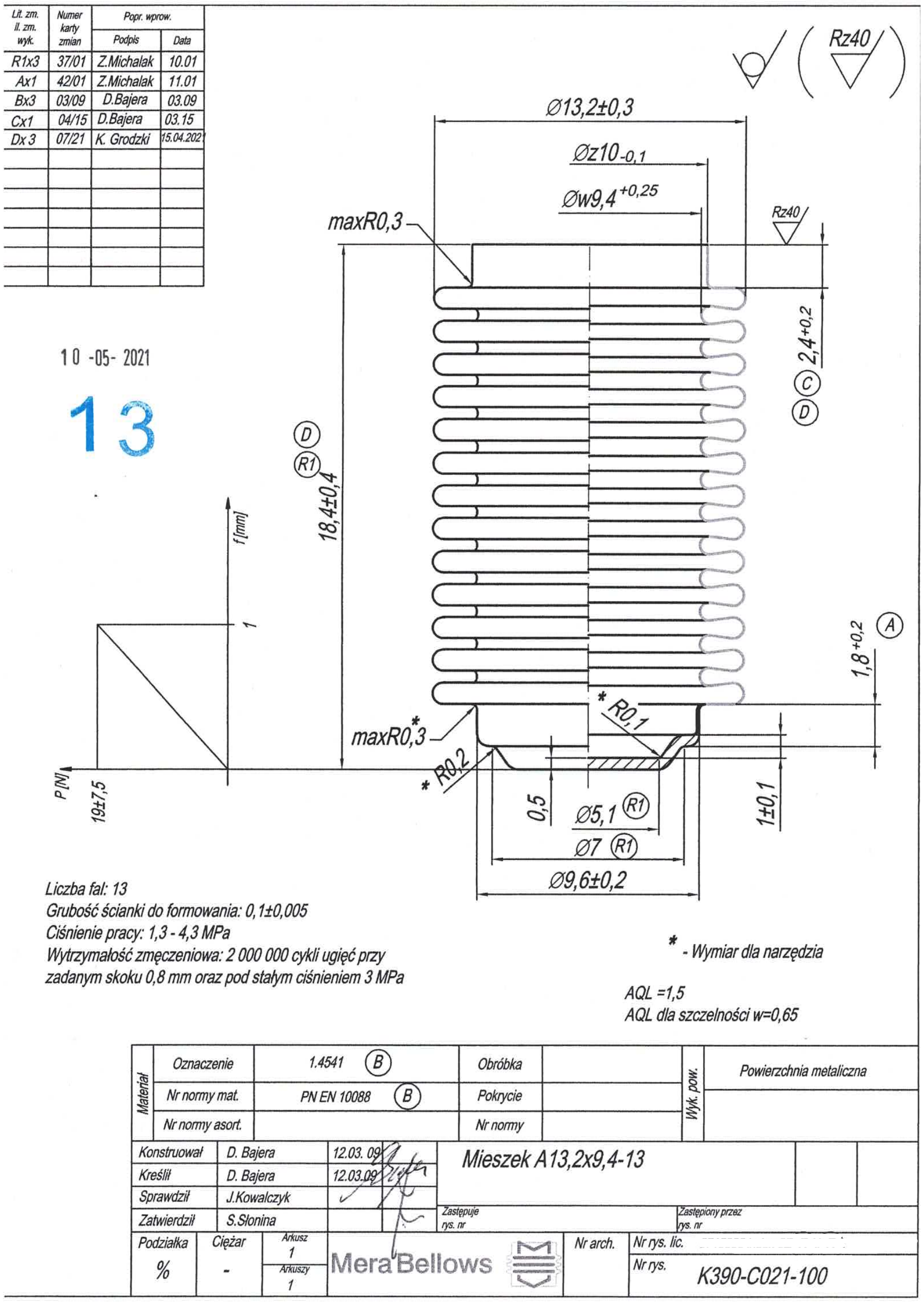


Figure 23. The hand part.

C TECHNICAL DRAWINGS



Lit. zm. Il. zm. wyk.	Numer karty zmian	Popr. wprow.	
		Podpis	Data
R1x3	37/01	Z.Michalak	10.01
Ax1	42/01	Z.Michalak	11.01
Bx3	03/09	D.Bajera	03.09
Cx1	04/15	D.Bajera	03.15
Dx 3	07/21	K. Grodzki	15.04.2021

10 -05- 2021

13

Liczba fal: 13
Grubość ścianki do formowania: 0,1±0,005
Ciśnienie pracy: 1,3 - 4,3 MPa
Wytrzymałość zmęczeniowa: 2 000 000 cykli ugięć przy zadanym skoku 0,8 mm oraz pod stałym ciśnieniem 3 MPa

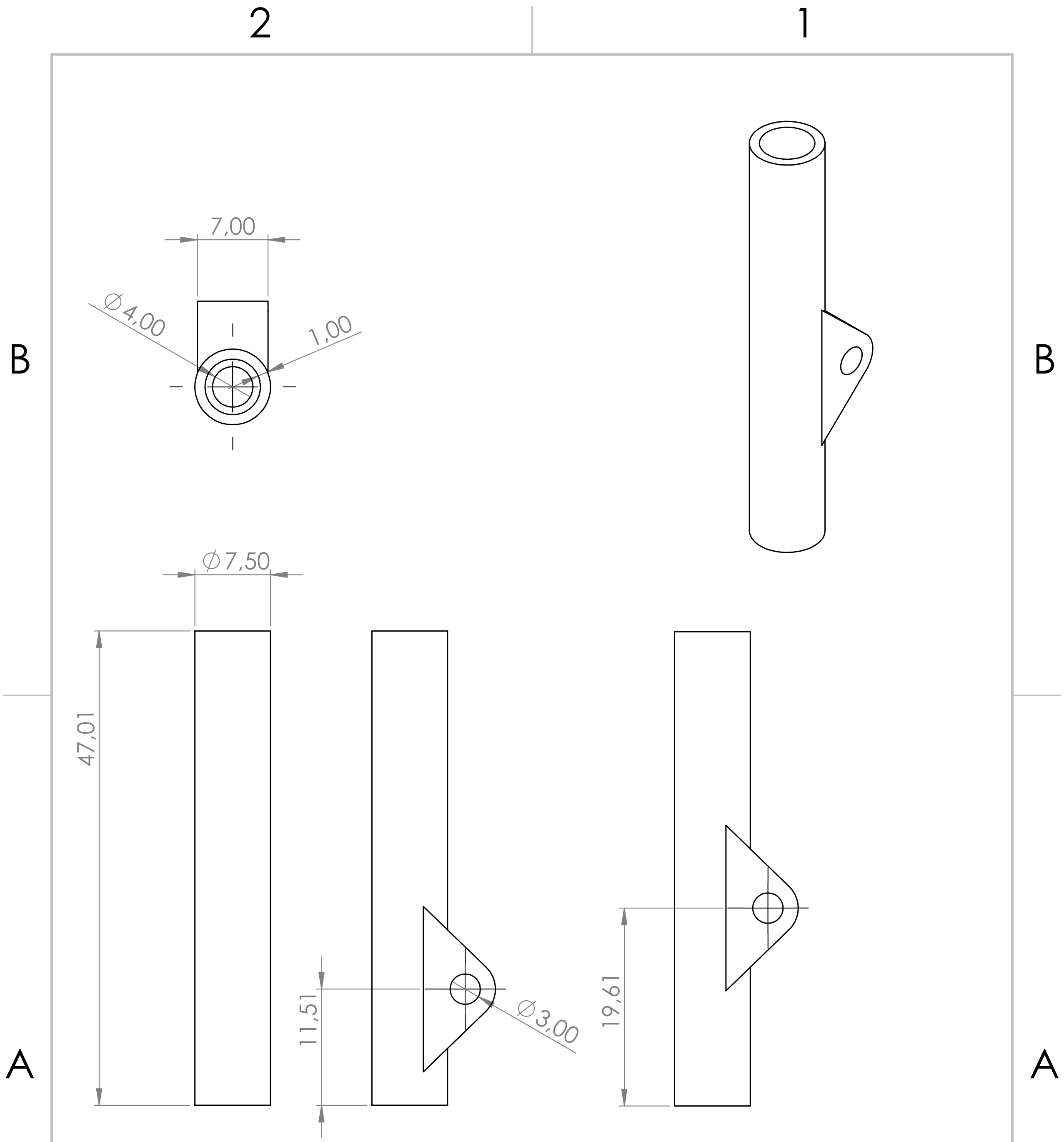
* - Wymiar dla narzędzia

AQL =1,5
AQL dla szczelności w=0,65

Materiał	Oznaczenie	1.4541 Ⓑ	Obróbka		Wyk. pow.: Powierzchnia metaliczna
	Nr normy mat.	PN EN 10088 Ⓑ	Pokrycie		
	Nr normy asort.		Nr normy		

Konstruował	D. Bajera	12.03. 09	Mieszek A13,2x9,4-13
Kreślił	D. Bajera	12.03.09	
Sprawdził	J.Kowalczyk	✓	
Zatwierdził	S.Słonina		Zastępuje rys. nr — Zastępiony przez rys. nr

Podziałka	Ciężar	Arkusz		Nr arch.	
%	-	1	Mera Bellows		Nr rys. lic.
		Arkuszy 1			Nr rys. K390-C021-100



NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

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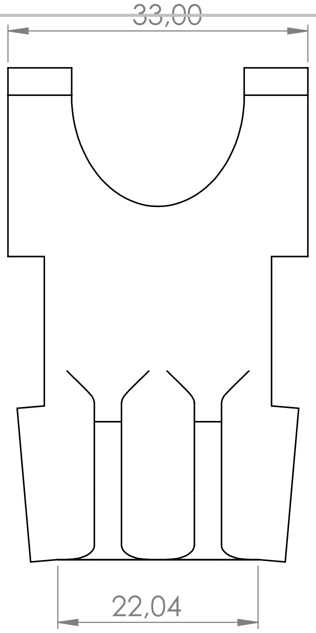

