Design of a Compliant, Multi-Phalanx Underactuated Prosthetic Finger

MASTER OF SCIENCE THESIS

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M.W.M. Groenewegen B.Sc.
Student No.: 1308815

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Board of examiners: Prof. Dr. Ir. J.L. Herder, Delft University of Technology
Dr. Ir. S.F.J. Flipsen, Delft University of Technology
M.E. Aguirre Jr, PhD, Delft University of Technology
Ir. A.L.M. Minnoye, Delft University of Technology

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology
This thesis consists of the research I performed on designing a printable prosthetic finger. The desire was to create a design that would provide a new view on simple, and low cost alternatives for existing prosthetic fingers and industrial graspers. Robotic graspers show some amazing grasping capabilities, but their complexity, high production cost, and overall weight, inspired me to research a simplified mechanism that could equal their capabilities.

The first part of my research consisted of a literature study on identifying all the existing working principles of mechanical graspers. The second part of my research consisted of coming up with a conceptual design that would be a simplistic, yet capable mechanism. Finally, an analytical model and prototype were constructed of my final design.

I would like to thank my supervisor Just Herder for his guidance and help with brainstorming in the early stages of my research. Also, for his part on igniting my passion for trying to find mechanical solutions for everyday problems.

Finally, I would like to thank all the people who have stimulated and supported me throughout my years of study at Delft University. Of course my family, whose love and support gave me the opportunity to try and push myself to thrive at Delft in the first place. For the incredible people from all over the world I met during my internship in the United States. Especially for the handful who have actively stayed in touch since.

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Last, but certainly not least of the friends group, Maarten, Remco and Wout, who helped keep me sane during the stressful final stages of graduation research. None of us expected that the introduction of a simple card game known as Shithead, would result in a shared all-out obsession. One that resulted in a daily lunch break intermission that would turn even the most tedious and stressful workday into a memorable one.

Thank you all.
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Chapter 1

Paper: Design of a Compliant, Multi-Phalanx Underactuated Prosthetic Finger
Design of a Compliant, Multi-Phalanx Underactuated Prosthetic Finger

M.W.M. Groenewegen
Delft University of Technology
Faculty of Mechanical, Maritime and Materials Engineering, Department of BioMechanical Engineering
Mekelweg 2, 2628 CD Delft, The Netherlands
Email: marcogroen@gmail.com

Abstract—Highly advanced robotic hand prostheses are praised for their impressive grasping and pinching capabilities. Nevertheless, a high demand remains for grasping mechanisms that are cheaper to produce, easier to assemble and lower in overall maintenance. In this paper, the idea of creating a 3D printable underactuated grasper was realized to fulfill these desires. Through a literature survey on existing grasper mechanisms, a basic structure was defined of a three phalanx finger with anthropomorphic dimensions. By using a Pseudo Rigid Body model, a generation optimization analysis was conducted that resulted in a partially compliant conceptual design. This underactuated, anthropomorphic compliant finger was able to reach a fingertip trajectory of 180 degrees. A prototype based on this final design was manufactured out of flexible, high strength nylon, and experimentally evaluated to compare with the simulation model. It was found that the finger met all the set design criteria. Furthermore, despite consisting out of multiple components, no additional assembly steps are required once the design is completed in the 3D printer.

In addition, a basic 3D printable compliant hand was created to further show the feasibility of the design as a compact yet versatile low-cost, underactuated hand prosthetic.

Index Terms - 3D-printing, Anthropomorphic, Compliant, Multi-phalanx, Prosthetic, Underactuation,

I. INTRODUCTION

MIMICKING the design of a human hand or making a system that can grasp objects has already been researched on a large scale, often with different reasons in mind. Centuries ago, different kinds of cosmetically correct hand prosthetics have been invented for users to offer an upper limb replacement. Further designs showed an ideal of designing actively moving graspers to replace some of the lost finger and/or hand function [01]. More advanced versions are still being research and designed, with graspers now used in far more fields than just prosthetics. Even in the last decade the field of robotics has been designing sophisticated robotic hand prosthetics, but also do research on multi-phalanx industrial graspers that are capable of many unique grasping capabilities [02][03]. Robotic graspers, especially designed to be deployed in dangerous work environments or ones that can be used on tasks which are considered excessive laborious or too monotonous for humans.

A. Underactuated Graspers

One main difference between existing grasping mechanisms is the possibility of the grasper to adapt itself around the grasped object, without the use of an additional actuator. This automatic enclosing around objects is known as underactuation, and is widely used in graspers today. Underactuated mechanisms have more degrees of freedom than number of actuators [04]. For underactuated graspers, this means that when the finger phalanx closest to the base of the grasper is obstructed by an object, the actuated force is transferred to the next unobstructed phalanx that is nearer to the tip of the finger. This way, the object is enveloped by the entire finger, showing multiple degrees of freedom, while using only one actuator.

The adaption to various object shapes and sizes helps to increase the overall control the user has on the grasper. Existing underactuated mechanisms are primarily consisting of linkages and kinematic joints. Various unique types of mechanism have been found that can give the underactuation capability (four-bar linkage, gear systems, seesaw mechanism and pulleys). Some of the recognized disadvantages of those kinds of mechanisms are friction, backlash, overall wear, and the required fabrication plus assembly costs. Also the need for maintenance of the mechanisms (like lubrication) is an often overlooked factor.

Using underactuation to reduce the amount of actuators, usually results in decreased weight for the entire hand. Weight is recognized as a huge influence on the comfort level of prosthetic users [05]. An alarming high number of upper limb device users do not actively use their device (27%) and others stops wearing it altogether (20%). Numerous papers have been published that had labeled the desire of making the grasper lightweight as a main design criterion [06]–[11]. These were mainly for user comfort reasons, as well as more simplistic reasons, as maintenance and repair aspects. Prosthetics hands designed in the field of robotics are less common to have underactuated mechanisms. The designers are more
comfortable to achieve the best grasping capabilities through multiple actuators that are software controlled and receive feedback from sensors. Surveys taken on the users of prosthetic hands have shown the desire for prostheses that are lightweight and more durable than the existing ones. When looking at the existing collection of prosthetic hands, the ones that are the lightest are the body-powered constructions that use tendon-like wire constructions as actuation. The robotics versions are more versatile and achieve better grasping capabilities, but the added weight of multiple actuators, electronics and required battery power sources, have all been a great factor on the high level of abandonment of upper limb prosthesis users [05].

B. Compliant

A different research field that also emphasizes on simplifying and weight reduction of existing mechanisms is the field of compliant material. Compliant mechanisms can be used to transfer the actuation (i.e. force, energy, motion) through deflection of elastic material. This transfer of the actuation can either be applied to the entire part of the mechanism (distributed), or be focused only on a deliberately designed weak point to achieve a flexure hinge (lumped compliant) [12]. Mechanisms can therefore be designed to consist either completely out of compliant material (fully compliant) or only have the bendable material at the motion system part of the design (partially compliant). The advantage of a fully compliant design is that the production costs and often the overall weight of the design can be reduced significantly.

Existing, spring based linkage mechanisms can be replaced by monolithic designs that use the flexing capabilities of the material to obtain the same mechanism movement. Advantages of compliant mechanisms are cost reduction (part-count reduction, reduced assembly time, and simplified manufacturing processes) and increased performance (reducing wear, weight and maintenance demands) [12].

C. Compliant Graspers

Recognizing the possible advantages of compliant designs for underactuated multi-phalanx graspers, a literature survey was conducted to help create a clearer overview of all the existing working principle mechanisms that were created to achieve underactuation in graspers [13]. The overview showed that for all the found, distinct working principle graspers, the use of tendons as actuation was overrepresented. The same was found for linkage transmissions, despite the filtering of all similar mechanism designs.

Based on defined properties, the field of compliant materials showed some real potential when used as motion system. Yet, a significant amount of research papers mentioned a desire to construct a simple and lightweight grasper, before showing their own non-compliant design. Furthermore, papers with other types of actuation (like electric or hydraulic), defend their choice of choosing their actuation over wire-driven ones, by mentioning numerous disadvantages. The used arguments are mostly friction loss, control delay, unpredictable non-linear behavior due to the friction and the elastic element of the wire [14].

Combining the desire of lightweight, simple designs, with non-tendon actuation, the low amount of existing graspers in the compliant field could show some real potential for possible designs. At this time, only a select few compliant graspers with lumped compliant segments exists [15]-[18] and only one underactuated, fully compliant with monolithic structure and distributed compliance grasper was found [19]. This monolithic design was the inspiration to research the possibility of combining the best of these two fields. A compliant finger design that is able to achieve a greater enveloping motion than the existing compliant graspers, making it more on par with the existing mechanical designs [13].

D. Objective

The goal of this paper is to present a design of a (partial or fully) compliant, underactuated finger, one that can achieve a fingertip trajectory of at least 180 degree, which is on par with the degree of enveloping motion as the majority of existing anthropomorphic mechanical graspers.

This desired grasper must consist out of the least amount of components as possible (striving to end up with a monolithic mechanism), has little to none assembly requirements and must be conforming to the anthropomorphic design limitations/criteria’s.

E. Outline

In order to end up with a unique and capable mechanism, a conceptual design is created, based on the findings of the literature survey in both the medical sector (prosthetics, surgery grippers etc.) as well as the industrial sector. With a better understanding of the existing designs, a compliant version of a multi-phalanx grasper can be designed. A numerical analysis with a finite element method is used to design a final mock-up and test its capabilities. Finally, a prototype will be manufactured and evaluated experimentally to compare the real-life results with the values obtained through simulation.

II. DESIGN CRITERIA

The intention of this paper is to design a multi-phalanx finger that can successfully be integrated into a prosthetic hand. The finger therefore has to be designed within the anthropomorphic dimensions of the human finger. The following phalanx dimensions of a typical index finger were taken based on a paper describing the average proportions of hand segments of adult patients (without any developmental abnormalities) [20][21].

**Index finger**

- Proximal phalanx: 42.5mm
- Medial phalanx: 25.0mm
- Distal phalanx: 20.0mm
Finger thickness (otherwise mentioned as ‘width’ of the design) is set at 13.5mm at the base and an undisclosed thickness that is <13.5mm, due to the tapering nature of the human finger.

With the possibility of body powered actuation, the total force required to cover the complete motion should be less than 40N for an entire hand, which is considered the operation force comfort limit [22][23]. Dividing this comfort limit force over the fingers equally, and striving to keep the operating force as low as possible, the design criteria is set at <6N of operation force required to move the finger.

Existing grasper designs with more than two phalanxes have shown the capability of letting the fingertip reach a bending motion beyond 180 degrees. While the majority of these graspers are built with conventional pin joints hinges, the field of compliant shows methods on designing flexural hinges that can achieve the same output as their conventional counter parts. Furthermore, the majority of these compliant mechanisms can easily be manufactured by 3D printing, laser cutting or mold injection. The goal is to complete a design with the least amount of parts possible, while maintaining its movement and capabilities requirements. Furthermore, once manufactured through one of the methods mentioned previously, the additional needed assembly requirements should be kept to a minimum, as well as any added external components like screws and cables.

Summarizing, the design has to consist of the following:

- Anthropomorphic finger dimensions
- Fingertip trajectory has to be able to achieve 180 degrees
- Actuation force of less than 6N for the entire motion
- Design consisting of the least amount of components
- After fabrication, minimal assembly requirements
- No, or minimal use of additional components

III. CONCEPTUAL DESIGN

The field of compliance has three main design approaches to create compliant mechanism designs [24]: the structural optimization, building blocks approach, and the kinematic approach. With the initial design criteria already predefined, it was clear that the final product would consist of sections with large, nonlinear deflections. Furthermore, the outer dimensions were also already defined by the anthropomorphic dimensions restrictions. Due to these factors, the Pseudo Rigid Body (PRB) methodology from within the kinematic approach was deemed the most appropriate. This method defines compliant segments as rigid segments, connected by ideal joints and torsion springs [12]. The compliant materials force/deflection ratio can be approximated, while the initial design process can be simplified by only focusing on using rigid linkages and pin joints with torsion springs. Due to the anthropomorphic design restrictions, the available working dimensions quickly showed that the use of distributed compliance would result in higher chances of material buckling and unnecessary high actuation forces. Lumped compliant design that would give flexure hinges showed much more promising results.

A. Design Synthesis

With the PRB method, the focus lay on using only rigid linkages and pin joints with torsion springs. The obtained literature knowledge of existing grasper working principles resulted into an initial design of three phalanxes with normal pin joints, and an inner linkage mechanism of L-shaped beams (Fig. 1).

By horizontally pulling the actuation bar, the angled sections of the beams would transfer the horizontal movement into an angled movement, giving the medial and distal phalanx a curling fingertip trajectory. Only one paper was found that showed a grasper with a similar design construction [25]. From the literature survey on existing grasper mechanisms, no other linkage transmission designs were found that had a pulling actuation without the use of cables and/or pulleys.

Consisting out of three phalanxes, and getting a complete fingertip trajectory out of one actuator, the finger motion could be labeled underactuated. However, the entire finger motion would be blocked completely once the proximal phalanx is halted by an object. The enveloping motion of the medial and distal phalanx can only be acquired when the actuation bar is pulled vertically. Vertical displacement of the outer end of the actuation bar will curl the medial and distal phalanxes towards the base of the finger, while keeping the proximal phalanx in place.

B. Dimensional Design

With this promising concept, a dimensional design was constructed to get the mechanism within the stated design criteria. For starters, the length ratio of the phalanxes was nowhere near those of anthropomorphic dimensions. It became clear that only a few linkages had fixed lengths. The connection points between the phalanxes and inner mechanism could be varied in both location and starting angle. Same was

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Fig. 1. Cardboard prototype of PRB model (without internal springs).
possible for the pin joints locations of the inner mechanism. Equations were made to obtain the movement of each individual phalanx, based on the displacement of the main actuation bar (Appendix B).

A design was constructed in Matlab, to obtain an optimized form of the PRB model, abiding to the stated dimension criteria, and assuring that it could reach the required fingertip trajectory (Fig. 2).

C. Flexure Hinges

Replacing the pin joints between the rigid bodies by flexure hinges, will give a compliant mechanism that is consisting out of the least amount of assembly parts. Flexure hinges can transfer motion and force by plastic deformation of flexible elements. Ideal flexure hinges usually consist of materials that have high stress limits, high endurance and low flexibility loss over time. Material properties like these can be found in metals, and applications with flexure hinges often are constructed with stainless steel or bronze [26]. The downside of using metal is their relative small level of strain, making them primarily useful for small deformation only.

When placing a flexure hinge in a mechanism, there are three main properties to keep in check: stiffness, deflection and strength. The first two are self-explanatory, and strength stands for the property of the material that specifies the stress it can withstand before failure [12].

Calculations and results from the optimization showed that the obtained design primarily needed large deformations. Deflection $\delta$ depends on both material properties and beam dimensions,

$$\delta = \frac{F \cdot L^3}{3 \cdot E \cdot I}, \quad I = \frac{b \cdot h^3}{12}$$

$$\delta = 4 \cdot \frac{F}{E} \cdot \frac{L^3}{b \cdot h^3}$$

with $L$ the total length of the beam, $b$ and $h$ the height and width (or thickness), $E$ the Young modulus of the material (modulus of elasticity) and $I$ the cross-sectional moment of inertia.

The main challenge of compliant mechanism is to allow deflections large enough for the mechanism to perform its function, while maintaining stresses below an allowable maximum stress [12],

$$\sigma_{\text{max}} = \frac{3 \cdot 6 \cdot F \cdot c}{L^2} = \frac{6 \cdot F \cdot L}{b \cdot h^3}, \quad c = \frac{h}{2}$$

with $c$ the location farthest from the neutral axis, where the maximum stress occurs.

The longer the beam, the more distributed the stresses are on the material, allowing a greater deflection. Furthermore, flexibility is highly dependent on beam thickness. Cutting the beam thickness in half would increase the beam deflection by a factor of 8 when applying the same load. Maximum deflection the beam will undergo before failure is therefore

$$\delta_{\text{max}} = \frac{2 \cdot \sigma_{\text{max}} \cdot L^2}{3 \cdot E \cdot h}$$

showing that the maximum deflection depends on both geometry $(L^2/h)$ and material properties $(\sigma_{\text{max}}/E)$.

The set design criteria showed that the flexure hinges for this PRB model would only have a very limited length (especially the ones for the inner linkage mechanism). Furthermore, the minimal thickness of the beams would depend on the manufacturing method, with its minimal wall thickness requirements.

A small literature research was started, trying to find the most promising construction method (3D printing, laser cutting, mold injection etc.), with the best possible material (adequate flexibility with high yield strength). Appendix C shows that flexible, high strength nylon had the best yield strength to flexibility ratio. This type of material can be used for 3D printing fabrication.

IV. OPTIMIZATION

To successfully analyze the maximum fingertip trajectory, while staying below the maximum stress level, a numerical analysis was executed with a finite element method (FEM). With the FEM analysis, the PRB model will be redefined with flexure hinges and optimized towards a final conceptual design.