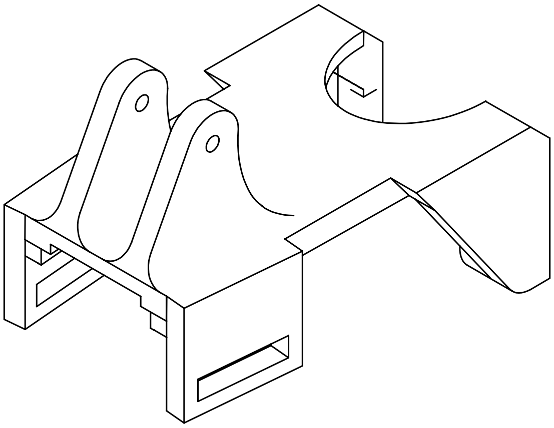

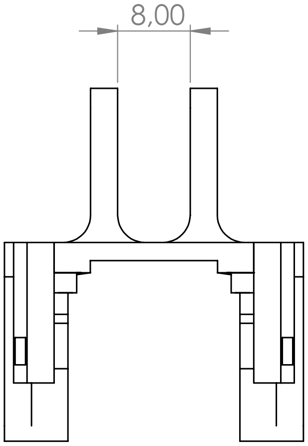

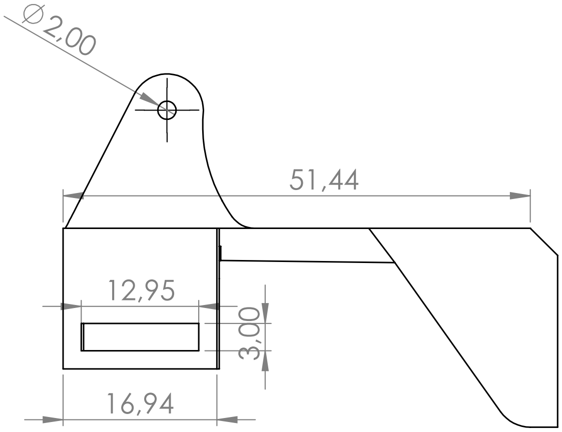

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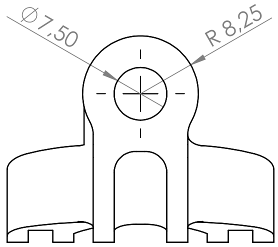

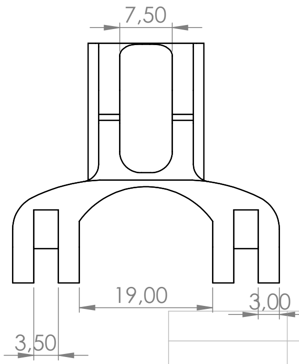

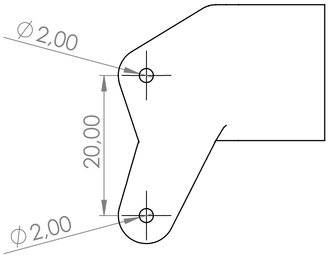

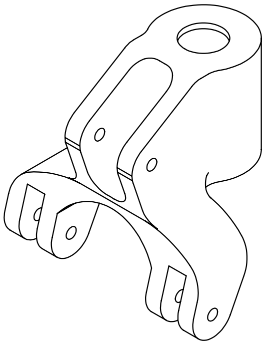

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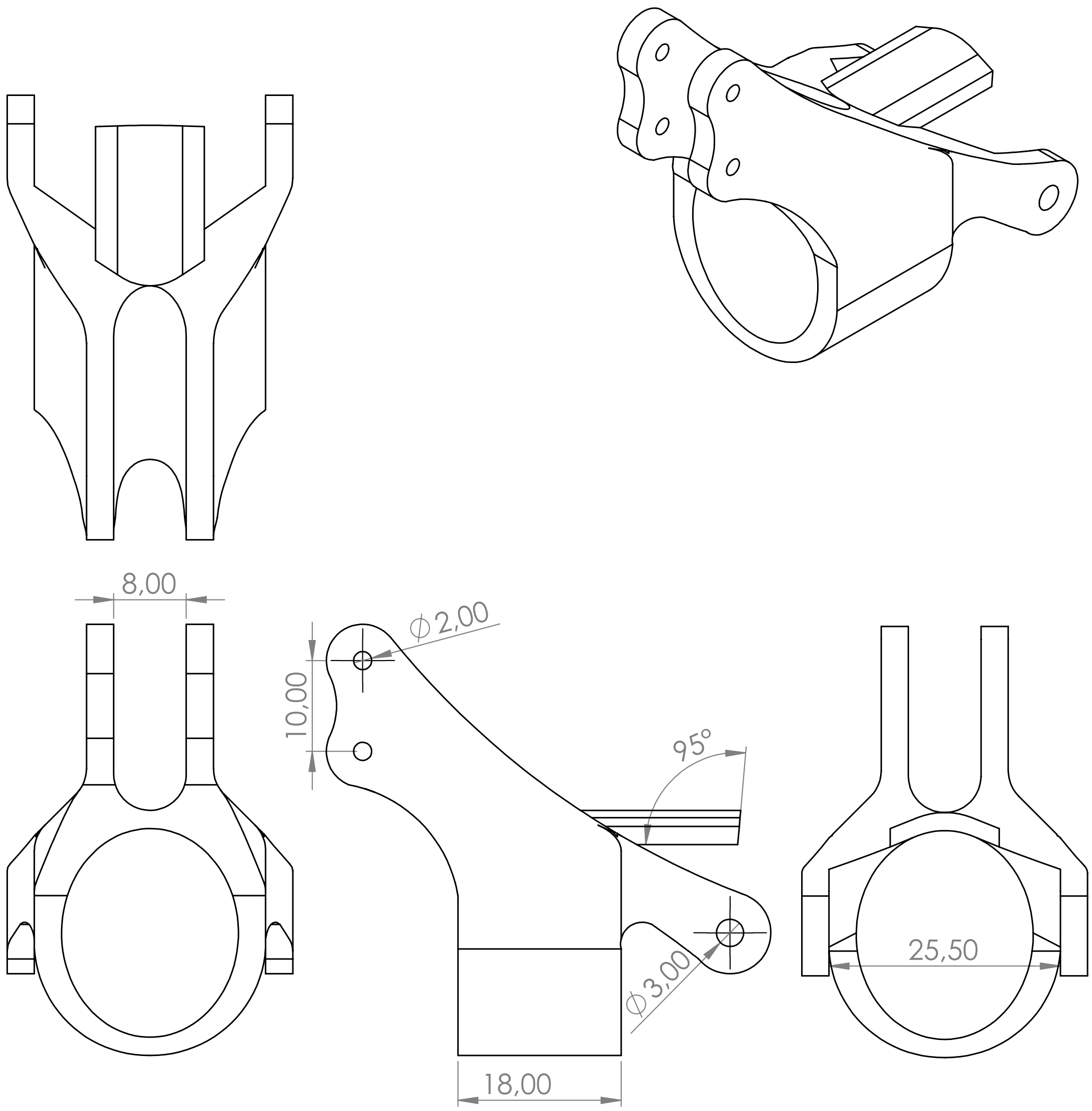

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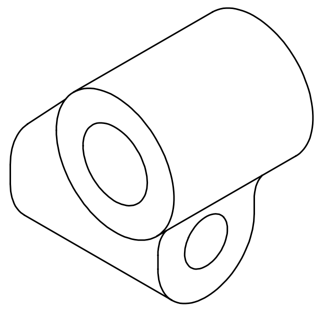

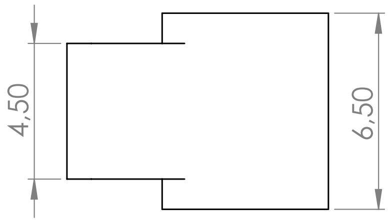

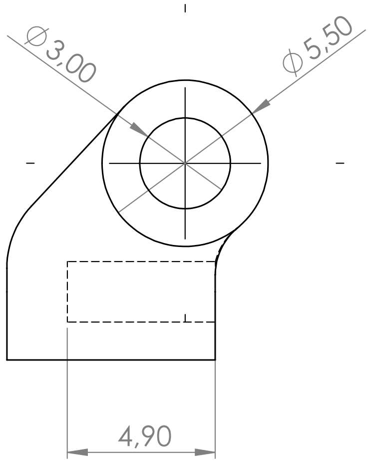

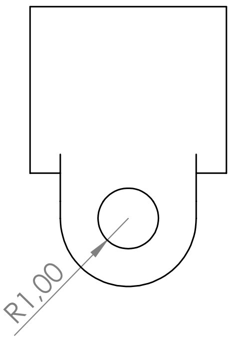

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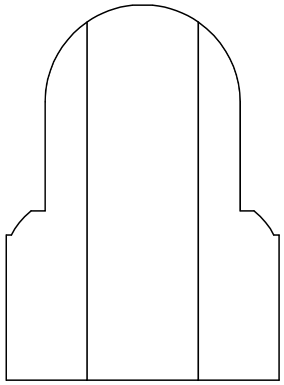

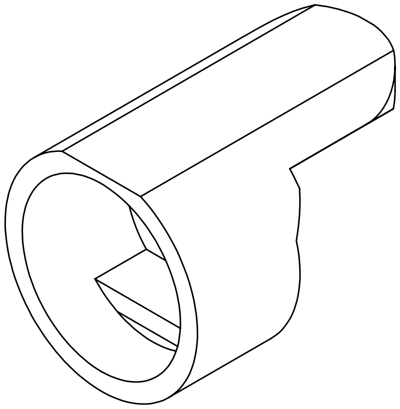

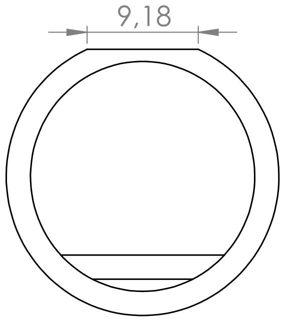

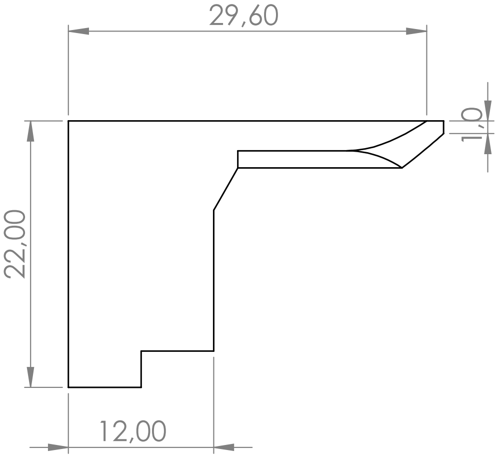

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D LITERATURE STUDY

Literature Review

Reversible Attachment for Orthoses

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Supervisor:
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July 22, 2020

TU Delft

Contents

Abstract

Introduction: Muscular or neurological disorders impair movement. Patients suffering from this kind of condition might desire a hand orthosis to aid in daily life activities. Among these movement disorders is Duchenne muscular dystrophy (DMD).