Fig. 2. Optimized PRB model for ideal fingertip trajectory within stated dimension criteria.
A. Finite Element Analysis

For the FEM analysis, the commercially available program ANSYS v14.5 was used. The PRB model obtained from the Matlab optimization was built in ANSYS, but now with flexure hinges instead of pin joints. A special correlation code was written between ANSYS and Matlab, optimizing the key points locations of the linkages and the behavior of the non-linear flexure hinges, based on a set wall thickness and material properties. A single simulation in ANSYS would actuate the finger by displacing the outer end of the actuation bar with a fixed (horizontal) displacement. The obtained fingertip trajectory, non-linear stresses on the nodes and required actuation force were all collected and fed into the Matlab optimization code. A generation optimization was used, to vary the key point locations. Only the key point locations of the main pivot, the fingertip and the outer end of the actuation bar remained the same. All the remaining key points were given a random displacement variation of maximal 3mm radius from the main starting positions (Fig. 3).

These randomized new key point positions were fed again into ANSYS, running a multi generation cycle to obtain the ideal set of key point locations within the set design criteria. The fitness values priority lay in the following descending order of importance: The rotational z of the fingertip node (giving the total fingertip trajectory), maximal stresses within the material and required actuation force on the actuation bar. By giving the fingertip trajectory the main optimization priority, the optimization simulation would result in a design with maximal deflection motion, while the other fitness values kept the stress levels and required actuation force as low as possible.

After numerous iterations, a few difficulties became apparent. With the minimal thickness set at 0.75mm (3D printer fabrication limitation), the only available method to keep the flexure hinges below the maximum stress limit, was by increasing their total length. Within the confinements of an average human finger, not every rigid linkage and flexure hinge could be elongated to such extent. Furthermore, the ones that could be elongated gave rise to another difficulty. The flexure hinge would be reshaped into an S-shape, pulling the next phalanx or inner linkage horizontally, rather than vertical to get the desired bending motion at the middle of the flexure hinge.

Despite a renewed research of possible other base material with better yield to flexibility ratios, none could be found that would suffice. Also a research was conducted on using another shape than the used arc-shape, in the hope of finding one that would be stiff in horizontal displacement, but flexible for bending motion. Again, the only promising ones had to be discarded due to limited working space possibilities.

The decision was made to abandon the monolithic structure idea and revert to using more than just a single part. All inner linkage flexure hinges had to cope with the greatest inner stresses, thus they were reverted back to pin joints. The phalanx hinges could remain flexure hinges, giving the entire mechanism still the torsion spring behavior to revert back to its original state once the actuator force was removed.

The manufacturer of the nylon showed that 3D printing of multiple parts was possible, as long as there was a clearance between the parts of at least 0.5mm. Separate calculations were made to ensure that the minimal diameter of the pin joints would be able to cope with the applied forces. From these findings, an adjusted ANSYS model was created, where the inner linkage flexure hinges were replaced by pin joints. The optimization process was repeated for the key points to end up with the final optimized ANSYS design (Fig. 4).
V. PROTOTYPE

With Shapeways’ SLS printer (EOS Formiga P100 SLS machine), a 3D model was fabricated, to confirm the results achieved in the ANSYS simulation. The decision was made to let the finger have a starting position of 3/10 of the total bending motion. In line with the desire to create an anthropomorphic design, it was recognized that the majority of prosthetic hand fingers are built in a rest state of slightly bended posture in order to give a more life-like appearance. The desired end state is kept the same, letting the top of the distal phalanx reach a horizontal, upside down position. For clarity reasons, the remainder of this paper will continue to refer to this end state as the 180 degree fingertip trajectory. With the information acquired from the fabricator Shapeways, it became clear that it was possible to print a multiple part mechanism in one setting, with all the components already in their desired position. The design would involve no additional assembly requirements and would immediately be functional once the print session was completed.

The mechanism was altered to such extent, that the three separate parts of the inner linkage mechanism would be enclosed by the main monolithic phalanx part. This increased the overall robustness of the design greatly, while only sacrificing the possibility of being able to replace the inner linkage mechanism parts. Due to the cheap printing costs and no additional assembly requirements, it was deemed that it is more time and cost efficient to replace a whole finger, rather than one part (Fig. 5). The total weight of the printed prosthetic finger was a mere 3 gram.

A. Alterations for 3D Design

The obtained simulation model showed primarily the 2D aspects of the final design. Some aspects of them could not be transferred to the 3D model and had to be adjusted.

The inner linkages were designed as straight, rigid bars. Their final bending state, combined with a height set at 4mm, meant that the linkages would overlap. Rather than placing the linkages on top of each other, the decision was made to interlock the pin joints key points. This was preferable for both inner moment forces as making it easier to keep the overall thickness of the finger minimal. The overlapping linkages could be avoided by curving their outer ends (Fig. 6, Table 1).

As an addition, the curves were set in such a way, that the inner linkages would act as a contact aided stopping mechanism. The finger bending motion would be blocked before the maximum stresses on the phalanx flexure hinges are reached.

B. Experimental evaluation

With a fabrication accuracy of ±0.15mm, the prototype ended up to have a slightly thicker wall thickness at the phalanx flexure hinges. Despite this small deviation, the prototype acted quite similar to the simulation model.

The goal of the prototyping was to determine if the design would reach the 180 degree fingertip trajectory without buckling, and how much force was required to reach this end state.

<table>
<thead>
<tr>
<th>Key point</th>
<th>Location (X,Y) [mm]</th>
<th>Key point</th>
<th>Location (X,Y) [mm]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>(0.000, 13.500)</td>
<td>10</td>
<td>(20.000, 1.871)</td>
</tr>
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</tr>
</tbody>
</table>

Table 1: Key point Location

Fig. 5. First prototype, obtaining 180 degree fingertip trajectory with one horizontal pull of 10mm

Fig. 6. Cross-sectional view displaying curved inner linkages.
- Side view of interlocking pin joints.
A linear actuator was used to pull the actuation bar with a constant velocity of 1 mm per second. The total displacement of 10 mm was the same as was modeled in ANSYS. A Futek LSB200 force sensor with a range of 10 lb was used to measure the required actuation forces of reaching the 180 degree fingertip trajectory (Fig. 7).

C. Results

The experiment with the prototype was executed 12 times, with a sampling frequency of 20 Hz. The data of these executions were combined into a single data set, using a fourth order polynomial fit to remove noise.

The force-displacement curves are shown in figure 8. The actuation bar is pulled for 10 mm, where the fingertip trajectory reaches the desired 180 degree end-state in both the ANSYS FEM analysis, as with the prototype. A total actuation force of roughly 1.6 N was required to obtain this curling motion. Increasing the actuation force to 5.0 N, while blocking the grasper’s flexing motion halfway, resulted in pinch forces of roughly 2.5 N for the proximal phalanx, 1.2 N for the medial, and 0.7 N for the distal phalanx.

The complete fingertip trajectory behavior of the prototype was as stated in the criteria. No buckling occurred on the flexure hinges at the maximal curled orientation. The total required actuation force was also well within the primarily set criteria.

VI. DISCUSSION

As highlighted earlier in section III.A. Design Synthesis, it became apparent that the finger was working adequate as an underactuated mechanism, but was not an underactuated grasper in the truest sense of the word. The research field of underactuated graspers usually pictures underactuation as more than just having a mechanism with more degrees of freedom than actuators. A true underactuated grasper would envelop itself around an object when the flexing motion is activated with the main actuator. The design in this paper focused only on pulling the outer end of the actuation bar in a horizontal displacement. Once the proximal phalanx is blocked by an object, the actuation bar can no longer be pulled horizontally, keeping the medial and distal phalanx in place as well. In order to get a true adaptive motion, a separate vertical displacement of the actuation bar’s outer end is needed when the proximal phalanx makes contact with an object, thus requiring a second actuator.

A. Tilting Mechanism

The design in this paper is technically still underactuated, because with the three phalanges, a total of three degrees of freedom can be achieved with one or two actuators. To end up with the desired true underactuated grasper, some kind of indicator that could register when the horizontal displacement needs to be converted into a vertical one was necessary. Staying within the design philosophy of only using printable material and no additional components like electrical sensors, the only available alternative method was to design some kind of a switch mechanism that can be placed between the outer end of the actuation bar and the horizontal displacement actuator. One that could transform the horizontal pull into a vertical displacement for the actuator bar once the proximal phalanx was halted by an object.

A literature survey about compliant switch mechanisms resulted in the same difficulties that were encountered during the initial grasper design, namely the high stresses in the material and limited working space (Appendix E). In order to make the finger feasible for prosthetic hands, this tilting mechanism should fit within the confinements of an average hand [20][21]. The Matlab PRB model (Fig. 2) already showed that the actuation bar had to be tilted to roughly a 45 degree angle to give the distal phalanx a 90 degree fingertip trajectory. The outer end of the actuation bar would stick completely outside the human palm dimensions. A simple solution would be shortening the bar, but the moment force...
required to get the bending motion from a short lever would increase tremendously.

Abandoning the switch mechanism as a separate mechanism, the realization came that compliant stiffness could be used as threshold value. Letting the actuation bar start at an upward tilted angle, tilting it downwards to a horizontal level would give the same vertical displacement, while staying more within the assigned working space. It would also be fundamental to only let the vertical displacement commence when a horizontal force value threshold was exceeded. With only a pin joint and no torsion spring as threshold, the vertical displacement would even commence earlier than the bending motion of the finger. In other words, the elongation of total horizontal length of the actuation bar would actually push the base of finger to the left, instead of pulling the actuation bar and thus moving the pin joint to the right. When replacing this pin joint by a flexure hinge, a threshold value is needed of somewhere around the total force required to reach the entire fingertip trajectory. A lower threshold value is also possible, because the final stages of the bending motion are primarily the outer phalanxes.

The obtained tilting mechanism succeeded in giving a true underactuated aspect, although the size limitations of the hand kept the distal phalanx bending motion below 90 degrees. For this paper, the tilting mechanism is therefore mentioned as part of discussion, rather than being part of the main design criteria. The obtained results were deemed acceptable, but not optimized to function on such a scale that it could be part of the main design.

After receiving and testing the first prototype, minor adjustments were needed to improve performance. This first version was built with only the bare essentials, and as open as possible to adequately show the inner workings. For the final design, a more cosmetically appealing version was constructed (Fig. 10). While retaining all the mechanical properties, the design showed less of the inner workings and was closer to resembling a human finger. This final design was built to show the capabilities of 3D printing as alternative to using a commercially used prosthetic glove for the 3D printed fingers. Adding a glove to the skeletal version of the finger would require additional research on how the flexibility properties of the material would influence performance (higher required actuation force, possible friction on components, hindering fingertip trajectory).

### B. Prosthetic Hand Feasibility

With all the criteria set at anthropomorphic hand dimensions, it was deemed enlightening to conduct a proof of concept build by creating an entire 3D printed hand prosthesis (Fig. 11). One that was created with the same design criteria as set for the finger, thus anthropomorphic dimensions and no additional materials were allowed such as screws and cables. By keeping within these anthropomorphic dimensions, the design would most clearly demonstrate the limitations that were experienced, due to the set design criteria. It would also show that the constructed index finger design could easily be altered to different finger lengths. The constructed hand would show the feasibility of designing a complete lightweight, body-powered hand prosthesis, which can be customized to the users’ hand dimensions (ranging from child to adult-size prostheses) and can be completely fabricated by a 3D-printer (Appendix F).

Ensuring that the hand would be capable of perfect grasping and pinching capabilities was considered to excessive for this research paper alone. The main focus lay on designing and building a simple hand as a proof of feasibility.

The only additional design goals that were set, was that the fingers should easily be replaceable in the hand, and that the hand would have a certain degree of differential force distribution between the fingers. This last goal was desired to adequate demonstrate the difference between pinch and power.
grasping during demonstrations. If one finger was halted by an object, the rest of them should continue their bending motion. For the differential, a rough adaption of Gosselin's 15 DoF hand [27] was used.

The finished product was a functioning 3D printed nylon prosthetic hand with a total mass of only 71 gram. A separate, detachable handle bar construction was designed to facilitate an easier grasping actuation. Including this handle bar construction, the weight of the complete design is now 112 gram (Fig. 12-16).

VII. CONCLUSION

This paper presented a design where for the first time a fingertip trajectory of 180 degree is reached with a three phalanx, partially compliant underactuated grasper. Fabricated entirely out of nylon, the total weight of the design was only 3 gram. The obtained grasper was constructed with the dimensions of an average index finger, and can be scaled to different finger lengths.

As a proof of concept, a complete lightweight hand prosthesis was constructed, one that is completely fabricated with a SLS 3D printer, and has minimal assembly requirements. The prosthesis shows reasonable grasping capabilities, for only a fraction of the fabrication and material costs of alternative prostheses.

ACKNOWLEDGMENT

The author would like to thank Prof. Just Herder for his help and guidance over the course of this research. A special thanks goes to ir. Wout Ypma for his tremendous help and assistance on getting the ANSYS programming code running properly.

REFERENCES


Appendix A: Conceptual Design

Underactuated grippers are considered a desirable alternative to complex robotic hand prostheses. Lightweight and less complex versions of multi-phalanx grippers can be more appreciated by upper limb replacement users for carrying comfort and maintenance [01]. Furthermore, the use of body powered prosthetics shows additional controller feedback benefits for the user. The harness system of a body powered hand offers proprioceptive force and position feedback to the user [02].

A literature study on categorizing existing non-electronic mechanisms for underactuated grasper was conducted, and it became apparent that only three main mechanisms were primarily used. Tendon based, cylinder based (hydraulic or pneumatic) and linkage transmission.

All three mechanisms have had multiple adaptations (also outside the field of prosthetics) claiming beneficiary over other systems on different aspects. For the tendons, concerns on the wear and tear of the cable, elasticity and possible run off were often mentioned. The cylinder based mechanisms required complex manufacturing methods and was more prone to failure (leakage, strict dimensions tolerances). Linkage transmission tended to be bulkier designs, when compared to tendon based mechanisms, and are experiencing more friction when compared to hydraulics.

One overarching aspect that the majority of grasper were striving for was to reduce the overall mass of the grasper to increase the comfort of the user [01]-[03]. An ideal design would thus consist of a simple, easy to fabricate design, while keeping within the anthropomorphic dimensions of a prosthetic hand.

One aspect that came apparent during the literature survey was that the tendon grasper was based on a pulling actuation force, while the cylinders and linkage transmissions were relying on a pushing actuation force. The tendon grasper are slim in design, but less beneficiary due to their cable, while the linkage transmission are usually bulkier but still considered adequate due simplicity of the design and fabrication methods. A linkage transmission that could mimic the cable-pulley mechanism would have the beneficial aspect of both mechanisms.
The realization came that the main principle of tendon and pulleys, was that the actuation force per phalanx is directed inwardly into the phalanx of the grasper itself. The first phalanx is flexing (curling towards the palm) due to pulling on a rigid linkage that is attached on the lower half of the phalanx. To make the second phalanx flex in respect to the first phalanx, the outer tip of the initial pulling rigid linkage should be rotated inwards. By constructing the linkage mechanisms as L-shaped beams, a moment arm is constructed. Rotating the L-shaped linkages around their connection point with the phalanx, an inward moment supplies the inward pulling motion for the next phalanx. Through reverse engineering, a 2D prototype could easily be constructed from cardboard pieces. With phalanges in a flexed position as starting point, the length and curve of the L-shaped beam could easily be found through rough estimation and trial-and-error.

Only one paper was found that showed a grasper with similar design construction [05]. From the literature survey on existing grasper mechanisms, no other linkage transmission designs were found that had a pulling actuation without the use of cables and/or pulleys.

The length ratios of the phalanges differed from the actual anthropomorphic dimensions, in both the Dechev design [05], as the self-made cardboard prototype. Converting them to the design criteria dimensions made the linkage mechanisms fail to actuate three phalanges. Both designs had in common that the connection points between the inner linkage mechanism and the phalanges were all fixed on the same horizontal line. By making these values variable, equations could be constructed that would give the key points of a working inner linkage mechanism, when the phalanx lengths and linkage lengths were given a fixed value. The same was used to define the specific angle that each phalanx would make, in respect to the previous one, based on the pull and/or tilt of the actuation bar [Appendix B]. The finished equations could be used to calculate each key point’s exact location after actuation, and what each phalanx flex angle was, all with only the link lengths as fixed values.

The resulted design was a construction that obliged to the design criteria, but was only a single solution, where numerous key point collections would result in similar results. As discussed in the paper itself, all key point locations we varied in a small amount through optimization, in order to obtain an improved mechanism.

Appendix B: Key Points Determination

Calculations that were made to define the specific angle that each phalanx makes during the flexing motion. The precise location of the key points would give an insight on how much flexing each phalanx would make, in respect to the previous one, based on the pull and/or tilt of the actuation bar. The finished equations could be used to calculate each key point’s exact location, purely based on the applied actuation. The angle per phalanx in respect to the previous (alpha for proximal, beta for medial and gamma for distal) were determined, based on the findings of the cardboard prototype.

Four scrapbook pages

1. Proximal phalanx, alpha angle
2. Medial phalanx, beta angle
3. Distal phalanx, gamma angle
4. Summarizing all obtained equations for Matlab programming code
Thesis MSc

Angle determination Pseudo Rigid Body Model

Getting $\alpha, \beta, \gamma$ from fixed link lengths

Freudenstein equation

$R_1 = L/4, R_2 = L/8, R_3 = (L+\frac{a^2+b^2}{2})/2.80$

$\alpha = \cos^{-1}\left(\frac{a^2+b^2-c^2}{2ab}\right)$

$\beta = \sin^{-1}\left(\frac{c^2-a^2-b^2}{2ab}\right)$

$\gamma = \cos^{-1}\left(\frac{a^2-b^2-c^2}{2ac}\right)$

PP1: 85

PP2: 79.058

PP3: 26.958

PP4: 65

LiP1: 90

LiP2: (45, 120)

LiP3: (25, 120)

LiP4: (30, 120)

LiP5: (45, 120)

LiP6: (30, 120)

LiP7: (45, 120)

LiP8: (30, 120)

LiP9: (45, 120)

LiP10: (30, 120)

LiP11: (45, 120)

LiP12: (30, 120)

LiP13: (45, 120)

LiP14: (30, 120)

LiP15: (45, 120)

LiP16: (30, 120)

LiP17: (45, 120)

LiP18: (30, 120)
\[ \text{Pnd} = \text{Pnd}_2 \times \cos(a) \]
\[ \text{Pnd}_2 = \text{Pnd} \times \frac{\cos(a)}{\cos(a_2)} \]

\[ \text{L} = \text{L}_2 - \text{L}_1 \]
\[ \text{Dist} = \text{Dist} + \text{L} \times \cos(\theta) \]
\[ \text{Dist} = \text{Dist} + \text{L} \times \sin(\theta) \]

\[ \text{Dist} = \begin{cases} \text{Dist} + \text{L} \times \cos(\theta) & \text{if} \quad \text{L} \times \cos(\theta) > 0 \\ \text{Dist} & \text{otherwise} \end{cases} \]
## Appendix C: Fabrication Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus [GPa]</th>
<th>Poisson’s ratio [-]</th>
<th>Yield strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (1095 Spring Steel)</td>
<td>206.8</td>
<td>0.33</td>
<td>413-517</td>
</tr>
<tr>
<td>Aluminum alloy (7075-T6)</td>
<td>71.7</td>
<td>0.33</td>
<td>434-503</td>
</tr>
<tr>
<td>ABS Plastic (Acrylonitril-Butadien-Styreen)</td>
<td>2.48</td>
<td>0.35</td>
<td>34.45</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.5</td>
<td>0.45</td>
<td>12-43</td>
</tr>
<tr>
<td>HDPE (Polyethylene High Density)</td>
<td>0.8</td>
<td>0.5</td>
<td>26-33</td>
</tr>
<tr>
<td>LDPE (Polyethylene Low Density)</td>
<td>0.3</td>
<td>0.49</td>
<td>15-20</td>
</tr>
<tr>
<td>PET (Polyethylene Terephthalate)</td>
<td>2.3</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Taulman618 Nylon</td>
<td>3</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>PA2200 Nylon plastic (Polyamide 2200)</td>
<td>1.7</td>
<td>0.35</td>
<td>48</td>
</tr>
</tbody>
</table>

http://reprap.org/wiki/Printing_Material_Suppliers  
http://taulman3d.com/618-features.html  
Appendix D: ANSYS Programming

D-1: Programming code used for the Generation Optimization cycle between ANSYS and Matlab.

Optimization_Code.m

```matlab
clear all
close all
clc

tic
%% Optimization code
Var = 30;
Gen = 10;
lb = ones(1,Var) * -pi;
ub = ones(1,Var) * pi;
options_ga = gaoptimset(@ga);
options_ga = gaoptimset('PlotFcns',{@gaplotbestf,@gaplotrange}, 'TimeLimit',300,'Generations',Gen)
[x,fval,exitflag,output] = ga(@objective_function,Var,[],[],[],[],lb,ub,[],options_ga);
toc
```

objective_function.m

```matlab
function result = objective_function(Pos)

Execute_ansys(Pos)
result = Retrieve_Result;
end
```

Retrieve_Result.m

```matlab
function result = Retrieve_Result

%% read results
filetoRead = ['FEA_Result','.txt'];

%%
out=dlmread(filetoRead,',',1,0);
Input_Angle = out(:,1);
Output_Angle = out(:,2);
Stress = out(:,3);

ratio1 = Input_Angle(end)/Output_Angle(end);
ratio = ratio1/abs(Stress(end));
result = abs([ratio,Stress(end)]);
drawnow
```
function Execute_ansys(Pos)

vars = {'FINISH', 'CLEAR', 'OUTPUT', '! ADJUSTABLE parameters '}
horzcat('*SET,Alpha1,' , num2str(Pos(1)))
horzcat('*SET,Alpha2,' , num2str(Pos(2)))
horzcat('*SET,Alpha3,' , num2str(Pos(3)))
horzcat('*SET,Alpha4,' , num2str(Pos(4)))
horzcat('*SET,Alpha5,' , num2str(Pos(5)))
horzcat('*SET,Alpha6,' , num2str(Pos(6)))
horzcat('*SET,Alpha7,' , num2str(Pos(7)))
horzcat('*SET,Alpha8,' , num2str(Pos(8)))
horzcat('*SET,Alpha9,' , num2str(Pos(9)))
horzcat('*SET,Alpha10,' , num2str(Pos(10)))
horzcat('*SET,Alpha11,' , num2str(Pos(11)))
horzcat('*SET,Alpha12,' , num2str(Pos(12)))
horzcat('*SET,Alpha13,' , num2str(Pos(13)))
horzcat('*SET,Alpha14,' , num2str(Pos(14)))
horzcat('*SET,Alpha15,' , num2str(Pos(15)))
horzcat('*SET,Alpha16,' , num2str(Pos(16)))
horzcat('*SET,Alpha17,' , num2str(Pos(17)))
horzcat('*SET,Alpha18,' , num2str(Pos(18)))
horzcat('*SET,Alpha19,' , num2str(Pos(19)))
horzcat('*SET,Alpha20,' , num2str(Pos(20)))
horzcat('*SET,Alpha21,' , num2str(Pos(21)))
horzcat('*SET,Alpha22,' , num2str(Pos(22)))
horzcat('*SET,Alpha23,' , num2str(Pos(23)))
horzcat('*SET,Alpha24,' , num2str(Pos(24)))
horzcat('*SET,Alpha25,' , num2str(Pos(25)))
horzcat('*SET,Alpha26,' , num2str(Pos(26)))
horzcat('*SET,Alpha27,' , num2str(Pos(27)))
horzcat('*SET,Alpha28,' , num2str(Pos(28)))
horzcat('*SET,Alpha29,' , num2str(Pos(29)))
horzcat('*SET,Alpha30,' , num2str(Pos(30)))
  % horzcat('*SET,Alpha31,' , num2str(Pos(31)))
  % horzcat('*SET,Alpha32,' , num2str(Pos(32)))

  fid = fopen('Code_Vars.txt', 'w');
  for i=1:length(vars)
    fprintf(fid,'%s\n', vars{i});
  end
  fclose(fid);

  % combine vars+geometry
  system('copy Code_Vars.txt+Code_Fixed.txt CompleteAnsys.txt');

  % execute ansys
  if exist('Quad8.lock', 'file')
    delete('Quad8.lock')
  end

dos(' "D:\Program Files\ANSYS Inc\v145\ansys\bin\winx64\ANSYS145.exe" -b -j Quad8 -dir "D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys9" -i "D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys9\CompleteAnsys.txt" -o "D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys9\output.out"');
## D-2: ANSYS Results

List of maximum stresses and actuation force.

### PRINT SUMMED NODAL LOADS

***** POST1 SUMMED TOTAL NODAL LOADS LISTING *****

<table>
<thead>
<tr>
<th>NODE</th>
<th>FX</th>
<th>FY</th>
<th>FZ</th>
<th>MX</th>
<th>MY</th>
<th>MZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.3997</td>
<td>-0.35051</td>
<td>0.57806E-15</td>
<td>-0.11098E-15</td>
<td>29731E-16</td>
<td>0.31706E-08</td>
</tr>
<tr>
<td>2</td>
<td>-0.25772E-03</td>
<td>-0.34214E-04</td>
<td>0.57760E-16</td>
<td>-0.9762E-18</td>
<td>0.90323E-18</td>
<td>0.31058E-08</td>
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<tr>
<td>3</td>
<td>0.76372E-07</td>
<td>0.20263E-08</td>
<td>0.10194E-17</td>
<td>0.70940E-18</td>
<td>0.21498E-16</td>
<td>0.21498E-08</td>
</tr>
<tr>
<td>4</td>
<td>-0.63885E-07</td>
<td>0.19909E-07</td>
<td>0.56826E-18</td>
<td>0.97662E-18</td>
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<td>0.21498E-08</td>
</tr>
<tr>
<td>5</td>
<td>0.11916E-03</td>
<td>0.35258E-03</td>
<td>0.42556E-19</td>
<td>0.58714E-18</td>
<td>0.90323E-18</td>
<td>0.21498E-08</td>
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<tr>
<td>6</td>
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<td>-0.71648E-07</td>
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<td>0.88217E-18</td>
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<td>0.21498E-08</td>
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<tr>
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<td>0.92195E-18</td>
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<tr>
<td>8</td>
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</tr>
<tr>
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<td>0.94476E-18</td>
<td>0.90323E-18</td>
<td>0.21498E-08</td>
</tr>
</tbody>
</table>

**TOTAL VALUES**

| VALUE | 0.21457E-08 | 0.35217E-10 | 0.19722E-29 | 0.48339E-16 | 0.74521E-16 | 0.34021E-06 |

### PRINT ELEMENT TABLE ITEMS PER ELEMENT

***** POST1 ELEMENT TABLE LISTING *****

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<thead>
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<tr>
<td>108</td>
<td>0.43081E+08</td>
</tr>
</tbody>
</table>

**MINIMUM VALUES**

| ELEM | 301 |
| VALUE | 0.0000 |

**MAXIMUM VALUES**

| ELEM | 82  |
| VALUE | 0.48374E+08 |
Plot of total displacement and graph of actuation force over displacement.
Element table plot of stresses in design
List of maximum stresses and actuation force for adjusted starting position.

**PRINT SUMMED NODAL LOADS**

***** POST1 SUMMED TOTAL NODAL LOADS LISTING *****

LOAD STEP= 1 SUBSTEP= 24
TIME= 1.0000 LOAD CASE= 0

THE FOLLOWING X, Y, Z SOLUTIONS ARE IN THE GLOBAL COORDINATE SYSTEM

<table>
<thead>
<tr>
<th>NODE</th>
<th>FX</th>
<th>FY</th>
<th>FZ</th>
<th>MX</th>
<th>MY</th>
<th>MZ</th>
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</thead>
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<td>0.46711E-18</td>
<td>0.25584E-09</td>
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<tr>
<td>4</td>
<td>0.10604E-07</td>
<td>0.76068E-08</td>
<td>0.5884E-18</td>
<td>0.6974E-18</td>
<td>0.70045E-18</td>
<td>0.25584E-09</td>
</tr>
<tr>
<td>5</td>
<td>0.88081E-08</td>
<td>0.33932E-08</td>
<td>0.38510E-18</td>
<td>0.91859E-18</td>
<td>0.93483E-18</td>
<td>0.25585E-09</td>
</tr>
<tr>
<td>6</td>
<td>-0.28146E-07</td>
<td>0.14309E-07</td>
<td>0.11612E-17</td>
<td>0.51704E-18</td>
<td>0.52419E-18</td>
<td>0.25586E-09</td>
</tr>
<tr>
<td>7</td>
<td>0.38384E-04</td>
<td>0.89367E-04</td>
<td>0.25064E-16</td>
<td>0.69928E-18</td>
<td>0.33203E-18</td>
<td>0.44005E-10</td>
</tr>
<tr>
<td>8</td>
<td>-0.71043E-08</td>
<td>0.10901E-06</td>
<td>0.18313E-18</td>
<td>0.53484E-18</td>
<td>0.58601E-18</td>
<td>0.25586E-09</td>
</tr>
<tr>
<td>9</td>
<td>0.63597E-07</td>
<td>0.10901E-06</td>
<td>0.13813E-18</td>
<td>0.6561E-18</td>
<td>0.43931E-09</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.11959E-06</td>
<td>0.2321E-06</td>
<td>0.8565E-18</td>
<td>0.72942E-18</td>
<td>0.43219E-09</td>
<td></td>
</tr>
</tbody>
</table>

...  
126 0.33034E-06 | 0.41669E-07 | 0.11935E-18 | 0.54766E-18 | 0.17298E-18 | 0.40326E-10  
127 0.11422E-05 | 0.18539E-06 | 0.17160E-16 | 0.90551E-18 | 0.46737E-18 | 0.2117E-10  
128 0.19104E-05 | 0.48697E-06 | 0.2319E-16 | 0.9081E-18 | 0.71851E-18 | 0.2801E-11  
129 0.25827E-05 | 0.96621E-06 | 0.31531E-16 | 0.91380E-18 | 0.93193E-18 | 0.27422E-10  
130 0.3105E-05 | 0.15593E-05 | 0.39969E-16 | 0.87050E-18 | 0.11003E-17 | 0.48280E-10  
131 0.34536E-05 | 0.22404E-05 | 0.44103E-16 | 0.99320E-18 | 0.12599E-17 | 0.61370E-10  
132 0.3581E-05 | 0.26633E-05 | 0.46127E-16 | 0.30603E-18 | 0.13631E-17 | 0.65672E-10  
133 0.34737E-05 | 0.36752E-05 | 0.46287E-16 | 0.27430E-17 | 0.14260E-17 | 0.53661E-10  
134 0.31270E-05 | 0.43204E-05 | 0.44834E-16 | 0.23811E-17 | 0.14465E-17 | 0.31678E-10  
135 0.25502E-05 | 0.48421E-05 | 0.3940E-16 | 0.9337E-18 | 0.16380E-17 | 0.10251E-12  
136 0.17688E-05 | 0.5187E-05 | 0.2881E-16 | 0.24126E-17 | 0.20212E-17 | 0.36712E-10  

**PRINT ELEMENT TABLE ITEMS PER ELEMENT**

***** POST1 ELEMENT TABLE LISTING *****

<table>
<thead>
<tr>
<th>STAT</th>
<th>CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEM</td>
<td>STRESS</td>
</tr>
<tr>
<td>103</td>
<td>0.35918E+08</td>
</tr>
<tr>
<td>102</td>
<td>0.3492E+08</td>
</tr>
<tr>
<td>104</td>
<td>0.34628E+08</td>
</tr>
<tr>
<td>101</td>
<td>0.34658E+08</td>
</tr>
<tr>
<td>100</td>
<td>0.34393E+08</td>
</tr>
<tr>
<td>106</td>
<td>0.33718E+08</td>
</tr>
<tr>
<td>99</td>
<td>0.33228E+08</td>
</tr>
<tr>
<td>107</td>
<td>0.32809E+08</td>
</tr>
<tr>
<td>69</td>
<td>0.16335E-23</td>
</tr>
<tr>
<td>68</td>
<td>0.16203E-23</td>
</tr>
<tr>
<td>67</td>
<td>0.16073E-23</td>
</tr>
<tr>
<td>66</td>
<td>0.15680E-23</td>
</tr>
<tr>
<td>70</td>
<td>0.17318E-24</td>
</tr>
<tr>
<td>301</td>
<td>0.0000</td>
</tr>
<tr>
<td>302</td>
<td>0.0000</td>
</tr>
<tr>
<td>303</td>
<td>0.0000</td>
</tr>
<tr>
<td>304</td>
<td>0.0000</td>
</tr>
<tr>
<td>305</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

ANSYS

APR 29 2014
14:43:34
PLOT NO. 1
Plot of total displacement and graph of actuation force over displacement
- Adjusted starting position.
Element table plot of stresses in design
FINISH
\CLEAR
\OUTPUT

'PARRES,NEW,\"Proto3\";''

*SET,Factor,1E-03
*SET,Length,3e-3
*SET,Length,5e-3
*SET,pi,3.14
*SET,L,2*Factor

!Phalanx
*SET,b1,2*Factor !\[m\] ,Width of the beam
*SET,h1,10*Factor     !\[m\] ,height of the beam
*SET,I1,h1*b1**3/12 !\[m^4\] ,moment of inertia
*SET,A1,h1*b1 !\[m^2\] ,Area

!Linkage
*SET,b2,4*Factor !\[m\] ,Width of the beam
*SET,h2,4*Factor     !\[m\] ,height of the beam
*SET,I2,h2*b2**3/12 !\[m^4\] ,moment of inertia
*SET,A2,h2*b2 !\[m^2\] ,Area