A side effect of DMD is impaired skin integrity and this increases sensitivity and makes the skin more prone to damage. DMD patients can experience discomfort while donning or doffing aforementioned orthosis. The goal is to investigate all possible attachment methods that might be donned and doffed repeatedly (reversible attachment) and select one or a few that are suited for use on an orthosis and for sensitive DMD skin.

Method: A literature search was instigated to find articles containing reversible attachment methods. The conclusion was drawn that the field of study concerning attachment methods is scarce. With a combination of scientific and non-scientific data a list was created.

To determine what mechanical properties healthy or DMD skin has, was difficult. Eventually, a series of articles discussing the behavior of skin under stress was found and used to determine some criteria the attachment method should abide by.

Results: The list of attachment methods that were found is elaborated. It includes shape grip, friction, hook-and-eye, Magnetism, Van der Waals forces and suction.

To determine which attachment mechanisms are suited for DMD skin a series of articles is presented that state causes of stress and give solutions to prevent this. Big transitions in stiffness, a high coefficient of friction (CoF) should be avoided, thin layers of soft tissue are more prone to experiencing high stress, skin moisture should be reduced. This can be done by increasing load bearing surface, using elastic garment, prevent the use of lotions or oils and utilize regions of thick soft tissue.

Discussion: Two sets of criteria were created. One defines the functioning of the attachment method. It consists of quality of attachment, easy donning/doffing, obstruction of orthosis use, weight/size and aesthetics. The other set of criteria states rules of thumb that reduce skin stress. It consists of: tapering the stiffness, ventilating the skin, absence of large shear or compressive forces and personalizing the attachment.

Conclusion: Methods that satisfied the attachment criteria as well as skin integrity criteria were shape grip, SMA, bat claw, Velcro and magnetic. It is concluded that bat claw, Velcro and magnetic are suited and that SMA shape grip is potentially the most promising and is advised to research.

Introduction

There is a plethora of articles about the design of orthoses and the evaluation of their functioning in practice (e.g. Amirabdollahian et al., 2014, Zhao et al., 2016, Baker et al., 2011). While this is positive, in these articles there is seldom focus on the attachment and detachment of the orthosis to the body. For patients that suffer from nerve damage or muscular dystrophy, donning and doffing might be difficult, because their ability to perform basic hand movements is impaired. This review will provide an assembly of attachment methods, with the purpose of finding fitting solutions or to support the currently used methods, which are mostly bands or straps, often with Velcro (e.g. Amirabdollahian et al., 2014, Zhao et al., 2016, Baker et al., 2011).

This review focuses in special on Duchenne muscular dystrophy (DMD) patients. DMD patients encounter an additional complication regarding orthoses. DMD compromises muscle tissue, decreasing muscle extensibility with a consequential loss of range of motion in joints. Lack of movement and static positioning in flexed state compromises skin integrity, making the skin more sensitive and prone to damage (Allen & Whitehead, 2011). Dissatisfaction in donning and doffing is a reason for rejection of the orthosis by the user. Donning and doffing mechanism is linked to stability and comfort, so the importance of a proper solution is emphasized (Batavia & Hammer 1990).

There is a need for an attachment mechanism that can be donned and doffed multiple times (reversible attachment). This mechanism must also uphold all standard requirements, a list of features will be provided in the text. The possibility of donning and doffing by the DMD patients without assistance is an advantage. Plus, the attachment needs to satisfy the skin needs of these patients. To summarize, what attachment methods are suited for a hand prosthesis designed for DMD patients, taken into account their skin properties and physical capabilities?

A general overview will be given of available literature on attaching and detaching mechanisms. This will be specified to useful solutions for orthoses based on criteria like size of mechanism and weight and will also be graded for user friendliness for patients with limited physical capabilities and impaired skin integrity.

Method

Because of the difference between the attachment method and the DMD skin subject, two separate searches were conducted. This results in two separate method sections, result sections and lists of criteria.

Attachment mechanism

To find the attachment mechanism, a general search was intended to identify different mechanism. There is a plethora of articles on attachment mechanisms, but yet it is proven difficult to find. This is because attachment mechanisms as a field of study does not exist. In most cases the attachment method is seen as the means to an end and not the subject of interest. There were no meta studies found to give a complete overview of different reversible attachment mechanism. Also, there are seldom common search terms that can be used to delimit the literature and many of the terms used for fitting articles are used in a plethora of different articles with a vast variety of different subjects. Filtering out the unsuited articles with Boolean operators proved impossible. Excluding terms was not feasible, because the terms that resulted in unsuited articles might also result in suited articles. The number of fields of study was too wide to narrow down to manageable proportion, because attaching and detaching are too common actions. Furthermore, the research question of these articles often was not how to attach or detach. The method of attachment was brought up in the answering of the question, but in most cases not even elaborated.

Eventually, a search term was created that included some useful terms and excluded some common, useless terms:

(attachment OR connector OR folding OR adjustable OR releasable OR releasing OR unlocking OR locking OR lock OR interlocking) AND (mechanism OR method) -molecular -biochemical -pharmacology -"life science" -phase -multicore -laser -skeletal -oscillating -cellular -oscillations -parallel -binding -protein -computing

The search engines used were Science Direct and the TU Delft library search, the latter one is useful because it also includes articles that have no digital copies. While the TU Delft, among others, also searches in the database of Science Direct it results in less hits than via Science Direct self. This lead to the believe that a separate search on the former site was useful. IEEE and PubMed were also used but delivered no useful papers. The search engines found hundreds of thousands of articles. The maximum number of characters possible in the search bar at Science Direct was reached after '-parallel' and so the inquiry had to be capped off at that point.

The purpose of this thesis is not to give a summarized overview of all literature concerning attachment methods, but it will organize the different categories of attaching with examples of every category. The purpose is to give a well-informed opinion about the attachment of the hand orthosis, so that no solution is overlooked. Yet, the reader should realize that within every category there are plenty possibilities, where only a few will be given.

Because the purpose is not to bundle all attachment mechanisms literature, finding possible categories can be and is done with more than scientific literature alone. Also a non-scientific internet search and daily life examples are used. Some scientific articles were later on found with search terms directly related to one category.

Skin integrity

The second literature search focused on human skin. Information regarding the skin of DMD patients was sought, preferably articles that contain objective measures, like mechanical properties (e.g. Young's modulus, hardness, etc). Note that alongside this would require documentation of pain levels at different stress levels, to rule out the possibility that pain arises without any mechanical damage to the skin.

The focus of this review also lies on grading the categories for skin with increased sensitivity. The first search served to get orientated within the literature. Four search inquiries were dedicated to find concrete information on pain thresholds or pressure limits of DMD patients, with the following search strings:

'(DMD OR "Duchenne Muscular Dystrophy")' together with one of four following terms:

- (acceptable OR maximal OR maximum) AND (skin OR dermis) AND (damage OR pressure OR friction OR load OR loading)
- (fingers OR hand OR skin) AND (comfort OR pain OR pressure)
- skin AND (shear OR compressive) AND (force OR stress) -blood
- human skin AND ("mechanical properties" OR yield)

Because of the biological nature of this search inquiry the search engine used was PubMed. Unfortunately there were no useful results. Data on healthy subjects was present, so the search was done again without the '(DMD OR "Duchenne Muscular Dystrophy")' part.

It was possible to find articles that had concrete results, the standard protocol for measurement of pain onset as a consequence of pressure is pressure algometry. But, the discussion of these articles were filled with footnotes about reliability of the results, these articles were discarded. See Discussion for elaboration.

By changing the intention it was possible to continue with this review. The goal became to gain an understanding in stress reducing strategies and determine which attachment mechanisms are fit to reduce stress.

A series of nine articles was found that provides a detailed explanation of the behavior of stress in human soft tissue. The articles describe the prevention of pressure sores, ulcers, blisters or skin abrasion. It is not likely that the DMD patients damage their skin to this level before experiencing pain. Still, these articles can be useful, because of techniques for the prevention of shear and compressive forces. Through references and citations of these articles three more useful articles were included.

Results I: Attachment mechanism

The results section consists of two parts. In this one, the first, the attachment mechanisms are elaborated, including some explanation and an example. These are the results from literature search number one. For skin sensitivity, consult 'Results II'. In the discussion results part one and two will be combined into an advice.

Categorization

Suited articles were categorized by attachment mechanism. Searching though scientific information, a book on biological examples of attachment methods had a rather complete list of mechanisms (Nachtigall, 1974).

At the most basic level attachment can be divided between force closure and shape closure. Force closures can be any force or a combination of forces working together. This makes that force closures can be subdivided into many categories. Shape closure is a separate method for its absence of force.

- Shape grip
- Force grip
    - Friction
    - Hook-and-eye
    - Van der Waals forces
    - Magnetism
    - Suction

Shape grip

Shape grip, also called shape closure, is the 3D surrounding of an object in such a way that it cannot be moved out of its enclosure by any translation or rotation. This can be achieved by a gripper, band, strap or likewise. A deformable object that folds around the object and hardens itself, similar to the tentacles of an octopus folding and then tightening.