!Hinge - Phalanx Double Stiffness (h3=10 ipv h3=5)
*SET,b3,0.75*Factor !\[m\] ,Width of the beam
*SET,h3,4*Factor     !\[m\] ,height of the beam
*SET,I3,h3*b3**3/12 !\[m^4\] ,moment of inertia
*SET,A3,h3*b3 !\[m^2\] ,Area

!Tilt
*SET,b4,0.75*Factor !\[m\] ,Width of the beam
*SET,h4,4*Factor     !\[m\] ,height of the beam
*SET,I4,h4*b4**3/12 !\[m^4\] ,moment of inertia
*SET,A4,h4*b4 !\[m^2\] ,Area

*SET,E,1.7e9  !\[Pa\] ,Youngh's modulus
*SET,v,0.35    !\[] ,Poisson ratio

*SET,N001X   ,  0.000000000000
*SET,N001Y   , 13.50000000E-03
*SET,N002X   , -0.5280287E-03
*SET,N002Y   ,  1.871358E-03
*SET,N003X   ,-28.68516E-03
*SET,N003Y   ,-1.496043E-03
*SET,N004X   ,-44.51249E-03
*SET,N004Y   ,-1.31247E-03
*SET,N005X   ,-35.94636E-03
*SET,N005Y   ,-13.82419E-03
*SET,N006X   ,-52.3664E-03
*SET,N006Y   ,-18.44571E-03
*SET,N007X   ,-58.05373E-03
*SET,N007Y   ,-26.46276E-03
*SET,N008X   ,-51.70573E-03
*SET,N008Y   ,-27.25034E-03
*SET,N009X   ,-66.2101E-03
*SET,N009Y   ,-39.54905E-03
*SET,N010X   ,-11.81061E-03
*SET,N010Y   ,  8.704859E-03
*SET,N011X   ,-0.5280287E-03
*SET,N011Y   ,  1.871358E-03
*SET,N012X   ,-6.219807E-03
*SET,N012Y   ,  7.5912E-03
*SET,N013X   ,-6.219807E-03
*SET,N013Y   ,  7.5912E-03
*SET,N014X   ,-35.94636E-03
*SET,N014Y   ,-13.82419E-03
*SET,N015X   ,-41.08034E-03
*SET,N015Y   ,-11.33902E-03

!---------------------------------------------------------------------
/PREP7
/PNUMKP,1
/PNUMLINE,1
/PNUMNODE,1
! Define keypoints
K, 1,N001X,N001Y
K, 2,N002X,N002Y
K, 3,N003X,N003Y
K, 4,N004X,N004Y
K, 5,N005X,N005Y
K, 6,N006X,N006Y
K, 7,N007X,N007Y
K, 8,N008X,N008Y
K, 9,N009X,N009Y
K,10,N010X,N010Y
K,11,N011X,N011Y
K,12,N012X,N012Y
K,13,N013X,N013Y
K,14,N014X,N014Y
K,15,N015X,N015Y
K,16,N016X,N016Y
K,17,N017X,N017Y
K,101,N101X,N101Y
K,102,N102X,N102Y
K,201,N201X,N201Y
K,202,N202X,N202Y
K,203,N203X,N203Y
! Define element
ET,1,BEAM188 ! Beam Elements
ET,2,MP,C184
KEYOPT,2,1.6  ! 2 Node Revolute Joint
ET,3,TARGE169
ET,4,CONTA171
!KEYOPT,4,4,2 ! Detection nodal point, normal to contact surface
!KEYOPT,4,4,2 ! Lagrange multiplier contact normal and tangent
!Vertical beam: Target
!Leaf Spring: Contact
!-------------------------------------------------------------------------------------
TYPE,1
Phalanx
SECTYPE, 1, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA,b1,h1

Linkage
SECTYPE, 2, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA,b2,h2

Flexure Hinge
SECTYPE, 3, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA,b3,h3

Tilt
SECTYPE, 4, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA,b4,h4

Define lines between keypoints
1-9
LSTR,1,2
LSTR,2,3
LSTR,3,1
LSTR,4,5
LSTR,5,6
LSTR,6,4
LSTR,7,8
LSTR,8,9
LSTR,9,7

10-15
LSTR,10,11
LSTR,11,12
LSTR,13,14
LSTR,14,15
LSTR,16,17
LSTR,201,203

16-18
LARC,3,4,101
LARC,6,7,102
LARC,10,201,202

Mesh, create elements
1-9
LSEL,s,LINE,,1,9
LESIZE,ALL, , ,5, ,1, ,1, ,1,
TYPE, 1
LMESH, 1,9

10-15
LSEL,s,LINE,,10,15
LESIZE,ALL, , ,5, ,1, ,1, ,1,
TYPE, 1
LMESH, 10,15

16-18
LSEL,s,LINE,,16,17
LESIZE,ALL, , ,20, ,1, ,1, ,1,
TYPE, 1
SENUM, 3
LMESH, 16,17

18
LSEL,s,LINE,,18
LESIZE,ALL, , ,20, ,1, ,1, ,1,
TYPE, 1
SENUM, 4
LMESH, 18

Define Local CS
LOCAL,11,0,kx(2),ky(2)
CSYS,0
LOCAL,12,0,kx(5),ky(5)
CSYS,0
LOCAL,13,0,kx(8),ky(8)
CSYS,0
LOCAL,14,0,kx(12),ky(12)
CSYS,0
LOCAL,15,0,kx(15),ky(15)
CSYS,0

Define Revolute Joints
TYPE,2
SECTYPE,5,JOIN,REVO,Hinge1
SEJOINT,LSYS,11
SENUM,5
EN,301,2,47
SECTYPE,6,JOIN,REVO,Hinge2
SEJOINT,LSYS,12
SENUM,6
EN,302,17,58
SECTYPE,7,JOIN,REVO,Hinge3
SEJOINT,LSYS,13
SENUM,7
EN,303,32,69
SECTYPE,8,JOIN,REVO,Hinge4
SEJOINT,LSYS,14
SENUM,8
EN,304,52,57
SECTYPE,9,JOIN,REVO,Hinge5
SEJOINT,LSYS,15
SENUM,9
EN,305,63,68

Target
TYPE,3
REAL,1
NSEL,S,NODE,,158,162
ESURF
NSEL,ALL

Solution
/SOLU
ANTYPE, STATIC
NLGEOM, ON
OUTRES,ALL,ALL
NSUBST,24,0,0
AUTOTS, OFF

Constraints
Time, 1
D,1,ALL
DDELE,1,ROTz
D,75,ALL
DDELE,75,UX
!D,7,ALL
D,75,UX,10*Factor
D,75,UY,-0.1*Factor
LSWRITE,1

! solve load step(s)
LSSOLVE,1,1,1
FINISH

! plot
/POST1
/PLDISP,2
!ANTIME, 20, 0, 0, 0, 0, 0
!EFACET,2 !Use 2 facets per edge (default for p-elements),
PRNLD, , ALL !List all Forces
NSORT,UY,1,0,0 !Sort on UY displacement
!PRNSOL,UY!List UY displacement
!PRNSOL,U,COMP!List U (x,y,z) displacement
PLNSOL,S,EQV,0,1,0 !Plot stress
SABS,1 !Abs value
ETABLE,stress1,SMISC,32
ETABLE,stress2,SMISC,37
SMAX,stress,STRESS1,STRESS2,1,1 !Define Max Stress
!ESORT,ETAB,STRESS,0,0, ,0 !Hoog naar Laag
!ESORT,ETAB,STRESS,1,0, ,0 !Laag naar Hoog
PLETAB,stress!List Element table Stress
PRETAB,stress!Plot Element table Stress
!*GET,MaxSEQV,PLNSOL,Max
!*GET,stress,SORT,,MAX

/POST26
RFORCE,2,75,F,X,FX_2
STORE,MERGE
XVAR,1
PLVAR,2,

!! Define variables
! /POST26
! NSOL, 2, 158,UX,158_ux
! NSOL, 3, 37,ROT,Z,37_ROTZ
! ANSOL, 4, 32,SEQV,32_SEQV
! RFORCE,4,158,F,X,158_FX

!! Create Table for Results
! *CREATE,scratch,gui
! *DEL,VAR_export
! *DIM,VAR_export,TABLE,20,4
! VGET,VAR_export(1,0),2
! VGET,VAR_export(1,1),3
! VGET,VAR_export(1,2),4
! /OUTPUT,'FEA_Result','txt','D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys9'
! *VWRITE,'Input_Rotz','Output_Rotz','Stress'
! %C, %C, %C
! *VWRITE,VAR_export(1,0),VAR_export(1,1),stress
! %G, %G, %G
! /OUTPUT,TERM
! *END
! /INPUT,scratch,gui
Appendix E: Switch Mechanisms

Only a few feasible bi-stable switch mechanisms in the field of compliant were found. However, these designs mechanisms with living hinges all required either a material with better yield strength to flexibility ratio, or larger geometry dimensions to cope with all the applied stresses.

Fig. 1 shows a bi-stable mechanism that would retain its shape when pulled below a threshold value [01]. The entire construction can travel along the horizontal axis, staying in this configuration. Once the horizontal movement is blocked, the mechanism stays on the same place, and in the same configuration, right until the threshold value is exceeded.

Fig 1. Bi-stable mechanism [01]

The Bi-stable clasp (fig. 2) is similar to the previous mechanism, but the total size of the mechanism required to obtain a vertical displacement was also exceeding the palm dimensions.

Fig 2. Bi-stable clasp in its (a) closed and (b) opened positions.  Fig. 3. Leaf spring contact stop

Instead of living hinges and torsion springs, a mechanism with a leaf spring, functioning as a mechanical stop was considered (fig. 3). The leaf spring contains all compliant behavior aspects and can also easily be printed. The leaf spring stops the right angle linkage from tilting, unless the leaf spring threshold is surpassed. Again, the length of the linkages influences the required moment arm for the tilting motion.

Final tilt mechanism, where the pull bar is no longer starting in the horizontal position, but tilting it horizontally is considered the end state (fig. 4). The pin joint was replaced with a flexure hinge that would keep the two beams in the tilted position, until the flexure hinge threshold is exceeded and both linkages are pulled in a horizontal position.

Fig. 4. Tilt mechanism used in final design

This mechanism showed to be the most compact of all the designs and required the least of extra actuation force for underactuated motion. The obtained tilting angle is still too marginal, and the ideal scenario of getting a 90 degree fingertip trajectory (with the proximal phalanx blocked) is not possible.

ANSYS Bi-stable Mechanism

! ADJUSTABLE parameters
*SET, Gamma1, 1.7423
*SET, Gamma2, 2.0688
*SET, Gamma3, 1.045
*SET, Gamma4, 1.2
*SET, Gamma5, 1.0574
*SET, Gamma6, 1.7731
*SET, Gamma7, -1.2374
*SET, Gamma8, 0.61304
*SET, Gamma9, 1.029
*SET, Gamma10, 0.6435

*SET, PLength, 3e-3
*SET, LLength, 5e-3
*SET, Factor, 1e-3

*SET, x1, 0*Factor
*SET, y1, 12.5*Factor
*SET, z1, 0*Factor

*SET, x2, 40*Factor
*SET, y2, 12.5*Factor
*SET, x3, 40*Factor
*SET, y3, 11*Factor
*SET, x4, 0*Factor
*SET, y4, 12.5*Factor
*SET, x5, 3*Factor
*SET, y5, 11*Factor
*SET, x6, 40*Factor
*SET, y6, 11*Factor
*SET, x7, 30*Factor
*SET, y7, 5*Factor
*SET, x8, 3*Factor
*SET, y8, 11*Factor
*SET, x9, 10*Factor
*SET, y9, 1*Factor
*SET, x10, 2*Factor
*SET, y10, -3*Factor
*SET, x12, -2*Factor
*SET, y12, 10*Factor

*SET, pi, 3.14

*SET, L, 2*Factor

!Phalanx
*SET, b1, 5*Factor ![m], Width of the beam
*SET, h1, 5*Factor ![m], Height of the beam
*SET, I1, h1*b1**3/12 ![m^4], Moment of inertia
*SET, A1, h1*b1 ![m^2], Area

!Linkage
*SET, b2, 4*Factor ![m], Width of the beam
*SET, h2, 4*Factor ![m], Height of the beam
*SET, I2, h2*b2**3/12 ![m^4], Moment of inertia

!Hinge - Phalanx Double Stiffness (h3=10 ip h3=5)
*SET, b3, 10*Factor ![m], Width of the beam
*SET, h3, 10*Factor ![m], Height of the beam
*SET, I3, h3*b3**3/12 ![m^4], Moment of inertia

!Tilt
*SET, b4, 4*Factor ![m], Width of the beam
*SET, h4, 4*Factor ![m], Height of the beam
*SET, I4, h4*b4**3/12 ![m^4], Moment of inertia

! Define element
ET, 1, BEAM188 !Beam Elements
ET, 2, MPC184
KEYOPT, 2, 1, 6 !2 Node Revolute Joint
KEYOPT, 2, 4, 1 !Revolve around z-axis (x-axis=0)
ET, 3, MPC184
KEYOPT, 3, 1, 8 !2 Node Slot Joint
ET, 2, MPC184, 6 !Revolute Joint
ET, 3, MPC184, 3 !Slider Joint
ET, 4, MPC184, 8 !Slot Joint

TYPE, 1
!Phalanx
SECTYPE, 1, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b1, h1

!Linkage
SECTYPE, 2, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b2, h2

!Hinge Phalanx
SECTYPE, 3, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b3, h3

!Tilt
SECTYPE, 4, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b4, h4

! Define lines between keypoints
LSTR, 1, 2, 8
LSTR, 2, 3
LSTR, 2, 3
LSTR, 1, 5
LSTR, 6, 7
LSTR, 8, 9
LSTR, 8, 11
LSTR, 11, 12
LSTR, 11, 10
LSTR, 1, 8, 9
LARC, 3, 9, 101
Define variables

POST26
NSOL, 2, 37, UX, 37, UX
NSOL, 3, 32, UX, 32, UX
!ANSOL, 4, 32, EQV, 32, SEQV
!FORCE, 4, 37, FX, 37, FX

Create Table for Results

*CREATE, scratch, gui
*DEL, VAR_export
*DIM, VAR_export, TABLE, 20, 4
VGET, VAR_export(1,0), 2
VGET, VAR_export(1,1), 3
VGET, VAR_export(1,2), 4

OUTPUT, 'FEA_Result.txt', 'D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys8'

*WRITE, Input_UX, 'Output_UY', 'Stress'
%C, %C, %C
*WRITE, VAR_export(1,0), VAR_export(1,1), stress
%G, %G, %G

OUTPUT, TERM
*END

INPUT, scratch, gui

Create elements

Real2 Linkage 1-8
LSEL, s, LINE, 1-8
LESIZE, ALL, , 5, , 1, ,
TYPE, 1
SECNUM, 2
LMESH, 1-8

Real3 Flexure Hinge 9
LSEL, s, LINE, 9
LESIZE, ALL, , 20, , 1, ,
TYPE, 1
SECNUM, 3
LMESH, 9

!!! *************** Define Local CS ************* !!!
LOCAL, 11, 0, kx(5), ky(5)
CSYS, 0
LOCAL, 12, 0, kx(5), ky(5)
CSYS, 0

!!! ********** Define Revolute Joints ************

TYPE, 2
SECTYPE, 5, JOIN, REVO, Hinge1
SECJOINT, LSYS, 11
SECNUM, 5
EN, 301, 16, 21

SECTYPE, 6, JOIN, REVO, Hinge2
SECJOINT, LSYS, 12
SECNUM, 6
EN, 302, 16, 21

Solution

/SOLU
/ESHAPE, 1
ANTYPE, STATIC
NLGEOM, ON
OUTRES, ALL, ALL
NSUBST, 20, 0, 0
AUTOTS, OFF

Constraints

Time, 1
D, 1, ALL
D, 2, ALL
D, 37, UX, 5*Factor
D, 32, UY, 3*Factor
LWRITE, 1

solve load step(s)
LSSOLVE, 1, 1, 1
FINISH

plot

/POST1
PLDISP, 2
!ANTIME, 20, 0.2, 0, 0, 0
!EFACET, 2
!Use 2 facets per edge (default for p-elements)
PRNLD, , ALL
NSORT, U, Y, 1, 0
PRNSOL, U, Y
!List UY displacement
!PLENSOL, S, EQV, 0, 1, 0
SABS, 1
!Abs value
ETABLE, stress1, SMISC, 32
ETABLE, stress2, SMISC, 37
SMAX, stress, STRESS1, STRESS2, 1, 1,
ESORT, ETAB, STRESS, 0, 0, 0
!Hoog naar Laag
ESORT, ETAB, STRESS, 1, 0, 0
!Laag naar Hoog
PLETAB, stress
PRETAB, stress
*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX

/*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX

Define variables

POST26
NSOL, 2, 37, UX, 37, UX
NSOL, 3, 32, UX, 32, UX
!ANSOL, 4, 32, EQV, 32, SEQV
!FORCE, 4, 37, FX, 37, FX

Create Table for Results

*CREATE, scratch, gui
*DEL, VAR_export
*DIM, VAR_export, TABLE, 20, 4
VGET, VAR_export(1,0), 2
VGET, VAR_export(1,1), 3
VGET, VAR_export(1,2), 4

OUTPUT, 'FEA_Result.txt', 'D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys8'

*WRITE, Input_UX, 'Output_UY', 'Stress'
%C, %C, %C
*WRITE, VAR_export(1,0), VAR_export(1,1), stress
%G, %G, %G

OUTPUT, TERM
*END

INPUT, scratch, gui

Create elements

Real2 Linkage 1-8
LSEL, s, LINE, 1-8
LESIZE, ALL, , 5, , 1, ,
TYPE, 1
SECNUM, 2
LMESH, 1-8

Real3 Flexure Hinge 9
LSEL, s, LINE, 9
LESIZE, ALL, , 20, , 1, ,
TYPE, 1
SECNUM, 3
LMESH, 9

!!! *************** Define Local CS ************* !!!
LOCAL, 11, 0, kx(5), ky(5)
CSYS, 0
LOCAL, 12, 0, kx(5), ky(5)
CSYS, 0

!!! ********** Define Revolute Joints ************

TYPE, 2
SECTYPE, 5, JOIN, REVO, Hinge1
SECJOINT, LSYS, 11
SECNUM, 5
EN, 301, 16, 21

SECTYPE, 6, JOIN, REVO, Hinge2
SECJOINT, LSYS, 12
SECNUM, 6
EN, 302, 16, 21

Solution

/SOLU
/ESHAPE, 1
ANTYPE, STATIC
NLGEOM, ON
OUTRES, ALL, ALL
NSUBST, 20, 0, 0
AUTOTS, OFF

Constraints

Time, 1
D, 1, ALL
D, 2, ALL
D, 37, UX, 5*Factor
D, 32, UY, 3*Factor
LWRITE, 1

solve load step(s)
LSSOLVE, 1, 1, 1
FINISH

plot

/POST1
PLDISP, 2
!ANTIME, 20, 0.2, 0, 0, 0
!EFACET, 2
!Use 2 facets per edge (default for p-elements)
PRNLD, , ALL
NSORT, U, Y, 1, 0
PRNSOL, U, Y
!List UY displacement
!PLENSOL, S, EQV, 0, 1, 0
SABS, 1
!Abs value
ETABLE, stress1, SMISC, 32
ETABLE, stress2, SMISC, 37
SMAX, stress, STRESS1, STRESS2, 1, 1,
ESORT, ETAB, STRESS, 0, 0, 0
!Hoog naar Laag
ESORT, ETAB, STRESS, 1, 0, 0
!Laag naar Hoog
PLETAB, stress
PRETAB, stress
*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX

/*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX

Define variables

POST26
NSOL, 2, 37, UX, 37, UX
NSOL, 3, 32, UX, 32, UX
!ANSOL, 4, 32, EQV, 32, SEQV
!FORCE, 4, 37, FX, 37, FX

Create Table for Results

*CREATE, scratch, gui
*DEL, VAR_export
*DIM, VAR_export, TABLE, 20, 4
VGET, VAR_export(1,0), 2
VGET, VAR_export(1,1), 3
VGET, VAR_export(1,2), 4

OUTPUT, 'FEA_Result.txt', 'D:\Documents\TU Delft\Dropbox\2012 MSc\Ansys\Ansys8'

*WRITE, Input_UX, 'Output_UY', 'Stress'
%C, %C, %C
*WRITE, VAR_export(1,0), VAR_export(1,1), stress
%G, %G, %G

OUTPUT, TERM
*END

INPUT, scratch, gui

Create elements

Real2 Linkage 1-8
LSEL, s, LINE, 1-8
LESIZE, ALL, , 5, , 1, ,
TYPE, 1
SECNUM, 2
LMESH, 1-8

Real3 Flexure Hinge 9
LSEL, s, LINE, 9
LESIZE, ALL, , 20, , 1, ,
TYPE, 1
SECNUM, 3
LMESH, 9

!!! *************** Define Local CS ************* !!!
LOCAL, 11, 0, kx(5), ky(5)
CSYS, 0
LOCAL, 12, 0, kx(5), ky(5)
CSYS, 0

!!! ********** Define Revolute Joints ************

TYPE, 2
SECTYPE, 5, JOIN, REVO, Hinge1
SECJOINT, LSYS, 11
SECNUM, 5
EN, 301, 16, 21

SECTYPE, 6, JOIN, REVO, Hinge2
SECJOINT, LSYS, 12
SECNUM, 6
EN, 302, 16, 21

Solution

/SOLU
/ESHAPE, 1
ANTYPE, STATIC
NLGEOM, ON
OUTRES, ALL, ALL
NSUBST, 20, 0, 0
AUTOTS, OFF

Constraints

Time, 1
D, 1, ALL
D, 2, ALL
D, 37, UX, 5*Factor
D, 32, UY, 3*Factor
LWRITE, 1

solve load step(s)
LSSOLVE, 1, 1, 1
FINISH

plot

/POST1
PLDISP, 2
!ANTIME, 20, 0.2, 0, 0, 0
!EFACET, 2
!Use 2 facets per edge (default for p-elements)
PRNLD, , ALL
NSORT, U, Y, 1, 0
PRNSOL, U, Y
!List UY displacement
!PLENSOL, S, EQV, 0, 1, 0
SABS, 1
!Abs value
ETABLE, stress1, SMISC, 32
ETABLE, stress2, SMISC, 37
SMAX, stress, STRESS1, STRESS2, 1, 1,
ESORT, ETAB, STRESS, 0, 0, 0
!Hoog naar Laag
ESORT, ETAB, STRESS, 1, 0, 0
!Laag naar Hoog
PLETAB, stress
PRETAB, stress
*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX

/*GET, MaxSEQV, PLNSOL, Max
*GET, stress, SORT, MAX
ANSYS Leaf Spring Contact Stop

FINISH
\*CLEAR
\*ADJUSTABLE parameters
*SET, Gamma1, 0
*SET, Gamma2, 0
*SET, Gamma3, 0
*SET, Gamma4, 0
*SET, Gamma5, 0
*SET, Gamma6, 0
*SET, Gamma7, 0
*SET, Gamma8, 0
*SET, Gamma9, 0

*SET, PLength, 3e-3
*SET, LLength, 5e-3
*SET, Factor, 1e-3

*SET, x1, 0*Factor
*SET, y1, 7*Factor
*SET, x2, 5*Factor
*SET, y2, 5*Factor
*SET, x3, 10*Factor
*SET, y3, 10*Factor
!*SET, x4, 5*Factor
!*SET, y4, 5*Factor
!*SET, x5, 15*Factor
!*SET, y5, 5*Factor
*SET, x6, -20*Factor
*SET, y6, 10*Factor
*SET, x7, 0*Factor
*SET, y7, 10*Factor
*SET, x8, 0*Factor
*SET, y8, 5*Factor
*SET, pi, 3.14

*SET, L, 2*Factor

! Flexure Hinge
*SET, b1, 0.75*Factor !Width of the beam
*SET, h1, 4*Factor !Height of the beam
*SET, I1, h1*b1**3/12 !Moment of inertia
*SET, A1, h1*b1 !Area

! Linkage
*SET, b2, 4*Factor !Width of the beam
*SET, h2, 4*Factor !Height of the beam
*SET, I2, h2*b2**3/12 !Moment of inertia
*SET, A2, h2*b2 !Area

! Define keypoints
K,1,x1 = Gamma1*Factor,y1 = Gamma2*Factor
K,2,x2 = Gamma3*Factor,y2 + Gamma4*Factor
K,3,x3 = Gamma5*Factor,y3 = Gamma6*Factor
K,6,x6 = Gamma1*Factor,y6 = Gamma2*Factor
K,7,x7 = Gamma3*Factor,y7 = Gamma4*Factor
K,8,x8 = Gamma5*Factor,y8 = Gamma6*Factor

! Define element
ET,1,BEAM188 !Beam Elements
ET,2,MPC184
KEYOPT,2,1.6 !Node Revolute Joint
KEYOPT,2,4,1 !Revolve around z-axis (x-axis=0)
ET,3,TARGE169
ET,4,CONTA171
!KEYOPT,4,2,0 !Use default Augmented Lagrangian contact model
!KEYOPT,4,7,4 !Use impact equations
KEYOPT,4,4,2 !Detection nodal point, normal to contact surface
KEYOPT,4,2,4 !Lagrange multiplier on contact normal and tangent

!Vertical balk: Target
!Leaf Spring: Contact conta171 (2nodes of xfo)

*******************************************************************************
MP, EX, 1, 1.7e9 !Tensile strength 48MPa
MP, PRXY, 1, 0.35
MP, DENS, 1, 930 !0.93 g/cm3 = 930 kg/m3
*******************************************************************************

TYPE, 1
!Hinge
SECTYPE, 1, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b1,h1

!Linkage
SECTYPE, 2, BEAM, RECT, , 0
SECOFFSET, CENT
SECDATA, b2,h2

! Define keypoints
!Real 1 Hinge Flexure
K,1,x1 = Gamma1*Factor,y1 = Gamma2*Factor
K,2,x2 = Gamma3*Factor,y2 + Gamma4*Factor
K,3,x3 = Gamma5*Factor,y3 = Gamma6*Factor

!Real 2 Linkage
K,6,x6 = Gamma1*Factor,y6 = Gamma2*Factor
K,7,x7 = Gamma3*Factor,y7 = Gamma4*Factor
K,8,x8 = Gamma5*Factor,y8 = Gamma6*Factor

! Mesh, create elements
!Real 1 Flexure Hinge 1
LSEL,x_LINE, 1
LESIZE,ALL, , , 20, , , 1, , , 1,
TYPE, 1
SECONUM, 1
LMESH, 1

!Real 2 Linkage 2-4
LSEL,x_LINE, 2-4
LESIZE,ALL, , , 20, , , 1, , , 1,
TYPE, 1
SECONUM, 2
LMESH, 2-4

!!! ***************** Define Local CS ***************
LOCAL, 11, 0,kx(7), ky(7)
CSYS, 9

!!! ********** Define Revolute Joints *************

TYPE, 2
SECTYPE, 5, JOIN, REVO, Hinge 1
SECJOINT, LSYS, 11
SECONUM, 5
EN, 301, 22, 43
!!! ********** Target ************
TYPE,3 ! Activate element 3
REAL,1 ! Activate Real set 1
NSEL,S,NODE,,63,82 ! Vertical Rigid Link below Pin Joint
ESURF ! Generates elements on surface selected elements

!!! ********** Contact Element **********
TYPE,4 ! Activate element 4
REAL,1 ! Activate Real set 1
NSEL,S,NODE,,1,5 ! Select nodes 1 to 5 - Left part Leaf Spring
ESURF ! Generates elements on surface selected elements
NSEL,ALL ! Select all nodes

!! Solution
/SOLU ! Enter solution phase
!ESHAP,E,1
ANTYPE, STATIC ! Static analysis ( D,Node,UX,Value )
!ANTYPE, TRANSIENT! Dynamic analysis ( F,Node,FX,Value )
NLGEOM, ON
OUTRES,ALL,ALL
NSUBST,20,0,0
AUTOTS, OFF

!! Constraints
Time, 1
D,2,ALL
D,23,ALL
D,63,UX,2.5*Factor
!F,63,FX,3
!F,42,FY,-0.5
!D,42,UY,3*Factor
LSWRITE,1

! solve load step(s)
LSWRITE,1

! plot
/LSSOLVE,1,1,1
FINISH

!! Define variables
/POST26
NSOL, 2, 63,U,X,63_UX
NSOL, 3, 42,U,Y,42_UY
!ANSOL, 4, 32,S,EQV,32_SEQV
!FORCE,4,63,F,X,63_FX

!! Create Table for Results
*CREATE,scratch,gui
*DEL_VAR_export
*DIM_VAR_export,TABLE,20,4
*VGET_VAR_export(1,0,1,2
*VGET_VAR_export(1,1,3
*VGET_VAR_export(1,2,4

/OUTPUT,FEA_Results.txt,D:/Documents/TU Delft/Dropbox/2012 MSc/Ans/s/Ans/s8
*VWRITE,Input_Rotz,Output_Rotz,Stress
%C, %C, %C
*VWRITE,VAR_export(1,0),VAR_export(1,1),stress
%G, %G, %G
/OUTPUT,TERM
*END
/INPUT,scratch,gui

!! Define Max Stress
ESORT,ETAB,STRESS,0,0, ,0
*GET,MaxSEQV,PLNSOL_,Max
*GET,stress,SORT,,MAX

!! Define variables
/PDLISP,2

!! Constraints
NSORT,UX,1,0,0 !Sort on UY displacement
PRNSOL,U,Y !List UY displacement
PRNSOL,COMP !List U (x,y,z) displacement

!! Define variables
PLNSOL, SEQV, 0, 1,0 !Plot stress
SABS,1 !Abs value
ETABLE,stress1,SMISC,32
ETABLE,stress2,SMISC,37

SMAX, stress, STRESS1, STRESS2, 1, 1, ! Define Max Stress

ESORT,ETAB,STRESS,0,0, ,0 !Hoog naar Laag
!ESORT,ETAB,STRESS,1,0, ,0 !Laag naar Hoog
PLETAB,stress !Plot Element table Stress
!PRETAB,stress !List Element table Stress

!*GET,MaxSEQV,PLNSOL_,Max

!! Define variables
/PDLISP,1
/DIST,1,1,5,1
/BEP,FAST
ANDSCL,10,0,2
Appendix F: Complete Hand

As a proof of concept, a prosthetic hand was designed, complete manufactured through 3D printing. The same main design principles were used as with the finger design. Everything had to be within anthropomorphic dimensions, no additional materials like screws or cables were allowed and the finished product would have minimal assembly requirements. The completed design resulted in a functioning multi-phalanx grasper, with basic underactuation capabilities. The design was not essentially capable of performing grasping capabilities like the commercially available prostheses, but functional enough to represent future research and design possibilities.

By combining the finger and palm geometry of both papers [01][02], a rough 3D model of an average sized male hand was constructed. In order to accommodate possible future connection methods between hand and wrist contraption, the bottom of the hand was designed with a circular, two inch outer diameter base (fig. 1).

To reach the inside of the palm base, a battery-cover-style lid was designed. With a clearance of 0.5mm on all sides, the battery-cover lid has three protruding pins that can hook in the palm base. As with most plastic battery-cover constructions, a compliant based push lever is used to release the main pin and lifting the complete cover from the palm base (fig. 2).

The four main fingers (index through pinky finger) are all fastened with one main pin inserted at the side of the palm. This pin functions as the main pivot point of these four fingers (fig. 3). The thumb is positioned on a different plane, and has its own pin connection. Similar to the main cover plate, a battery-cover-like lid was constructed to hold the thumb (fig. 4). A pivot pin is used to connect the finger to the lid, and the complete construction is then attached to the palm base by hooking two protruding pins.
The outer ends of all the fingers pull bars are connected to a differential mechanism, inspired by the contraption used by the 15 DoF Gosselin Hand [03] (fig. 5). Instead of cables, a collection of rigid linkages and pin joints was created to function like a whippletree mechanism [04]. When one finger is halted by an object, other fingers can still be pulled along by the distribution the main actuation force over the remaining fingers.

Fig. 5. Whippletree mechanism differential

To demonstrate the grasping function of the hand, an attachable handle bar construction was designed that could easily be fastened and removed from the palm base (fig. 6). In order to connect, a simple twist lock mechanism was designed. The handle bar construction has two extruding pins that fit in the slots and get locked into place by performing a quarter turn clockwise.

Fig. 6. Three steps necessary to attach the handle bar construction to the palm base.

The handle bar construction itself is consisting out of three parts. As with the finger design, this construction can be printed in one setting and cannot be disassembled once completely printed. The inner ring provides the slots for the handle bar to slide along. It also has the connection pins for the palm base at the bottom. The outer ring has a concealed function of transforming the handle bar construction into a pedestal. In closed form, the user can perform the grasping motion of the hand by pulling the handle bar. In open form, the construction now present four evenly spaced points from the center, to let the hand be positioned in an upright position on any flat surface. The handle bar can still slide along the inner ring slots freely.