Such an adapting variant was designed by Hirose & Umetani (1978). It has tentacles made of multi-links actuated by pulleys as seen in fig. 1. The grip wire is pulled by an electric motor, the force is transmitted through the trolley in the current joint onto the next wire, which passes on its force to the next joint. This process repeats till the end of the tentacle. The tentacle wraps itself around the object making a copy of its shape. See fig. 2 where a random shaped object is grabbed. In this setup with two tentacles the attachment is a combination of Shape closure with force closure because friction is still needed to prevent lateral movement. This 2D shape grip is a simpler version that can be modified into 3D by adding more tentacles in perpendicular direction.

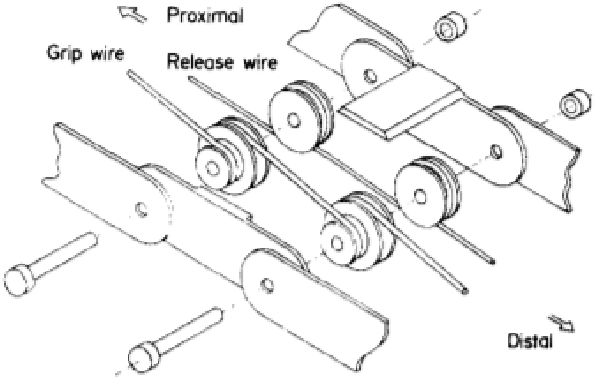

Figure 1: Anatomy of the multi-link grabber. Adapted from Hirose & Umetani (1978)

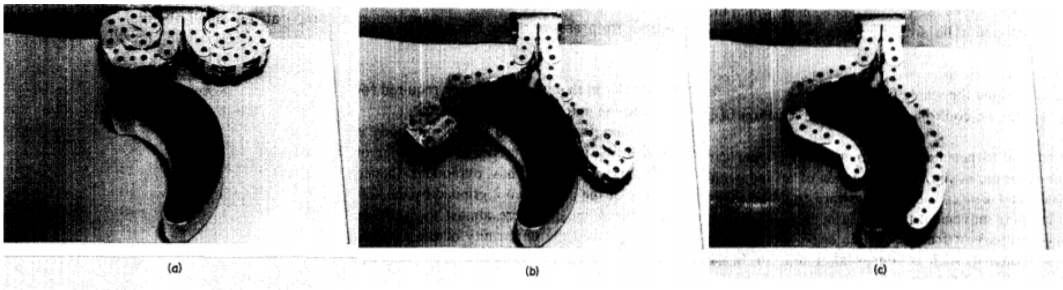

Figure 2: Demonstration of the tentacle function around an object. Adapted from Hirose & Umetani (1978).

Another form of shape grip is the zipper. See fig. 3 for the way in which the two sides attach to each other, called interdigitation. They are only to be disconnected by deformation of the fabric between the zipper teeth, that increases the space between the teeth. This is done starting from one end of the zipper and working towards the other end, carried out by the slider.

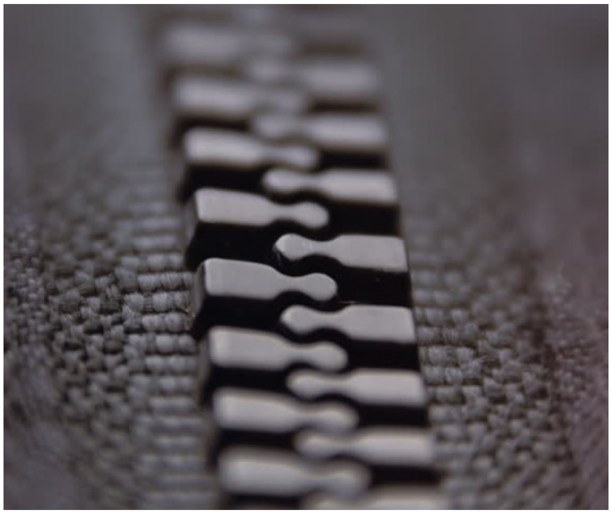

Figure 3: A close up of a zipper that shows interdigitation.

SMA wire

To conclude shape grips, there is an article presenting an idea for the reversible attachment of a hand exoskeleton by Hasegawa & Suzuki (2015). They suggest the use of shape memory alloy (SMA) wires. The alloy used in their experiment is Nitinol, a Ni-Ti compound with a transition temperature (Tt) of 5 °C between austenite and martensite. During normal orthosis use at room temperature it will be in austenitic phase. The mechanisms functions because of the superelastic properties of austenitic Nitinol.

The SMA wire's are nearly closed C-shapes that fit around the fingers or wrist. See fig. 4 for the design of a single attachment, the nitinol wire is attached to an air chamber. Inflating the air chamber stretches the SMA, so that the exoskeleton can be donned or doffed.

Their motivation for developing this new method is the improvement of comfortableness and easiness to wear. They argue that comfortableness increases with this mechanism compared to Velcro, because the surface area of the straps over the fingers is smaller, leaving more skin to be used for haptics. They tested the attachment mechanism and it reportedly decreases donning time with 80% and doffing time with 83% compared to Velcro.

The increase in donning and doffing time is achieved because the exoskeleton is donned with only two on-off switches. The switches turn on or off air pressure and will inflate or deflate the air chambers. One switch is for the thumb and the other for the remaining fingers and wrist. First you open the fixtures by turning both switches on. You put your thumb in and close these fixtures with by switching off switch one. Then you can put the rest of the hand into the other fixtures and close them with switch two. Since there are seven points at which the exoskeleton is connected to the hand (see fig. 5) the two switches are operated faster than seven pieces of Velcro.

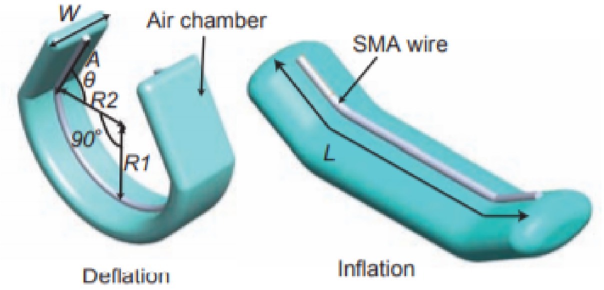

Figure 4: The SMA wire's relaxed state is folded. Air chamber inflation opens it for donning or doffing. Adapted from Hasegawa & Suzuki (2015).

The attachment strength is low, but it is reportedly enough to carry the weight of the orthosis. They claim that with the right adjustment, the mechanism does not restrict blood flow, where Velcro might. With another advantage that these attachments are tailored to ones specific needs and then be always equally firm attached, where Velcro can be wrongly donned which causes restricted blood flow through the skin.

Because of the generally less active lifestyle of the patients that need an exoskeleton, Hasegawa & Suzuki (2015) reason that that the lesser attachment strength is sufficient. With a second design, adjustments might be possible to assure sufficient attachment strength.

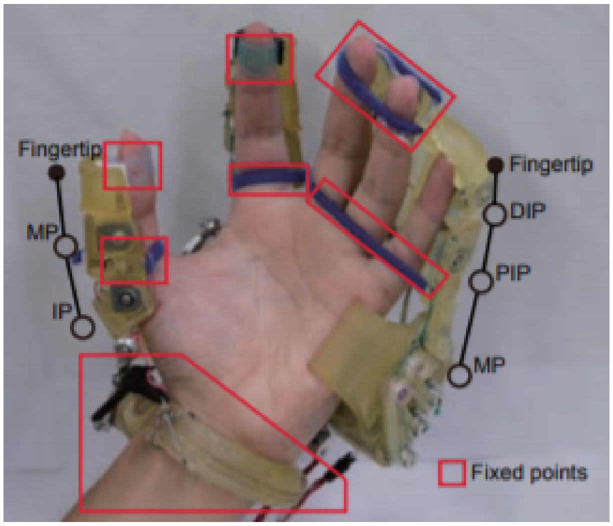

Figure 5: The location of the seven places the exoskeleton is connected to the hand and wrist. Adapted from Hasegawa & Suzuki (2015).

Force grip

Force grip incorporates all other types of reversible attachments. This is a wider section with more variation in mechanisms with different uses and characteristics. A number of forces such as friction or normal forces play a role in the attachment of objects.

Friction

One force that can be used to attach is friction. It will play some role in many attachments (e.g. expansion fasteners). But there are some attachments where it is essential and this section will discuss these situations. One of these is the screw mechanism. A screw or nail detaches from a wall without friction. A sock also needs friction to not slide from the foot and a prosthetic socket to not slide from a stump.

Glove

One daily life attachment that mainly uses friction is a glove. Connecting the orthosis to a glove can be a solution. A firm frame that can support the weight of the orthosis, connected to glove that is firm in some places to support weight and flexible and soft to be pleasant to wear.

Bat claws

Bat species are known for their ability to hang and sleep upside down. They use their hind legs, with large claws, to grab tree branches and alike and can hang upside down for multiple hours (Quinn & Baumel, 1993). For most species this would cost large effort, let alone be able to do this during sleep. Bats have developed a method to do this passively. Their pedal flexor tendon (see T in fig. 6) has a rough, scaled patch. When the bat uses the claw to grab a branch as in fig. 6b, the scaled patch glides over the retinaculum (R) and creates a friction force that passively holds the claw in place and enables the bat to hang upside down for long periods of time (Quinn & Baumel, 1993).

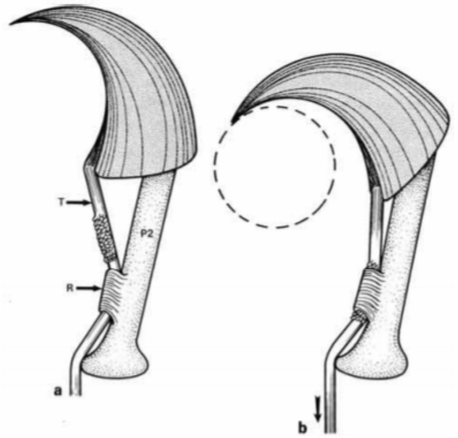

Figure 6: The claw of a bat, the scaled patch on the tendon slides under the retinaculum, R, to create a passive lock through frictional force. Adapted from Schutt (1993).