Fig. 7. Changing the handle bar construction into a pedestal


F-1: Photo Collection
## Appendix G: SolidWorks Drawings

<table>
<thead>
<tr>
<th>Component</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FingerAssembly 01</td>
<td>44</td>
</tr>
<tr>
<td>FingerAssembly 02</td>
<td>45</td>
</tr>
<tr>
<td>FingerPhalanx</td>
<td>46</td>
</tr>
<tr>
<td>PalmBase</td>
<td>47</td>
</tr>
<tr>
<td>PalmBaseCover</td>
<td>48</td>
</tr>
<tr>
<td>ThumbBaseCover</td>
<td>49</td>
</tr>
<tr>
<td>WhippleTree</td>
<td>50</td>
</tr>
<tr>
<td>WhippleTreePullbar</td>
<td>51</td>
</tr>
<tr>
<td>HandleBarConstruction</td>
<td>52</td>
</tr>
<tr>
<td>Finger01 (Index)</td>
<td>53</td>
</tr>
<tr>
<td>Finger02 (Middle)</td>
<td>54</td>
</tr>
<tr>
<td>Finger03 (Ring)</td>
<td>55</td>
</tr>
<tr>
<td>Finger04 (Pinky)</td>
<td>56</td>
</tr>
<tr>
<td>Finger05 (Thumb)</td>
<td>57</td>
</tr>
</tbody>
</table>
Appendix H: Component and Costs List

Both initial finger prototypes, as the final cosmetic hand version were all fabricated by Shapeways (www.shapeways.com). Their production pricing is only based on the used volume of material, rather than dimensions of the designs, like most commercial printing companies often use. Their wide material selection and reasonable shipping costs made this company most beneficiary.

The final cosmetic hand version was fabricated with additional coloring and polishing of the material. The total costs of this cosmetic demonstration model is shown in Table 1.

Table 1: Complete cosmetic version

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Finishing</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PalmBase</td>
<td>Black</td>
<td>69.69</td>
</tr>
<tr>
<td>PalmBaseCover</td>
<td>Black</td>
<td>11.41</td>
</tr>
<tr>
<td>Finger01 (Index)</td>
<td>RoyalBlue</td>
<td>6.94</td>
</tr>
<tr>
<td>Finger02 (Middle)</td>
<td>RoyalBlue</td>
<td>9.29</td>
</tr>
<tr>
<td>Finger03 (Ring)</td>
<td>RoyalBlue</td>
<td>6.94</td>
</tr>
<tr>
<td>Finger04 (Pinky)</td>
<td>RoyalBlue</td>
<td>5.74</td>
</tr>
<tr>
<td>Finger05 (Thumb)</td>
<td>RoyalBlue</td>
<td>5.40</td>
</tr>
<tr>
<td>ThumbBaseCover</td>
<td>Black</td>
<td>3.35</td>
</tr>
<tr>
<td>ThumbBaseCoverPin</td>
<td>Black</td>
<td>1.62</td>
</tr>
<tr>
<td>BasePin</td>
<td>Black</td>
<td>2.33</td>
</tr>
<tr>
<td>WippleTree</td>
<td>WSF</td>
<td>5.11</td>
</tr>
<tr>
<td>WippleTreePullbar</td>
<td>RoyalBlue</td>
<td>3.25</td>
</tr>
<tr>
<td>HandleBarConstruction</td>
<td>RoyalBlue</td>
<td>58.54</td>
</tr>
<tr>
<td>Taxes and Shipping costs</td>
<td></td>
<td>5.68</td>
</tr>
<tr>
<td><strong>Total - Cosmetic Version</strong></td>
<td></td>
<td>€195.29</td>
</tr>
</tbody>
</table>

Rather than ordering a display model, money can be saved by only using the main material, without any additional polishing and coloring. If this design ends up to be used as a real hand prosthetic, and additional €54.10 can be saved by not ordering the handle bar construction, as it is not needed when connected to an wrist connection (see Table 2). Adding the non-colored handle bar to the basic version, will result in a total cost of €167.97 (see Table 3).

Table 2: Basic version

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Finishing</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PalmBase</td>
<td>WSF</td>
<td>55.86</td>
</tr>
<tr>
<td>PalmBaseCover</td>
<td>WSF</td>
<td>9.22</td>
</tr>
<tr>
<td>Finger01 (Index)</td>
<td>WSF</td>
<td>5.94</td>
</tr>
<tr>
<td>Finger02 (Middle)</td>
<td>WSF</td>
<td>8.15</td>
</tr>
<tr>
<td>Finger03 (Ring)</td>
<td>WSF</td>
<td>5.94</td>
</tr>
<tr>
<td>Finger04 (Pinky)</td>
<td>WSF</td>
<td>4.83</td>
</tr>
<tr>
<td>Finger05 (Thumb)</td>
<td>WSF</td>
<td>4.52</td>
</tr>
<tr>
<td>ThumbBaseCover</td>
<td>WSF</td>
<td>2.77</td>
</tr>
<tr>
<td>ThumbBaseCoverPin</td>
<td>WSF</td>
<td>1.38</td>
</tr>
<tr>
<td>BasePin</td>
<td>WSF</td>
<td>1.96</td>
</tr>
<tr>
<td>WippleTree</td>
<td>WSF</td>
<td>5.11</td>
</tr>
<tr>
<td>WippleTreePullbar</td>
<td>WSF</td>
<td>2.51</td>
</tr>
<tr>
<td>Taxes and Shipping costs</td>
<td></td>
<td>5.68</td>
</tr>
<tr>
<td><strong>Total - Basic Version</strong></td>
<td></td>
<td>€113.87</td>
</tr>
</tbody>
</table>

Table 3: Addition to basic version

<table>
<thead>
<tr>
<th>Component</th>
<th>Material Finishing</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>HandleBarConstruction</td>
<td>WSF</td>
<td>54.10</td>
</tr>
<tr>
<td><strong>Total - Complete Basic Version</strong></td>
<td></td>
<td>€167.97</td>
</tr>
</tbody>
</table>
Appendix I: Literature Study
Overview and Classification of Working Principles in Underactuated Grippers

TU Delft
M.W.M. Groenewegen
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Abstract

Grippers have been used as hand prosthetics for centuries, ranging from simple designs to complex and anthropomorphic mechanisms. Thanks to modern science, grippers are now also widely used outside the field of prosthetics, like the packaging industry or in hazardous environments (deep sea, outer space, inside nuclear power plant reactor).

While looking for lightweight and less complex versions of grippers with multiple phalanxes, a lot of research has gone into underactuated gripper designs. Recognizing the advantages of underactuated multi-phalanx grippers, this literature survey was written to help create a clearer overview of all the working principle mechanisms that were created to achieve underactuation in grippers. Previously existing overviews tended to only make a listing of the current most popular grippers. The similarities between those gripper mechanisms made it harder to make a clear distinction between them. Because not every design paper showed the grippers usage data (force ratio, grip robustness, weight, etc.), it has become hard to recognize potential advantages or flaws when searching for the gripper that would accommodate your own specific needs.

For this overview, a distinction between the grippers used motion systems and the used drive or transmission is made. Both these categories are defined into further detail to get a better understanding on the basic working principles of every gripper. By filtering the grippers whose mechanism had too many correlations with other grippers, a listing was created of 51 grippers who had a distinct working principle design. With all of these grippers broken down into specific mechanism categories, a clear overview of all available working principles was created.

The categories were defined separately, explaining on how these designs could work in combination with the other categories. By describing their properties, in combination with the found grippers as examples, a few of the possible advantages or disadvantages were defined. Readers can use this overview to help choose their desired gripper, based on the specific mechanism and personal preferences.

It became clear that for all the found (distinct) grippers, the use of tendon as actuation was overrepresented. The same was found for rigid linkage connections, despite the filtering of all similar mechanism design. A few grippers with very similar designs have remained in the overview, rather than being filtered out. Those grippers are being widely recognized in their field and were referred to far too frequently to be simply left out of the overview.

Based on defined properties, the field of compliant materials shows some real promise when used as motion system or as drive/transmission. A significant amount of research papers mentioned a desire to construct a simple and lightweight gripper, before showing their own (non-compliant) design. It is therefore noted that the low amount of existing grippers in that specific area could show some real potential for further research.
1 Introduction

Both the industrial and the medical sector are using grippers that can mimic, or substitute the human hand [01],[52]. The industrial sector uses grippers to remove the human element from the dangerous, monotonous or excessive laborious work. This could be in areas like the deep sea [41], outer space [54], or nuclear power plants [55] where humans would be at risk. Also the more mundane tasks can be done by grippers, in order to take over the monotonous and laborious tasks like transporting and positioning objects for packaging industries [01],[37].

In the medical field, grippers can be required for their use in minimal invasive surgery [56], and another often used application is that of the prosthetic sector. Grippers can be used there as prosthesis for people that are missing an upper extremity, using it as artificial fingers and hands [57] - [59].

The artificial fingers that come closest to the human finger require over a dozen actuators and sensors [60]. Earlier designs like the Okada hand [61], Stanford/JPL [62], Utah/MIT [63] and the more advanced versions like the iLimb [59], UB Hand III [50], DLR [64], Karlsruhe Hand [65], Shadow Hand [66], Schunk Dexterous Hand [67] and the Kinetic Humanoid Hand [68] are all hands with versatile grasping abilities. These joints require separate actuation and thus multiple motors, gear boxes etc. Finding a grasper that suits specific needs can be challenging due to the similarity of all the existing gripper designs. For this literature overview, the main focus will be on the underactuated aspect of the grasping fingers, were the finger has fewer actuators than degrees of freedom (DoF) [08].

Goal

The goal of this literature research is to construct an overview of existing multi-phalanx underactuated grippers. By filtering on specific representatives for every working principle, a clear collection of all the available working principles on grippers will be documented, helping future designers in the search for their most ideal gripper. The reader can make an educated decision on what would make the ideal gripper, based on personal criteria that are deducted from the category descriptions.

In summary, the sub goals for this paper will become the following:

- Creating an overview of all the working principles in underactuated grippers.
- Sorting the grippers under different categories for clarity.
- Discuss the basic principle of the grippers per category to help recognize possible benefits and limitations of the grippers.

At the completion of this article, a more in-depth classification will be defined and used to organize the grippers into categories. The resulting overview should show a more balanced listing of all the used working principles that have been designed to acquire an underactuated, multi-phalanx gripper.

Outline

Chapter 2 will discuss the method and approach that were used for this literature survey, in order to find all relevant grippers that were consistent with the set criteria. In chapter 3, a deeper explanation is given about the definition and basic principles of underactuation, in order to help explain the reasoning why some types of grippers were not included into this survey. For chapter 4, all the used classification terms will be discussed in their general principles. The grippers are then sorted into their specific categories and in chapter 5 discussed on basic working principles and listing of possible advantages or drawbacks. This chapter ends with a final overview table of all categorized relevant grippers. Chapter 6 will discuss this literature survey, with a conclusion in a separate chapter 7.
2 Method and Approach

At the start of the literature survey, a broad research was performed over the existing grippers, in the field of robotics and upper limb prosthesis. This was done to get a better understanding of the existing mechanisms in these specific fields.

The main search engines (Scopus, ISI Web of Knowledge, Scholar Google, IEEE Xplore Digital Library) showed a massive amount of papers when only the keywords “gripper” or “grasper” were used in the article title, abstract or keywords. Although both terms are used for robotics hands, the medical field uses the term “grasper” mostly for their single phalanx, jaw-like grippers that are used in minimal invasive surgery. Because this report will keep a broad perspective of grasping mechanisms, the term “gripper” will be the main term used to refer to the multi-phalanx grasping mechanisms. Furthermore, the multi-phalanx appendixes of the grasper will be referred to as the “fingers” of the gripper.

The research for this survey emphasizes on the mechanical solutions for adaptive grasping of multi-phalanx grippers. Any robotics gripper that has the same amount of (electric) actuators (inside the finger mechanism) as DoF, will be ignored. This is done, because the finger adaptation around the object is more software based. Rigid single phalanx grippers are considered here as none-adaptive to the grasped object and are also not included in this survey.

One known and important aspect of grippers that shape themselves around the object (adaptive grasping) is the mechanism of underactuation. All grippers that were not underactuated were excluded from this article. To give a better understanding on why those grippers were left out of the overview, an in-depth explanation of underactuation will be discussed in the next chapter.

Using the same searching engines, another search inquiry was done with only the term “underactuation”, and also done in combination with the previous terms of either “gripper” or “grasper”. All relevant gripper mechanisms were collected from those results as a first selection. As a second selection step, all papers were examined individually and selected on their unique working principle of the underactuation mechanisms. This left over forty distinct grippers, and by going through their references, another dozen or so grippers could be added.

The final selection was studied and assorted under specific classification, which also became more fine-tuned during the sorting process. Any last gripper mechanism that had too much of a correlation with other grippers was filtered out to showcase the main mechanisms, leaving an overview of all existing working principles in underactuated mechanisms for grippers.

The basic principles of the gripper are recognized as the used drive (or transmission) of the gripper and the mechanism that is used to give the motion capabilities. Both these main classes are defined in even more categories within their own sector, making it easier to judge each gripper on possible positive or negative aspects, depending of their required use or durability.

The actuation method of the grippers has been defined as the method used to transfer the actuation over the multi-phalanx gripper. These methods are classified into four main categories.

- The use of rigid linkage systems
- Compliant materials
- Pneumatic/hydraulic actuation
- The use of tendons (or other cable-like materials)

Each of these four methods will be defined in 4.1 Drive or Transmission, accompanied by a few example grippers that make use of that function. Because the rigid linkage system can represent a wide selection of working principles, is this category divided into three more distinctive sub-categories, namely four-bar linkage, seesaw mechanism and gear linkage.
For the motion capabilities, the main difference in methods of motion mechanisms were defined as rigid materials (as in linkages and sorts), and compliant materials. With these motion systems, the emphasis lies on the material or mechanism that was used to achieve the bending motion of the finger. Instead of looking at the entire finger, only the hinge mechanism used for the bending motion is defined.

By defining the different methods of actuation and motion transfer, an overview can be created where the existing grippers can be sorted into their specific category. With two main methods of motion and four main methods of transmission, a total of eight possible category combinations can be defined. Because every category has its own set of benefits and limitations, all eight combinations will be discussed on those factors.
3 Underactuation

A gripper is considered underactuated when it has fewer actuators than configuration variables [69], i.e. fewer actuators than degrees of freedom [51], or the input vector is consisting of a smaller dimension than the output vector. Instead of using a complex command and coordination of several actions, underactuation can help simplify the control by using mechanical systems where the finger can adapt itself to the shape of the object (adaptive grasping). Grippers that can make a grasping movement that consists out of multiple DoF, can result in an enveloping power grasp that forms around the object itself, giving the gripper a more robust grip [70],[71].

Underactuation is a relatively old concept, with examples of it already been found in Leonardo DaVinci’s *Codex Atlanticus* (ca 1496). Here he proposed a mechanism to drive an artificial wing for one of his flying machines [72].

![Mechanical wing from Da Vinci's Codex Atlanticus (ca 1496)](image1)

![Abstracted sketch of Da Vinci's mechanism](image2)

![Götz von Berlichingen's prosthetic Hand](image3)

It wasn’t until 1982 before a very similar design with cables and pulleys was patented as underactuated mechanism for a robotic finger [73]. Before that, the majority of the found underactuated designs primarily used rigid links to drive the mechanism.

One of the most famous and earliest anthropomorphic\(^1\) prosthetic hands dates back to 1504 and was owned by Götz von Berlichingen (Fig. 3). The design consists of an underactuated ratchet mechanism where a separate switch was used to release the grip.

In 1864, an underactuated mechanical hand was patented by E. Spellerberg, where the underactuation between the fingers was achieved by the use of a rigid link seesaw mechanism [11]. This mechanism was a technique that was not even claimed yet [74], and ended up to be rediscovered for more recent grippers [13].

Nevertheless, most authors credit Prof. Hirose with his Soft Gripper [29] for designing the first prototype of modern underactuated fingers (ca. 1978). From there, the underactuated gripper has been widely used in robotics due to its advantages over simple parallel grippers [75].

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\(^1\) described or thought of as having a human form or human attributes
In the field of prosthetics, underactuation came mostly as the result of pragmatic choices to create adaptive and functional mechanisms, when looking for methods to reduce the mass and size of the prosthesis [76]. The popularity of this concept in the robotics field is partly through the desire of grasping an object through enveloping. [77]-[81].

Pioneering research on underactuation has been done by Gosselin and Laliberté in the mid 90’s, where they tried to bridge the gap between industrial robotic grippers and fully actuated hands through underactuation. The robotic grippers of that time existed mostly out of parallel grippers, and the high tech fully actuated hands [74]. Their work was inspired by the early papers, going back to the late 70’s, [29],[75],[82].

Other papers have already made an overview of sorts, but they were often only a listing of existing underactuated grippers without any real categorization on the kind of mechanisms or actuation. The author Krut was one of the few that made a distinction of sorts by dividing the grippers in different categories that one can recognize in underactuation mechanisms [23]:

- Differential mechanisms: relying on classical technologies (i.e. planar differential) or made of specific arrangements of linkages [83] or pulleys and cables [84].
- Compliant mechanisms: non-rigid bodies such as the “adaptive grasp mechanism” proposed in [85].
- Triggered mechanisms: once the torque exceeds a certain value, the joint locks. On the Barrett Hand, the transmission disengages and an irreversible mechanism prohibits back drivability of the joint [86].
4 Classifications

Out of the found existing grippers, an overview is constructed to categorize the used mechanisms. The main working principle of every gripper is divided into the used drive (or transmission) of the gripper and the mechanism used to give the motion capabilities. These two main classes are subdivided further into categories within their own sector, making it easier to judge each gripper on possible positive or negative aspects. Readers can therefore make their own educated choice of possible best gripper, depending on their required use or desired durability.