Hooks

The next force grip mechanism is hooks-and-eyes, or in short, hooks. Hooks are a straightforward attachment method. It can be found in wind hooks, like on a shed door or industrial hooks used for lifting. These two examples requires a force (e.g. gravity) to stay attached since the hook does not encapsulate the eye. This trait differentiates it from shape grip. The attentive reader might notice that the bat claw mechanism resembles a hook. Yet, it is placed under friction because the force keeping the mechanism attached to the hand is friction.

Velcro

A different hook mechanism is Velcro. Technically called a loop-and-hook fasteners, the nylon and polyester made attachment method consists of small hooks. The flexible characteristics of the fabric makes it easily to adjust the Velcro to shape of any object. For most hook attachments an exact relative orientation between the hook and the eye is required, with Velcro this is less important. This increases ease of use and gives the opportunity to tighten or a loosen a strap to set the pressure of the attachment. It is not surprising that bands and straps are often used to attach exoskeletons and ortheses (e.g. Banala et al., 2006, Colombo et al., 2001, Pfurtscheller et al., 2000) as can be seen in figures 7 and 8.

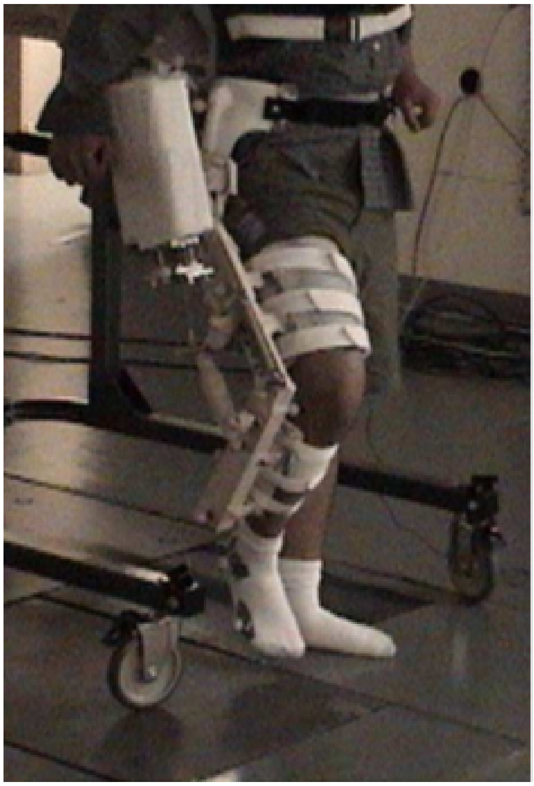

Figure 7: A leg orthosis attached with Velcro. Adapted from Banala et al. (2006)

Figure 8: An electrical hand orthosis attached with Velcro. Adapted from Pfurtscheller et al. (2000)

Velcro is a hooks-and-eyes type attachment, but not one relying on gravity like the examples given before. The soft side of a piece of Velcro exists of many eyes (or sometimes called loops), where the hard side consists of many hooks. When put together, the hooks slip into the loops. By pulling the pieces apart the hooks elastically deform and straighten, slipping off of the eyes.

Velcro is a unique attachment method in the way it can be connected and disconnected many ways and how the exact positioning of the two sides is not relevant. This makes it convenient in combination with elastic straps and bands.

SMP Velcro

A new and different development is the use of shape memory polymer (SMP) to create a hook-and-eye attachment which can endure larger shear and normal forces. The principle and attachment strength was studied by Chen et al. (2013).

Their method is the forging of two plates, comparable with the two sides of Velcro. Both sides are covered with pillars of a SMP material that has stiffer properties below critical temperature (Tg) of 60 ℃ and changes to a polymere with lower Young's modulus when heated above Tg. This SMP property is used to shape the pillars to interlock, interdigitate or indent. After cooling below Tg the high Young's modulus prevents pulling apart by normal or shear forces. This can be seen in fig. 9.

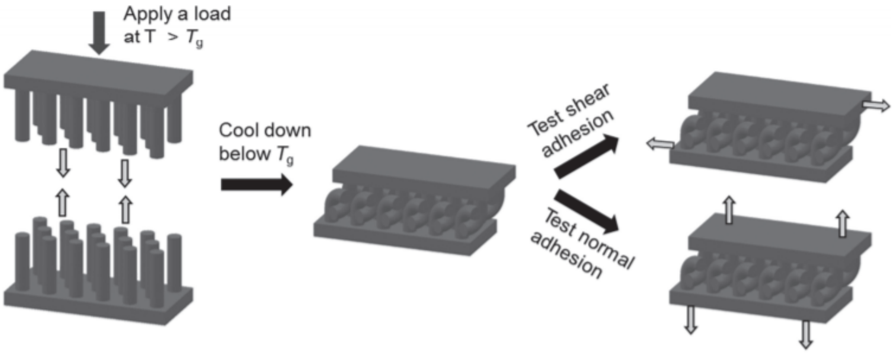

Figure 9: The SMP is heated above Tg and the layers are compressed. After cooling below Tg the SMP hardens and the interlocked pillars are tested for resistance to large shear and normal forces. Adapted from Chen et al. (2013).

Chen et al. (2013) reported a maximum normal force of 53 N/cm^2 against a maximum of 120 N/cm^2 for regular Velcro. While being significantly lower, a possible advantage of SMP Velcro is that the needed force can be lowered even further by thermal energy, as can be seen in fig. 10. Both normal and shear forces are significantly decreased at 80 ℃ This might give new opportunities for the use of SMP Velcro.

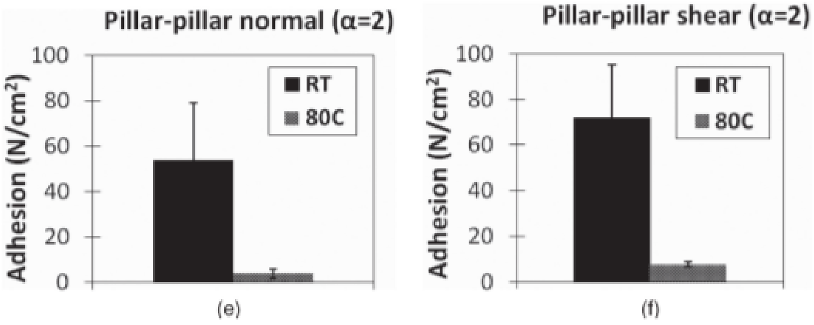

Figure 10: Results of the needed normal and shear force to separate the two sides at room temperature compared to T>Tg (namely 80 ℃).

Magnetic force

Whiteboard erasers and magnetic door stoppers (see fig. 11) are two daily-life examples of magnetic attachments. Door stoppers are turned on, they function on electromagnets, until the button is pushed and the current disrupted. A power source is needed to keep the magnetic force on, presenting both an upside and a downside to electromagnets.

Attaching by the use of magnets is easily done because of the magnets tendency to push themselves in the desired direction, towards the other magnet. But, this system has two problems. Permanent magnets are either easy to detach and will do this at undesired times, or are hard to remove even when you want to. Electromagnets don't have this problem but require a power source and a coil around the soft iron core.

Figure 11: Electromagnetic door stopper, an example of a reversible attachment.

Gecko feet

Gecko's are known for their ability to walk across walls and ceilings. They do this with specialized attachment pads on their feet covered with small hairs, called spatulae. These are bundled on a larger structures named seta, which can be found in the wrinkles on the feet of Gecko's, called lamallae, as visualized in fig. 12. This complex hierarchical structure is designed to increase the contact area between the Gecko feet and the walking surface (Kwak & Kim, 2010). Fig. 13 demonstrates how the spatulae can deform to maintain large contact area, even on a rough surface.

Two rough and rigid surfaces might seem to be in contact, yet are only able to make actual contact on a small portion of the surface. The area where surface to surface distance is small enough to establish Van der Waals force is between two and six orders of magnitude smaller than the 'apparent' surface. To prevent this, the Gecko uses the spatulae. The small hairs are flexible so they can fill a large portion of the rough surface (Bushan, 2007). The hairs fill the cracks and grooves of the walking surface so that Van der Waals forces can be established on a very large portion of the apparent surface.

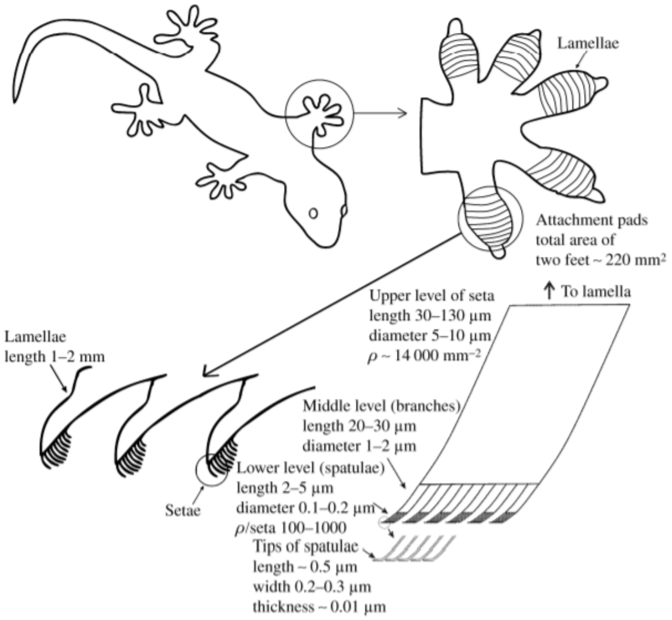

Figure 12: The hierarchical structure on a Gecko foot that forms the foundation of Van der Waals force with the surface. Adapted from Kwak & Kim (2010).