4.1 Drive or Transmission

The actuation method of the grippers has been defined as the method used to transfer the actuation over the multi-phalanx gripper. These methods are defined into four main categories.

- The use of rigid linkage systems
- Compliant materials
- Pneumatic/hydraulic actuation
- The use of tendons (or other cable-like materials)

Each of these four methods will be explained in the following paragraphs, accompanied by a few example grippers that make use of that function.

4.1.1 Linkage

Even for the mechanisms that are powered by a small electric actuator, the transfer of motion to the fingers can be done by either rigid linkages or gears. Rigid linkage systems will therefore divided into more specific categories to help distinct the different grippers in their specific working principles.

4.1.1.1 Four-bar Linkage

With one joint connected to the surface, four additional connected bars form roughly a rectangle shape. By applying an actuation force on the driving bar, a moment is achieved around the joint connected to the surface. Fig. 4 shows a schematic representation of a four bar linkage mechanism that has a 2 DoF and is underactuated. The tip of the finger (blue) adapts itself to the object, while the driving bar keeps on rotating [03]. Due to the spring between the bars (passive elastic element), the resistance within the four bar linkage is high enough that only the joint fixated to the surface will turn.

Fig. 4: Schematic representation of a Four Bar Linkage Mechanism used for a Two Phalanx Finger
When one of the bars is obstructed by an object, continuing to apply a moment on the driving bar, will result in the actuation force being transferred and distributed over the other bars. This results in an enveloping movement of the multi phalanx finger around the object. With this mechanism, both a precision grasp as a power grasp can be achieved, depending on the size and position of the object. With precision grasp, only the tips of the finger are making contact with the object, where a power grasp has multiple points of contact of the different phalanxes on the object [78].

Every separate linkage system can be considered as a finger phalanx. When using multiple four bar linkage systems, or applying a fingertip to the top bar, a motion with multiple DoF can be obtained when the proximal phalanx is halted by an object, thus given an underactuated motion [60].

Fig. 5: Birglen Optimal Laval Finger

Fig. 6: TBM Hand
4.1.1.2 Seesaw Mechanism

A seesaw mechanism starts out as a something very similar to a normal linkage system, whenever an actuation force is applied to the center of the beam. Similar to the differential, it gives equal reaction forces to the end of the linkages. In the example of the finger, both phalanxes receive an equal force from the actuation force, which triggers the bending of the finger. During the bending, the center of the seesaw beam is guided along a vertical sleeve. When the proximal phalanx comes in contact with an object, the center of the seesaw mechanism will start rotating, allowing the distal phalanx to keep on bending, despite the proximal phalanx being blocked.

![Fig. 7: Schematic representation of a Seesaw Mechanism used for a Two Phalanx Finger](image)

Found examples of the seesaw mechanism which were used in the fingers of grippers consisted of rigid linkage. The Southampton Hand [12] uses pin joints and rigid linkages to achieve the underactuated motion where the finger adapts itself around an object. In that paper, the used term for the seesaw mechanism is the Whiffletree mechanism (or whippetree).

A whippetree is a mechanism to distribute force evenly through linkages. The mechanism may also be referred to as an equalizer, leader bar or double tree. It consists of a bar pivoted at or near the center, with force applied from one direction to the pivot, and from the other direction to the tips. Several whippetrees may be used in series to distribute the force further, such as to simulate pressure over an area as when applying loading to test plane wings.

One widely known use of the whippetree mechanism (outside of the field of grippers) is that of draft animal harness, to let multiple animals pull a vehicle (see Fig. 9).

![Fig. 9: A set of whippletrees for a three-animal team](image)

By examining the schematic sketch shown in Fig. 7, and comparing them with the Southampton Hand, the same effect could be reached by the use of tendons/wires, instead of rigid linkages. The Southampton paper makes no mention on possible advantages of using rigid linkages over the use of cables, but they do make a reference on trying to design in favor of size and weight. One can make the assumption that the motivation of choosing rigid linkages over tendons was to achieve a better sturdiness and robustness in the finger itself.
Although this overview emphasizes on the finger mechanism of grippers, rather than the entire hand, examples of the seesaw mechanism were also found in the palm of the gripper. The mechanism in the palm helps distributing the actuation force of the driving tendon in a desired ratio over all the fingers of the gripper.

Early designs that use rigid linkages are the artificial hands made by Spellerberg (1864) and Henning (1918) [11], and a more recent use was with the TUAT/Karlsruhe Hand [13].

An interesting example of the seesaw mechanism with tendons was found in the Gosselin 15 DoF Hand [26]. This anthropomorphic gripper has a thumb that receives an actuation force, powerful enough to oppose the rest of the fingers. Thus, by using a tendon and a sliding pulley as a seesaw mechanism, the thumb receives an equivalent force as the sum of the forces of the other fingers. After that, the force is divided equally between the remaining fingers, again by the use of sliding pulleys.
4.1.1.3 Gears Linkage

For the gears, there are multiple mechanical methods available that result in the same function. One main gear gives an input, which in turn actuates multiple sub gears through an actuation moment. With differential gear mechanism, equal magnitude moments will be transferred to these sub gears, and otherwise distributed to the other gears if one sub gear is blocked. Varying the diameter and teeth for every gear can be used to achieve different rotation ratios and moment values. Although the gears are not exactly comparable with the other linkage systems, several grippers are using the gears as actuation, in combination with the other linkage systems. For those, the gears were used to apply underactuation between the separate fingers. No examples of systems were found where the gears would produce the underactuation within the finger itself.

Fig. 14: DH-2 (Delft Hand 2)

Fig. 15: Nasser Underactuated Passive-Adaptive Grasping
4.1.2 Compliant
Compliant mechanisms are able to deliver energy and motion from specified input ports to output ports utilizing elastic deformation of structures [87]. Where the linkage drive or transmission uses movable joints and rigid links, which are generally consisting out of multiple and moving parts, the compliant mechanism is consisting of bendable, elastic elements (usually designed as a monolithic structure). Concepts of it have been around since the 80’s, but compliant mechanism used as a drive mechanism with a linkage mechanism for motion is rather counter intuitive. During this literature research, no feasible or relevant result had turned up. For the mechanical fingers, compliant mechanisms were only found when used as joints between the phalanxes (Ciocarlie Data-driven Optimization Hand [48], SDM Hand [49]), or when the finger was a monolithic structure (Festo Fin Grasper [37]). These existing compliant grippers were only found in combination with non-rigid linkage for drive or transmission, and will be discussed further in the corresponding chapter 4.2.1 Compliant.

Fig. 16: Ciocarlie Data-driven Optimization Hand

Fig. 17: Festo Fin Grasper
4.1.3 Pneumatic/hydraulic

With gas and liquid being a deformable liquid, one provision can be used to influence multiple sections. Because the substance can be transferred into separate tubes, the actuation force also becomes divided into multiple reaction forces. This also explains the underactuated aspect of this system. When one of the phalanxes reaches an obstruction or mechanical limit, the force applied by that phalanx will remain the same, while the substance continues flowing to the other phalanx(es) and thus continuing the grasping/bending motion. With all the phalanxes blocked, the actuation force will be divided equally over the phalanxes.

Different types of pneumatic/hydraulic mechanisms for grippers were found for this overview. Either in combination with the rigid linkages (TWIX Pneumatic Hand [20]), as a substitute for the tendon or other form of actuation, or in the use of compliant material that has no distinctive phalanxes but still shapes itself around the object (Octarm [39]).

Fig. 18: Pneumatic triggered differential mechanism

Fig. 19: TWIX Pneumatic Hand  
Fig. 20: Octarm
4.1.4 Tendon

One or multiple wires/cables can be guided through, or alongside the finger, attached at the far end of the phalanxes. In the majority of gripper papers (especially the anthropomorphic ones), the term tendon is used to indicate the cable mechanism. This is mainly done due to the similarity of the wire with the tendon of the human hand. The bending motion of the finger is achieved by pulling the cable with an actuation force. As long as there are more DoF than actuators, than the method can be labeled as underactuated, making them relevant for this literature research. Comparing the hinging joints with pulleys, multiple DoF can even be reached with a single actuation cable. Like any typical pulley, the actuation force of the main cable on the base of the pulley is divided over two other cables. The output forces on them remain equal, despite the orientation of the pulley. With the pulleys fixed on the rotational joints between the phalanxes, the actuation force will still be transferred to other phalanxes when the proximal phalanx is obstructed or reached its mechanical limit. Since the pulley on the distal phalanx joint can rotate separate from the proximal phalanx joint, an underactuated bending motion can be achieved.

A nice use of this concept was found with the Gosselin 15 DoF Hand [26] and was also already mentioned at 4.1.1.2 Seesaw. Both the finger mechanism itself used tendons for underactuation, but inside the palm of the gripper, sliding pulleys would distribute the actuation force over the fingers in different stages.
4.2 Motion Systems

The existing main two methods of motion mechanisms were defined as rigid materials (as in linkages and sorts), and compliant materials. With motion systems, the emphasis lies on the material or mechanism used to achieve the bending motion of the finger. Instead of the entire finger, only the hinge mechanism used for the bending of the finger is defined. Similar to the human finger, the majority of the grippers mentioned in this overview, have phalanx movements that stay within the same plane (as in 2D movement).

4.2.1 Compliant

Opposite from the compliant mechanism discussed in chapter 4.1.2 Compliant, the compliant mechanism of this section comprises of the parts in the finger that gives the system the motion capabilities. The bendable aspect of compliant materials, give way to make hinging mechanisms that can be designed as a monolithic structure. The material properties can also give additional mechanical benefits, like moving the construction back into its original state, once the actuation force is removed.

By using elastic elements in favor of existing mechanical solutions, many movable components can be removed from the equation. Mechanical effects like wear or friction can become obsolete and joints no longer have any backlash effects. This and other effects will also lower the need for any high maintenance of the complex mechanical components. One of the noted main drawbacks of compliant mechanisms is that due to the storage of the energy in the elastic material itself, the ratio of output force can become distorted [88]. During the research, three main categories were recognized as the main design methodologies for compliant mechanism:

- Topology optimization [89]-[92]
- Pseudo rigid body model [88], [93]-[95]
- Building block approach [96]

These methods were mostly used when designing specific complex mechanisms. Simple, small deviations can also be determined with typical linear beam equations. For larger deviations (which is mostly the case for the grippers), non-linear equations are required to determine the characteristics of the mechanism.

Regardless of the design methodologies, the main principle of compliant mechanisms is that when the object is bended out of its steady-state shape, the energy is stored and transferred through the elastic elements. Depending on the elastic surface, high stress on a small area can cause buckling of the material. As described by Steutel [36] and Chen [97], buckling can be prevented by keeping the two main deformation methods of compliant mechanism in mind: lumped and distributed.
4.2.1.1 Lumped Compliant Mechanism

With lumped compliant mechanisms, stresses (and thus deformations) are concentrated on small parts of the mechanism. The majority of the object undergoes a rigid-body bending movement, except for the purposely designed weak points. Elastic deformation through stress will occur on those places, rather than the bending of the entire model. The majority of the existing compliant grippers are working with this concept. Obviously, fatigue, fracture and normal wear and tear will be found primarily at these hinge mechanisms, because that is where the stress is reaching the highest level. Currently, lumped compliant mechanism is mostly used in micro mechanics where the deviations are relatively small [97]. By adjusting the material thickness or choosing a different material, the input can remain within a certain range, making sure that the material properties can accommodate the applied stresses. The trade-off is in the ratio of deviation and stiffness that can be received with the chosen total stiffness of the mechanism, while still preventing buckling.

![Image](image1.png)

Fig. 23: Doria Three-stage Driving Mechanism Architecture

4.2.1.2 Distributed Compliant Mechanism

Contrary to the lumped method, the distributed compliant mechanism spreads all the stresses (and thus the deformations) over a larger elastic surface, making the overall stress level on the surface lower and the yield stress higher for distributed elements. This also makes the risk of fractures and wear and tear lower for distributed designed concepts. The main drawback is that with the bending of a larger surface, the typical hinge principle is harder to mimic.

With a larger surface that needs to be able to deviate, a general lower stiffness is needed over a large area. When compared to the lumped compliant mechanism, the distributed compliant mechanism is much more prone to deviations by external forces. Using different material or thicker surfaces could compensate for that, but would also mean that the needed actuation force for bending should be higher. Similar to the lumped compliant mechanism, a certain ratio has to be determined for optimal results.

![Image](image2.png)

Fig. 24: Steutel Fully Compliant Underactuated Finger with Monolithic Structure
4.2.2 Rigid

With many similarities to the linkages described in chapter 4.1.1 Linkage (when used as drive or transmission), the rigid elements here are defined as the joints that transfer motions and forces from an input to an output. Besides joints, an overall term that could cover most systems would be the hinge. For this table overview, an additional distribution of different hinge types will be discussed.

4.2.2.1 Pinned linkage

The most often encountered connection method in the rigid linkage section, mainly due to its simplicity. The two components can rotate freely in respect to each other, and are also sharing a common axis. By using this type of joint, the exact method of actuation is less relevant, whether it is by tendon, hydraulic or linkage.

![Fig. 25: Birglen Optimal Laval Finger](image)

A nice proof of this statement is found by comparing the Birglen Optimal Laval Finger [03], and the ZJUT Hand [22]. The Birglen Finger can be moved by applying a force on the outside perimeter of the finger itself. With the ZJUT Hand, the flexible pneumatic actuator changes in shape, bending the linkages into their new position.

4.2.2.2 Gear linkage

Different from the other joints, the main principle of geared mechanisms is that the force applied at the base of the finger, is transferred to the interlocking gears and used there for the bending. The different kind of gear mechanisms that were found in this survey were the bevel, spur and worm wheel gears. The fingers of the grippers only bend in the same plane, but the worm wheels and bevel gears change the plane of rotation. None of these two gears were found in the fingers itself, but only in the base of the gripper, transferring the actuation input towards the rest of the finger.

![Fig. 27: Bevel](image)  ![Fig. 28: Spur](image)  ![Fig. 29: Worm wheel](image)
4.2.2.3 Rolling joints

The performance of pin joints, sliders, gears, and cams is compromised due to friction, which in turn can create inconsistent force transmission, excessive wear and thermal losses. When using these kinds of mechanisms, compensation for frictional losses and the possible need for lubrication and feedback control have to be kept in mind [98].

When using those kinds of joints, positioning accuracy is only limited due to the static friction forces. It requires clearance at the joints to achieve mobility, which can leave it prone to backlash in the overall mechanism, making it difficult to reproduce motion transmission. This lack of precision and overall inefficiency when using the more traditional rigid-link mechanisms is being accepted for most cases, but might prove inadequate in others.

Rolling contact joints may be beneficial for designs that require low friction and backlash; however, the circular contact surfaces and associated kinematics developed to date are characterized by large Hertz contact stresses [99]. Furthermore, one can expect large bending stresses that occur when contact-aided compliant flexures are used between the surfaces to stabilize the joint. Finally an added complexity will present itself for pure rolling where two constraints are required, namely no slip (like gear teeth) and engagement through connecting links. One of the found grippers that make use of the rolling joints is Herder’s Force Directed Design Hand [34].

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![Herder Force Directed Design Hand](image)

**Fig. 30:** Undesirable characteristics of circular rolling contact joints in compression:
- a) Large Hertz contact stresses due to small radii
- b) Gear teeth or other no-slip provision required for tractive rolling
- c) Large bending stresses when flexures are used

**Fig. 31:** Herder Force Directed Design Hand
5 Category combinations

By recognizing and defining the different methods of actuation and abilities to transfer input into motion, the existing grippers can be sorted under their specific category. See table 1 on page 31 for the final division of all the found underactuated grippers. With two main methods of motion and four main methods of transmission, a total of eight possible combinations can be defined. This chapter will discuss every combination through definition and show some real-life examples of the found grippers.

5.1 Rigid Linkage

The combination of categories that, together with the tendon actuation, is the most common and logical working mechanism for an underactuated gripper.

Whether the input force of the hand is done with pneumatic, electric or some other actuation, the basic input motion that the fingers uses, is the movement of a rigid bar. This motion (either shortening or extending the rigid bar) can be used as input to make the fingers itself curl around the object.

Similar to the tendon mechanism, underactuation can be achieved by shortening the main bar by moving it towards the palm of the hand. Curling one phalanx while shorten the rod attached to the next phalanx, making it curl as well and thus give an underactuated motion [01], [06],[12], [15].
Another main method is similar to a four bar mechanism, where the four bar section driving bar pushes against the next phalanx section [02]-[04].

Sticking with these more traditional four bar mechanism, the fingers tended to be thicker, having a larger overall diameter, with a few exceptions through ingenious design [09], [13]. Comparing again with the pulling linkages, those designs tend to be more compact and anthropomorphic.

This section ended up containing both the complex (and often costly) models, used for high-end robotics [01],[08],[16], as well as the minimalistic and easy buildable solutions [03],[13].