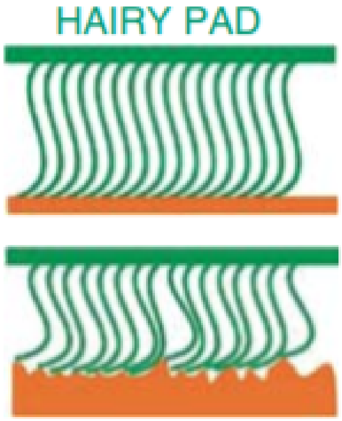

Figure 13: The hairs on Gecko feet form themselves to the surface. Adapted from Creton & Gorb (2007).

The spatulae create Van der Waals force with the surface. Capillary force is sometimes present as a second, but only on hydrophilic surfaces. Yet, these do not significantly add to the total attachment strength (Autumn et al., 2002).

While this ability is standard for insects such as flies and beetles, lizards have about two to six orders of magnitude more mass than insects (Bushan, 2007) and this eventually becomes problematic. When the dimensions of the animal become larger, the surface of the body grows to the power two, but the volume and thus the mass grows to the power three. This creates the need for a larger portion of the body surface to make Van der Waals bonds. This is why Geckos need proportionally larger feet and a larger percentage of the spatulae under the feet to connect to the surface (Creton & Gorb, 2007).

To detach the feet easily, the Gecko spatulae are all facing the same direction. This makes that in walking direction the spatulae can resist large forces, but in opposite direction come with less resistance. This reduces Gecko energy consumption (Creton & Gorb, 2007).

Suction

The last form of force grip is the suction pad. It functions by making an airtight seal between the pad and a smooth surface and lowering air pressure under the pad by removing air or increasing the volume. Some, that remove the air under the pad, are connected to a pump and will continuously and actively create a pressure difference by sucking out air (e.g. fig. 14). Others rely on one moment of active force delivery to remove air under the pad or increasing the volume under. These are passive pads, like basic household suction pads in the bathroom.

The pressure under the pad will drop below atmospheric pressure and this creates a net force in normal direction to the surface the pad is attached to. This prevents the suction pad from moving in normal direction. Some friction can occur that will prevent the movement in shear direction. Both surface characteristics and the water presence influence the friction coefficient.

In surgery, suction is also used (e.g. to grab slippery tissue). During coronary bypass surgery one problem the surgeon faces is to incise and work in an artery that is constantly moving due to the pumping of the heart. To hold the heart in place two strips of suction pads are placed on the heart parallel to the coronary artery. This holds this side of the hart and the artery in place, so that the surgeon can perform the bypass safely (Jansen et al., 1998). See fig. 14.

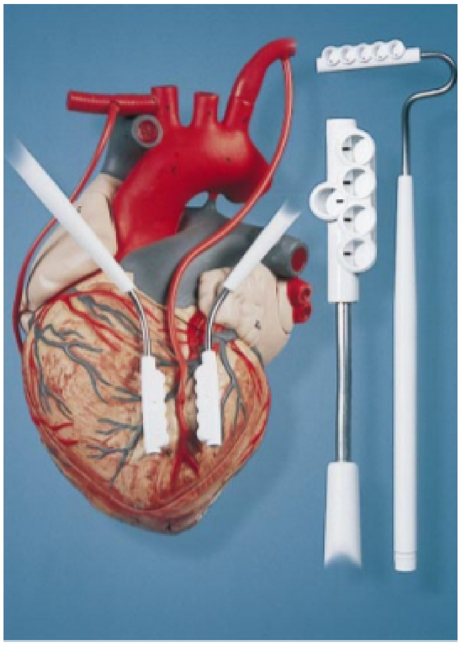

Figure 14: The placement of two suction instruments, called the Octopus tissue stabilizer, to restrict coronary artery movement due to heart movement. Adapted from Jansen et al. (1998).

Results II: Skin sensitivity

The section Results II will discuss the human skin and the basics of transferring load to soft tissue. The main causes of stress will be summarized, followed by ways to prevent high stress levels and the importance of tailoring to personal differences.

Soft tissue under stress

In the 1970's the groundwork for transmission of forces through soft tissue was made by Murphy and Bennett in a series of nine articles called 'Transferring load to flesh' published in The Bulletin of Prosthetic Research. They explain the behavior of tissue under stress by some theoretical and physical experiments. Because of computational limits, their results displayed on the y-axis were incorrect, and often by large difference (e.g. compressive and shear stress were in most cases to high). Nevertheless, their hypothesis on the shape of the graphs and their size relative to each other showed their knowledge on the subject and the reliability of the results in a strictly qualitative manner. For the rest of this paper, their theory will be assumed to be valid, but the values obtained from theoretical models will be discarded. See fig. 15 for one of the experiments, where they showed the compressive stress right under the tip of the dull chisel (line A) and more laterally (lines B and C) either close to the surface and deeper in the artificial soft tissue called Spence Gel (in the drawing vertical direction and in the graph displayed on the x-axis). The nine parts of 'Transferring load to flesh' make a detailed review of skin stress and its prevention.

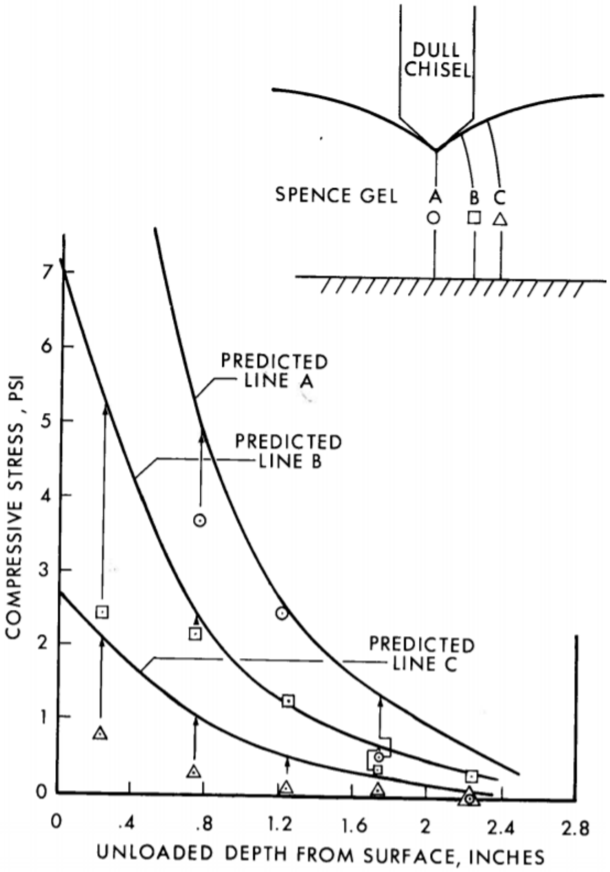

Figure 15: Theoretical versus actual compressive stress, adapted from Bennett (1973).

Causes of stress

Force transmissions from orthosis to hand do not translate linearly to stress levels in soft tissue. Levels of stress and strain are dependent on factors like the shape, stiffness or coefficient of friction (COF) of the orthosis. Also soft tissue thickness is an important factor, plus there are differences in behaviour between shear and compressive forces. A more elaborate summation is read below.

- Big transitions in stiffness between adjacent materials results in three problems.
  - Point one is the even spreading of the force delivered by the hard structure evenly over the soft structure. When the shape of the two objects are not an exact match, the surface contact is restricted to certain points where pressure 'hot spots' form. This is most important when the soft tissue is thin, because a thin soft tissue layer cannot form itself according to the hard structure (Bennett, 1973).

  - Point two, the soft tissue will be impinged between the hard structure and the bony prominence underneath the tissue. Dissipation of stress evenly throughout the soft tissue will not be possible (Bennett, 1973). This also works the other way around. Imagine the case of fig. 16. Again, some gel simulates soft tissue, with thickness H, is placed on a hard structure. A rigid block is pushed into gel by a load, P_o. This translates into applied pressure, p. P_o has influence on radius of contact, R_o, because a higher load makes the block sink deeper in the soft tissue. $P_o/(2*R_o)$ determines the experienced pressure, q. This shows us that load, P_o, or pressure, p, are not directly linked to reaction pressure, q. Soft tissue thickness, H, determines R_o. According to Bennett (1972) this makes q vary between p and 0.5p. Soft tissue can lower reaction pressure with a factor 2.
  - Point three is the high shear force in the soft tissue around the sharp edge of the harder material. As can be seen in fig. 15 at line B and C, the surface of the soft tissue is not only pushed down but also pulled laterally towards the chisel, caused by the large difference of compression of lines A with respect to the more laterally placed lines. An extra shear stress component is added. Mind that this effect is not present on for example the back of the hand, where the soft tissue layer is very thin over bony structures and where large compressive strain difference cannot occur (Bennett, 1973).

- A high COF can be a problem. In some cases it can be beneficial if slipping happens more easily, when slipping occurs early the maximum peak shear force is lower. Note that slipping lowers stability, a trade-off has to be made tactically.

- Shear forces on the skin translate into large shear forces when the soft tissue layer is thin, the force is concentrated in the small area between the orthosis and a bony prominence. (Bennett, 1973).

- Moist is known to increase the COF between some materials and human skin. This can also occur with the use of creams and oils originally used to lower the COF. They retain the water in the skin and after 3 hours the extra moist out-weights the lower COF of lotion on prosthetic (Carlson, 2006).

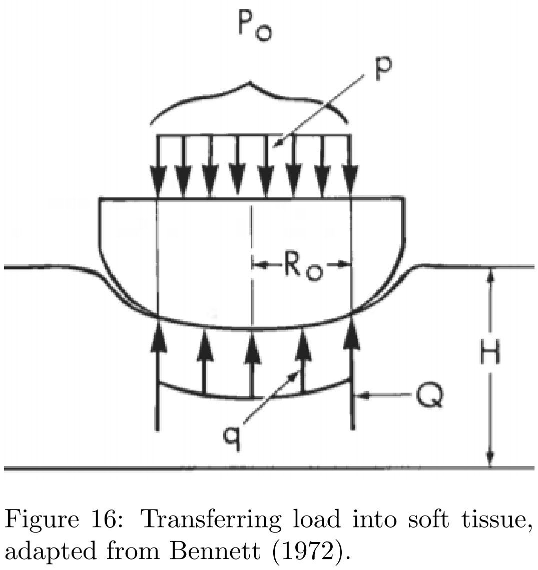

Figure 16: Transferring load into soft tissue, adapted from Bennett (1972).

Stress reducing strategies

The series of articles from Murphy and Bennett provides general rules to reduce stress peaks. It is summarized in the following list.

- Increase load bearing surface. At fig. 16 you can see that a larger R_o will decrease reaction pressure, $q = P_o/(2*R_o)$.
- Taper the stiffness. This method prevents high shear force and high compressive force. Mainly on thin flesh compressive forces are less evenly spread, causing the 'hot spots' mentioned earlier. In shear direction it facilitates some extra movement which also helps to spread out forces, lowering strain. Using liners might increase shear stress, but with a trade-off. Shear stress increases, but compressive stress is lowered, decreasing peak values. This is reported to be more pleasant for the wearer (Bennett, 1974).
- Using elastic or cotton garment. This does partially defeat the purpose of an easy to use orthosis, since donning and doffing a second object is needed. it could decrease the friction, because cotton and standard orthosis materials have generally a lower friction coefficient then skin and the orthosis would have (Carlson, 2006). A trade-off between slipping and good stability is key. Also, at the border of the adjacent soft and hard material will be less shear force, because the garment transfers some of the forces from line A to lines B and C. Constructing the orthosis of other materials is an option. A good understanding of the places where shear forces may be highest or lowest is needed to find balance between stress and stability. There are many materials available with a known COF with cotton and a qualified material can be found for every location (e.g. Carlson, 2006).
- Using lotion or oils on skin to decrease the COF is most likely not advisable. Only when strictly donning the orthosis leads to pain this could be helpful, but in every other situation it would eventually lead to an increased COF. A well ventilated design or the knowledge that the skin should preferably be dry when the orthosis is donned is preferred.
- For above-knee amputees there have been inventions like the double socket (e.g. Koike et al., 1981) or the suspended inner socket. Two sockets between which limited slip is possible. Yet, this does not aid with donning or doffing and the hand is relatively small, so possibilities for a hand orthosis are limited.
- Try to use locations with thick layers soft tissue. Prosthetic wearers often complain of discomfort at bony prominence (Bennett, 1971). Make curved edges on deep soft tissue. A little side step is made to a more recent study revolving around surgical instruments that pinch soft tissue, in this case the Babcock grasper (De et al., 2007). Looking at fig. 18B the stress localizes beyond the border of the clamp and not directly under it, caused by shear stress as a consequence of the steep inclination of the tissue. A less steep gradient from high to low compressive forces ameliorates shear in these places. Comparing this with fig. 17 you can see that the problem is partly solved by rounding of the edge of the hard material. As a trade-off the compressive force under the hard structure starts to increase (Bennett, 1972). For this reason there is an optimum edge curvature, Bennett (1974) has found this to be 1.27 cm diameter for thick soft tissue sites (7.62 cm).

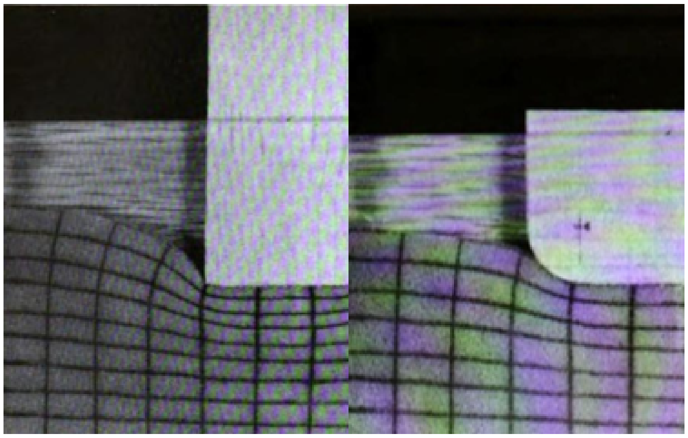

Figure 17: Shear stress comparison between a square and rounded hard object into gel, adapted from Bennett (1972).

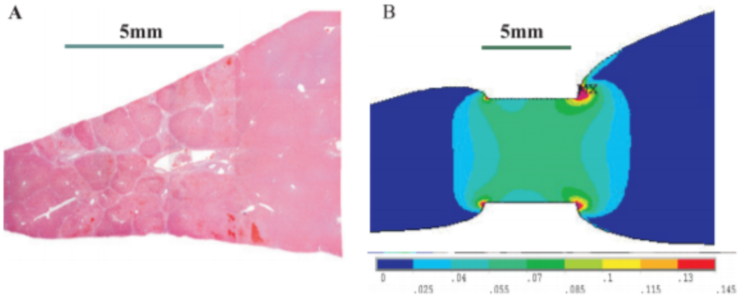

Figure 18: Real-life damage (A) and Finite Element Analysis von Mises stress (B) of tissue impingement. Adapted from De et al., 2007.

Individual requirements

The skin is an organ with inter-individual differences that determine resilience against damage. The differences include, but are not limited to, ethnicity (Rawlings, 2006), age and gender (Giacomoni et al., 2009). Even in same sex, same ethnicity women differences are significant (Meidan & Roper, 2008). This indicates the presence of more important underlying factors. The differences are present in all levels of skin, also the protective layer, the epidermis. Some properties like thickness (in # of cells) of the epidermis are thought to be important in protection, places like foot soles have a thicker epidermis than e.g. the eyelids. Skin thickness in # of cells of the epidermis differ per person (Rawlings, 2006). So every person is believed to be able to endure different levels of stress before onset of pain.

The inter-individual differences are reason to make the attachment method patient specific. We have seen that a trade-off can be made between stress levels and stability. Possibly the orthosis design can adjusted to give as much stability as possible without the patient reporting discomfort.

Discussion

For the attachment mechanisms, a list of five criteria has been made that can assess basic attachment demands. For the skin sensitivity a list of criteria has also been made. It contains rules of thumb that can determine the amount of stress an attachment mechanism will cause on the wearer's skin.

Attachment Criteria

An attachment mechanisms has to meet certain criteria to evaluate its functioning. Not all mechanisms will be fit for exoskeletons for a variety of reasons. Besides regular demands, as was discussed in the introduction, donning and doffing can ideally be performed by a DMD patient without assistance.

The following criteria are set up to identify fit from unfit mechanisms. The first three are called the primary criteria and are essential to the functioning of the orthosis and must be met. The last two (secondary criteria) are only taken into account when the initial criteria are met.

- Does not lose proper fixation or come undone during regular activities.
- Easy donning and doffing, manageable for patients with impaired movement capabilities. Benefits are e.g. donning/doffing possible without help from others, no large forces or complex movements needed, only one hand required.
- Does not obstruct normal use of orthosis.
- Weight and size of the attachment mechanism are minimal, ideally no more than a few millimeters thick, thick attachments will negatively affect haptics. Weight of the attachment mechanisms is not set to a limit since this is dependent on the weight of the orthosis. Estimated weights will be compared between mechanisms.
- Minimally affects aesthetics.

Skin criteria

Setting a maximum compressive and shear force limit could be an ideal way to grade attachment methods. This requires, besides force limits, an estimation of the forces the attachment will cause. However, as explained below, both are difficult to determine and for this reason the search for an objective limit was discarded.

In practice, the most used way to determine the onset of pain in patients is pressure algometry. A small pin, connected to a force meter, is gradually pressed against the skin of the patient until the patient reports the onset of pain. Clinically, this method is used to determine the effect of drugs, overventilation, stress or to test for fybromyalgia (Kosek et al., 1993). Pressure algometry is used because the clinician requires the most precise measurement. However, pressure algometry is a semi-objective method.

Onset of pain is perceived by the patient and this is, largely influenced by interpretation and has also proven to be very susceptible to differences like gender or body part (Melia et al., 2019). More discrepancy is added by the force distribution under the pin of the force meter. When the pin is placed over thick soft tissue, the pressure spreads mostly to the edges of the pin. Over a bony prominence it shifts to the centre. This uneven distribution makes the measurement unreliable (Melia et al., 2019).

Establishing a reliable coefficient of friction (COF) for skin is also challenging. Because skin is a living material, it changes over time and the COF changes with it. Factors that influence the COF are e.g. skin moisture. The more the skin is hydrated, the higher the COF. This relationship only goes up to a certain point, after which it will descent. On wet skin the fabric slides over the water without direct skin contact. COF's differ per material (Carlson, 2006). The inter-individual differences of skin also influence COF (Buchholz et al., 1988).

To judge skin sensitivity, the series of articles from Murphy and Bennett, 'Transferring load to flesh', is used. These together with the articles mentioned above a list of criteria concerning skin stress reduction was put together. It consists of four requirements:

- It is possible to taper the stiffness, this decreases shear and compressive forces on the skin.
- It is possible to ventilate the skin, this prevents an increase in skin COF.
- No large shear or compressive forces occur during donning and doffing.
- Personalized design possible, to suit individual skin properties. This serves to secure the orthosis as well as possible without causing discomfort for a given individual.

Conclusion

The mechanisms will be graded, given the knowledge obtained in the results and the two sets of criteria that were formed from this information. The mechanisms are assessed separately for attachment and skin criteria, because of the different nature of the criteria. In the text this is discussed in detail, consult table 1 and 2 for a summary. Finally, the mechanisms that are deemed best will be recommended for testing.

Note that from the results section 'Hooks' only Velcro is assessed. The SMP Velcro is as it is now requires temperatures above 80 ℃ for donning and doffing. Also note that hooks is only assessed in Velcro form because hooks-and-eyes is difficult since the hand does not have any eyes. And multiple hooks around the hand would start to resemble shape grip.

Table 1: Attachment assessment

	Attachment	Donning/doffing	Orthosis use	Weight & size	Aesthetics
shape grip	+	+	+	+	+
Zipper	+	+-	-	+	+-
SMA	+-	+	+	+	+
Friction	+-	-	+	+	+
Glove	+	+-	+	+	+
Bat claw	+	+-	+	+	+
Velcro	+	+	+	+	+
Magnetic	+	+-	+	+-	+
Van der Waals	-	+-	+	+	+
Suction	-	+-	-	-	-

Table 2: Skin sensitivity assessment

	Tapering stiffness	Ventilation	Shear and compression	Personalization
shape grip	+	+-	+	+
Zipper	-	-	+-	-
SMA	+	+-	+	+
Friction	+-	+	+-	+
Glove	+	-	+-	+
Bat claw	+	+	+	+
Velcro	+	+	+-	+
Magnetic	+	+-	+	+
Van der Waals	+	-	-	+-
Suction	-	-	-	-

Shape grip

As discussed in results, shape grip was one of two main categories, together with force grip. Shape grip had some examples. Namely, SMA and zipper. Shape grip as a general concept will be assessed, and the two examples as well. For all three, note that an attachment would have to be made around the wrist as well, like a handcuff, for the orthosis to have a shape grip around the hand. Donning and doffing would require inserting the hand and closing a few attachments and this would most likely stay attached well. The SMA wire design, most likely because of mechanical limitations, has not succeeded in making the fixtures close completely. To prevent the exoskeleton from slipping, the inside of the fixtures consisted of a substance with a high CoF. This goes against the skin sensitivity assessment, but the orthosis from Hasegawa & Suzuki (2015) is attached in eight places. Changing the lining when the attachments are designed stronger is a possibility.

Donning and doffing the shape grip would be easy, while the zipper might offer a slightly larger challenge and the SMA wire is expected to be very easy at temperatures above 5 °C. For the zipper, a suited place on the orthosis needs to be found, which might be difficult. Also more than one zipper would increase easiness of donning and doffing but negatively affect donning and doffing time (note that they are assessed together under 'donning and doffing' in table 1). Also note that some flexible or fabric parts need to be present. Wearing comfort might be decreased if the zipper touches skin, some fabric between might solve this problem but this can get stuck between the zipper teeth, causing difficulty for impaired patients.

The transition temperature (Tt) of 5 °C requires some caution for the SMA attachment. It restricts the possibility of orthosis donning when the fixtures are cold, since the Nitinol will be in martensitic structure which does not have superelastic properties, thus will not bend back to it's original C-shape (Hasegawa & Suzuki, 2015). Donning the exoskeleton is not impossible but would require bending the fixtures back to the C-shape with manual force or by heating. This would only cause problems when the orthosis is donned outside, not the most likely scenario, yet it might happen if the attachments are not strong enough and involuntary doffing has occurred.

A final note for zippers, they can obstruct normal orthosis use because of their limited flexibility. This is the only shape grip variant here that is expected to limit orthosis use.

Sizewise, it seems that a small design would be possible with some strategically placed attachments for either shape grip in general, as well as SMA wire and zippers. Weight can be minimal as well, aesthetics will not be a mayor issue. Yet, zippers will be larger and thus more prominent.

Tapering the stiffness will not be possible for a zipper mechanisms, but fot the air chamber from the SMA and shape grips in general it will be possible. For ventilating, the same applies, a zipper is not permeable and would be attached to a piece of cloth covering a large part of the hand. The general shape grip and the SMA wire cover only a small part of the hand. Keeping the skin dry under a plastic air chamber might be difficult in very hot weather, yet the attachments are small. No shear forces present during donning or doffing also makes this problem smaller.

The shape grips are ideal for patient skin, since their absence of shear forces during donning and doffing. The load bearing surface with the SMA superelasticity is not unnecessarily small so high compression is avoided. Besides, the low force per attachment from the SMA wire Hasegawa & Suzuki (2015) discussed is actually ideal, as long as it suffices for staying donned.

Tapering the stiffness seems possible. The air chamber from SMA wire might be suited already. Otherwise, the air chamber could require some lining.

Friction

First, the initial attachment criteria. It is possible to securely attach a screw, but screws can require large forces to tighten. A large screw head can prevent this, given that it does not interfere with using the orthosis. Note that this might also interfere with secondary criteria. A glove is also attached through friction. It connects to every part of the hand, reducing friction might be difficult. The glove cannot be fitted very tightly, attaching the orthosis to a loose glove causes problems.

The bat claw (fig. 6) can be attached firmly and can be donned without shear stress and without large compressive stress. For doffing, however, this is different if the claw is opened by pushing the claw open. Possibly a smart opening mechanism can prevent this.

Either one of the friction based mechanisms does not have to obstruct orthosis use and can be minimal in weight, size and their effect on aesthetics.

Friction on skin seems like a bad idea for the orthosis. A mechanism that needs constant friction to remain fixed would not do good for the patient. Yet, a glove does only apply so much friction on one patch of skin. More information should be known about the limits of DMD skin to answer this question. Use of garment would counteract the principle. Keeping the skin dry under spots of constant touch might be challenging on warm days. Screws would likely be small and require high forces for tightening or be big and cumbersome. Ventilation would not be a problem, same as the bat claw. Keeping the skin well ventilated is possible. Tapered stiffness and large load bearing surface can be possible. The screw, bat claw and glove mechanism would all be possible to personalize in terms of stiffness.

Hooks

Regarding the hook-and-eye mechanism, only Velcro will be discussed. As can be seen from the many articles mentioned that use velcro for orthoses the attachment is strong (e.g. Banala et al., 2006, Colombo et al., 2001, Pfurtscheller et al., 2000) and donning and doffing does not take up a significant amount of time, if donning and doffing are manageable for patients might differ between patients, a narrower piece of Velcro might make doffing somewhat easier in a trade-off to attachment strength. Because of the simplicity of the design and the elastic bands orthosis use is not affected and both weight and size are minimal so aesthetics is not influenced more than acceptable.

The elastic properties of the band might mean that tapering the stiffness is not necessary but might still be possible through adjusting bands or lining them with a low CoF material, there are no hard structures causing stress on the tissue of the hand. There will be some ventilation present but shear forces might be somewhat of a problem. Compression can be adjusted with the bands easily and because of this personalizing the design will not be necessary.

Magnetism

For an analysis of the suitability magnets will be divided into permanent magnets and electromagnets. Electromagnets require an energy source and a coil around the soft metal core. Besides, a few smaller magnets that click the orthosis attachments into place is preferred over one big magnet, creating the need for multiple electromagnets, all with their individual coil. This idea is not regarded any further.

Using permanent magnets leaves the question if it is possible to find a strength that can be detached by patients but can withstand impacts of daily life. Donning is made very easy, because the magnets pull themselves into place. Attaching the magnets to a band gives it roughly the same characteristics as the Velcro attachment, with some extra weight but easier donning.

Tapering on skin can be possible by putting the magnet at the end of a band or a rigid bar that goes around the hand. Both have possibilities to taper the stiffness as discussed above at 'shape grip' and 'Velcro'. For Ventilation and shear and compressive force the same is true. Personalizing can be done by changing the magnetic force or, again, the elastic properties of the band.

Van der Waals forces

For an orthosis it seems plausible but not ideal. Products are currently available on the market that mimic the spatulae and function of Gecko feet (fig. 12). Gecko's can produce an attaching force of 10 N·cm^{-2} (Geim et al., 2003). But even if products can match that, the question remains if that is enough force and how these delicate structures withstand repeated donning and doffing, contamination and sweating. Frequent replacement of the tape is optional but not ideal. Orthosis use is not affected and the tape does not have to be visible so aesthetics are not affected at all. The question remains if one would trust this relatively new product to hold up a piece of equipment this significantly expensive.

Considering tapering the stiffness, ideally Gecko Tape has a stiffness close to that of human tissue. Keeping the skin ventilated will most likely be an issue, even though it is claimed that water does not affect sticking performance. So, ventilated skin might be irrelevant.

Gecko Tape uses pulling and shear force during doffing if the tape is peeled of the skin. Tapering donning and doffing to the individual might be adjusting the tapes holding force per cm^2 but this is a very difficult level of customization.

Suction

Using the suction pads on the skin does not seem reasonable since skin attributes like elasticity, wrinkles and hairs make it less suitable for creating airtight seals. When the seal is broken the pressure difference will be gone. Passive pads will not regain their attachment. Active pads use energy constantly. The suction pads are likely too big to fit on a finger and might obstruct orthosis use. Even while donning and doffing could be easy, especially with active suction, there are many downsides. In conclusion, suction will not be used.

During suction tapering the stiffness is impossible. The suction cup has to have certain characteristics. Keeping the skin ventilated is is also not possible under a suction cup. The cup needs a constant high force so is not ideal for the patients skin. Adaptability per patient seems unreasonable. A certain level of suction force is needed, which will be a significantly higher force than every other option.

Recommendations

Firstly, it is recommended to examine special skin needs of DMD patients. So that concrete recommendations on skin sensitivity and attachment of orthosis can be given. Secondly, it is recommended that some research is put into the testing of different attachment mechanisms, since there is significantly little information available about this subject.

Further, to objectively assess table 1 and 2 a score is calculated. At first without the secondary attachment criteria ('Weight & size' and 'Aesthetics'), If a '+' is a score of 1, '+-' is a 0 and '-' a -1, high scores are obtained by shape grip (6), SMA (5), Bat claw (6), Velcro (6) and Magnetic (5). Including the secondary criteria adds two points to each score, except magnetic, which only gets one because of the higher weight of magnets.

The bat claw mechanisms might offer a different path of donning and doffing and experiments must show if this is preferable above the standard Velcro. About the same goes for the magnets. With relative few adjustments these two methods could be integrated into existing orthoses and I recommend these for possible simple alternatives, to examine if this can offer advantaged over Velcro. Think of less precise finger movements needed for donning and doffing or a greater possibility to customize the design for patients that experience difficulty doffing Velcro.

This leaves shape grip, SMA as a slighly different option. SMA can be a very promising solution, attachment strength is one area that needs further research, ventilation under one of the air chambers might be sub optimal, yet some fabric liner might solve this. This has the potential to solve any difficulty regarding donning and doffing, eliminates shear force during donning and doffing while enlarging the area of uncovered skin, to increase haptics and also has the possibility for personalization.

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