For those minimalistic models, Birglen, Gosselin and Liberté wrote some excellent papers on the basic kinematic principles of underactuated linkage fingers [60],[98], based on their previous work of the renowned underactuated MARS finger and SARAH hand [08]. A lot of other grippers (mostly humanoid robotics) were filtered out of this overview, because the basic principle of the gripper
mechanism did not differ much from the ones mentioned above. This composes of high tech alternatives like the iLimb [59] or the Shadow Hand [66] that have been left out of this overview.

The rigid body linkages are mostly connected by pin-in-hole joints, where not every joint is reachable to be lubricated adequately. With friction, highly reduced force transmissions, and considerable play can occur [16]. The used reference also states that by using designs based on rolling joints, the mechanical efficiency would improve significantly, but at the cost of a fairly complex mechanism.
5.2 Rigid Pneumatic

All the grippers within the rigid pneumatic section start in a fully extended, with the help of spring elements. By filling up the bellow sections between the joints, the finger can wrap itself around the object. Gas or other fluid substance can flow freely to all the joint sections, pushing the distal phalanxes even when the proximal phalanx is halted by the object.

Looking at the possible benefits of this type of grippers over the rigid linkage ones, some papers refer to the lightweight construction, which would be beneficial when the gripper is used as prosthetic hand. Or that one can achieve a more smooth, fluid-like movement, as oppose to jerky, robot-like movement [18],[21]. Another paper mentions a major advantage of pneumatic systems over electromagnetic motors [42]. Although the motors can give a reasonable power density and a good bandwidth, the torque density is very low compared to human joint actuation. To accommodate this difference, gearheads are used to get a significant transmission ratio, which in turn significantly reduces the power density of the actuator (50 W/kg compared to the mammalian skeletal muscle that has 150-250 W/kg [102],[103]). Gas-type actuators give significantly better gravimetric and volumetric power density relative to electromagnetic-type actuators [104].

Another often claimed advantage for pneumatic use is that power transmitted by cables or gears will be prone to vibration, friction and relaxation, making it more difficult to control the gripper [22]. One of the possible major drawbacks is the method of powering the mechanism. Compressor-based approaches have a low power density, taking away the advantages of using a gas-type actuator over an electrical [42]. A suggested solution in that paper is the use of carbon dioxide (CO$_2$) canisters, where the gas is stored in a liquid form. CO$_2$-powered upper extremity prostheses were developed by several groups in the ‘60s and ‘70s, where a single CO$_2$ cartridge would provide an entire day of use [105]-[110]. If the desired gripper is needed for a portable use, like prostheses, then pneumatic actuation that needs a replaceable power source could be considered a disadvantage over tendon and rigid actuation that is powered by body movement. In the same way, a rechargeable electrical battery might have some benefits over a depleted power source that needs to be replaced.
5.3 Rigid Tendon

With the humanoid robotic approach of underactuated mechanism already well represented, other papers are often proposing to constrain the design towards simple control and realization, while trying to keep most of the robotic hand functionalities [111]. Based on the most basic of principles, wires and pulleys are often used and are also associated with the basic working of the tendons inside the human hand. When compared with the grippers that are electrical actuated and/or have gears mechanisms, the tendon actuated linkages tend to be lightweight alternatives. Lightweight and less complex mechanisms are qualities that are mostly sought after in the field of human prosthesis (both for the rigid and compliant motion category with tendon actuation) [34],[112].

The majority of the used mechanisms to achieve underactuation are showing correlations with the rigid linkage mechanisms. Instead of a rigid bar, a wire is pulled towards the base of the gripper. Together with the use of springs, or material stiffness, pulling the wires can be used for voluntarily closing [26] or opening [32] of the gripper.

Some papers mention that wire-driven is less reliable due to multiple drawbacks: friction loss, control delay, unpredictable non-linear behavior due to the friction and the elastic element of the wire [113]. All of these aspects would make the control precision of the gripper worse, and is used as an argument to prefer the gear mechanism over the tendon ones.
5.4 Rigid Compliant (non-existing)

As mentioned in section 4.1.2, the use of compliant material as a drive or transmission is already counter-intuitive. Especially, if one would try to combine this with a rigid hinge or joint connection as motion system. No feasible or relevant grippers were found during the research stage of this literature report. A basic system that comes closest to this kind of transmission is the Series Elastic Actuator [114]. If an elastic element is placed in series with the output of an electric motor, the force control performance of the motor is improved. This improvement means better shielding of the motor from shock loads, backlash effect, torque ripple and friction.

![Fig. 44: Schematic of Series-Elastic Actuator](image)

Based on the way the categories are defined in this paper, the Series Elastic Actuator is considered more of a gimmick to improve an existing drive or transmission, than really a separate method. Grippers that might have this type of actuator are rather classified under the tendon or linkage category, if the basic principle is recognized in that fashion.
5.5 Non-rigid Linkage *(non-existing)*

Combination of categories were the phalanxes would be bendable or adaptive, but the actuation would be achieved by a rigid bar or gear system. At first glance not that farfetched as a concept (for example, the use of gears) but no relevant results were found that weren’t more appropriate in another combination of categories.

The grippers that came closest to this category combination were Steutels Fully Compliant Finger [36] and the Carrozza Soft Hand [46].

![Fig. 45: Steutel Fully Compliant Finger](image1)

![Fig. 46: Carrozza Soft Hand](image2)

The first one is consisting completely out of compliant material, but the pushing action of the actuation bar comes close to the rigid bar as actuation. The second gripper uses a stiff metal wire as actuation, with compliant material forming the rest of the gripper, but the wire falls more under the tendon category.
5.6 Non-rigid Compliant

In this combination of categories, both the actuation as motion mechanism consists of mechanisms with bendable material properties. Existing grippers with this kind of combination were mostly found in the micro technology field, but those grippers were mainly single phalanx graspers. Furthermore, the majority of those grippers where also using rigid phalanxes for parallel phalanx grasping.

Besides one example of a multi-phalanx gripper in the field of micro technology (the earlier mentioned Doria gripper [38]), only two other compliant grippers were found outside this field: the Steutel Fully Compliant Finger [36], and the Festo Fin Grasper [37].

![Fig. 47: Doria Three-stage Driving Mechanism Architecture](image)

![Fig. 48: Steutel Fully Compliant Finger](image)

![Fig. 49: Festo Fin Grasper](image)

Both of them are lacking a clear distinction between phalanxes, but they were still added to this overview because of their unique approach and adaptive grasping. The compliant material properties were used as a method to envelop the to-be-grasped object. Contrary to the rigid single phalanx grippers, the compliant versions obtain multiple contact locations because of the adaptive grasping, and therefore qualify to be mentioned in this overview.

Using a lumped compliant mechanism might result in buckling when the material properties cannot accommodate the input force correctly over the hinge mechanism. On the other hand, energy might be better guided through the finger with the use of the distributed compliant mechanism, but that method takes away the distinct separation of the phalanxes. This would result in grippers that are not as anthropomorphic as other hand prosthetics.

Compared with the other grippers, the non-rigid compliant ones also seem to be limited in achieving a maximum bending angle. The three examples shown in Table 1, all have a bending angle that does not really exceed beyond 90 degrees. Other grippers (often the linkage and tendon) are showing performances with much larger bending capabilities, along the lines of 120 degrees. This can mostly be credited to distinctly designed phalanxes. Despite the use of lumped compliant mechanism with the Doria Three Staged Gripper [38], the separate phalanxes are more used as method to overcome the limitations of distributed compliant mechanism.

As mentioned in the main compliant section, recognized advantages include the absence of friction and backlash and the reduction of parts [101]. A disadvantage, in certain applications, is that the energy storage in the flexible members is distorting the input-output relationship [88],[101].
5.7 Non-rigid Pneumatic

Flexible fingers where the air-pockets within the fingers can be filled up with a pressurized gas or liquid to force the fingers of the grasper into a different configuration. In the case of the Octarm [39], there is not even a gripper shape to speak off, but only one long finger that can curl around an object, much like an elephant’s trunk.

There are not that many differences with the rigid pneumatic types of grippers, having roughly the same benefits and drawbacks as mentioned in chapter 5.2 Rigid Pneumatic. With the motion system as bendable material, rather than rigid, drawbacks like vibration and friction are even less likely than the rigid pneumatic grippers.

Out of the four grippers found with these characteristics, only two of them (RAPHaEL [40] and Fite Gas-actuated Hand [42]) can be considered anthropomorphic. With the rigid pneumatic section, the majority was anthropomorphic, but they were more qualified for the robotic field and are not really for the hand prosthetics.

The non-rigid motion system that is used for these grippers are significantly different. Where the RAPHaEL is using a strip compliant material as a ligament type of motion system, is the Fite Gas-actuated Hand using a simple torsion spring as compliant hinge. Torsion springs can be considered fully compliant, as they lack the shafts and bearings. The compliance of both systems provides a return force that simplifies actuation of the joints, since active extension of the joints via an extensive tendon is not necessary. Compliant joints also provide insensitivity to shock, which is an important characteristic in prosthetic devices, and enables limited deformation along other axes such as finger abduction.
5.8 Non-rigid Tendon

The final combination shows an intuitive and simple design that can be roughly divided into two groups. Because one of the main categories is the motion system itself, it does not show a clear distinction if the gripper is consisting completely out of compliant material, or if only the hinges are.

The first group has the entire finger consisting out of a compliant material, and the tendon actuation delivers the input force to grasp the object. With the UAPH [44] and Carrozza Soft Hand [46], lumped sections separate the finger into phalanxes, giving a more anthropomorphic feel to the grippers bending motion.

Other grippers like the IOWA [43] and Becker Lock-Grip [45], use the bending capabilities of a spiral spring for the bending motion and take the exterior of the spiral spring as the base look of the gripper.

Amusingly enough, a combination of previously two mentioned methods has been invented in the early 20th century. The tendon actuated hand prosthetic by Pringle [51], shows a spiral spring for the girth of a typical finger. Once tensioned by a wire, the strip with indents on the sides of the spiral spring will fit together, giving a more anthropomorphic bending motion.
The second group consists of the fingers where only the hinge mechanism qualifies for the non-rigid category. The phalanxes are rigid sections and the pieces that connect the hinges, can buckle under the tension of the actuation wire. This method is much like the buckling mechanism of the lumped compliant mechanism, but the non-rigid tendon grippers also have correlations with the tendon actuated rigid joint connections. Possible benefits and drawbacks of this type of gripper therefore show similarities with the earlier mentioned ones. A lightweight design, low production costs, where the production method (for example injection molding) can also be seen as cost efficient. Another advantage that all tendon actuated grippers have, is that the actuator for the drive or transmission does not necessarily have to be a complex or costly power source, but could also be body-powered. Of course, the disadvantages are similar to the ones discussed earlier for the other category combinations. For tendon actuation, situations like friction loss, control delay, and more were mentioned in 5.3 Rigid Tendon. The use of compliant material over rigid elements could result in a lower overall robustness of the gripper itself.

Fig. 58: SDM Hand

Fig. 59: Ciocarlie Data-driven Optimization Hand

Fig. 60: UBH3 (University of Bologna Hand, version 3)
## 5.9 Table 1: Overview

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<td>[51] Pringle (1919)</td>
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6 Discussion

At the start of this literature research, the assumption was that the majority of underactuated multi-phalanx grippers would consist of tendon based actuation systems. This was indeed the case (both rigid and non-rigid section), but the results also showed a large amount of grippers in the rigid linkage section. Keep in mind, that for this literature survey, all grippers that showed too many similarities were filtered out the overview. The overview would have ended up with a far larger number of tendon-based, both in the rigid and non-rigid section. The other sections had none or very few grippers that were filtered out. During the research itself, it also became clear that by using underactuation as one the main selection criteria, a significant amount of grippers in the robotics field were left out of the selection. Based on that, one can make the assumption that in controlled areas, manufacturers and users apparently feel more comfortable with high-tech and complex solutions. Despite the need for specific software input for every single hinge of the multi-phalanx gripper, in order to achieve adaptive grapping around an object. If these (electric) actuated grippers were added to the overview in the same manner as the other grippers, only a few designs would have been added in the table because of the filtration for all the working principles of mechanisms.

One criterion that could be used for choosing the ideal gripper is the total production costs and the overall complexity of the design. When comparing most designs with the pneumatic/hydraulic grippers, one can make the assumption that rigid connections and the use of gears and/or electrical motors will result in less complex and more cost efficient designs. Less complex designs would also mean easier to maintain and possibly easier to repair by changing parts. These distinctions as (dis)advantage, have all been left out in the category discussions, because no official paper was found that showed a clear and significant difference in production costs and maintenance.

During the research phase of this literature study, it became evident that only a select few of the papers showed clear data about the grippers’ characteristics. Examples of data that I was hoping to find was if one gripper could achieve a better or more stable grasp, compared to the other. Or if the gripper would have lower power consumption, better resistance to outside conditions and other influences one could encounter in real life use. Since the papers were mostly about the steps taken that resulted in the final design, no real competitive comparisons were made. In some cases, no real explanation was given on why their design would result in something more beneficial than the other underactuated grippers they had referred too in the introduction. Only a handful of papers were found that made a reference one why one mechanism was deemed cheaper, less complex or more efficient than the other. Unfortunately, these claims were often made without any real data or other references, and were assumed as common knowledge. The overall goal of helping future designers choosing their ideal gripper is thus only partly realized. The final decision will still be based on assumptions of the design complexity or the costs for manufacturing and maintenance.

Some of the used papers are using the term robustness to indicate the stability of the grasp [71],[90],[115]. For this paper, the term robustness is used as indication of ease of maintenance and low probability of mechanical failure. With the more general types of mechanical hinges and complex machinery like pneumatic or electronics, the chances of mechanical failure or need for maintenance is deemed higher than those of the compliant mechanisms.

Reading the papers about new underactuated designs, one often recurring design criteria was the desire to build a cheaper and more lightweight version than the existing robotics versions. Both weight reduction and cost efficiency can be achieved by removing the multiple actuators from the design and come up with an underactuated method that can reach the same dexterity. Having the finger adapt itself to the object, allows for a wide range of objects that can be picked up.
Furthermore, no complex and expensive sensors are needed or additional software to navigate the fingers of the gripper. The qualities of both lightweight and ease of manufacturing can be credited to compliant mechanisms, although only three (distinct) examples of fully compliant grippers were found. By only looking at the hinges of the grippers, a larger section of compliant based grippers could be identified, in combination with the widely used tendon actuation. Not necessarily used in grippers, but compliant mechanisms itself have been around since the 1980’s [115]. Recognizing these qualities of fully compliant grippers, it is sort of surprising that only a handful of grippers can be labeled as fully compliant. Designing a monolithic gripper can result in tremendous cost reductions for both manufacturing as the assembly of the gripper. It’s therefore this author’s opinion that a lot more research could be done for the designing of grippers or even hand prosthetics in that field of research.

7 Conclusion

This paper has succeeded in categorizing the grippers into their working principles. For the first time, a clear overview is created where the grippers can be sorted according to their mechanism, rather than making a listing of commercially available (underactuated) grippers. Depending on the used criteria the desired multi-phalanx underactuated gripper should accommodate, the most common choice appears to be a tendon based (with either rigid link connections or compliant material for the motion mechanism). Compliant designs could show a benefit in production costs and overall robustness of the gripper. Limitations of compliant designs are found in the material properties, where the storage of energy in the material cannot always accommodate the desired bending angle. The ratio of output force of the linkage is also more beneficial with the rigid linkage mechanisms.
References

**Grippers**

*Rigid Linkage – See Appendix pp. 44*


Rigid Pneumatic/Hydraulic – See Appendix pp. 51


Rigid Tendon – See Appendix pp. 54


**Non-rigid Compliant – See Appendix pp. 60**

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[37] Festo, **Bionictripod 2.0,** retrieved from [http://www.festo.com](http://www.festo.com).

Non-rigid Pneumatic/Hydraulic – See Appendix pp. 62


Non-rigid Tendon – See Appendix pp. 64


Other relevant papers


[67] Schunk GmbH & Co., **Schunk dexterous hand (SDH)**, retrieved from [www.schunk.com](http://www.schunk.com).


## Appendix

### Overview Table

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Grippers

Rigid Linkage


Three phalanxes


Each finger could individually be adjusted and locked by using a ratchet mechanism. The device could be unlocked by pushing a knob which permitted the springs to return the hand into an extended position.

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<thead>
<tr>
<th>Page</th>
<th>Images</th>
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<tbody>
<tr>
<td>[10]</td>
<td>![Image](98x345 to 339x430)</td>
<td>Second Jagthäusen Hand (1509)</td>
</tr>
<tr>
<td>[11]</td>
<td>![Image](443x139 to 573x320)</td>
<td>Another seesaw mechanism, underactuated with four bar linkage</td>
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<tr>
<td>[12]</td>
<td>![Image](213x202 to 345x293)</td>
<td>Seesaw mechanism</td>
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Birglen, L., Laliberté, T., Gosselin, C. (1946)


Passive mechanical adaptation


### Rigid Pneumatic/Hydraulic

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<th>Reference</th>
<th>Authors</th>
<th>Title</th>
<th>Conference/Proceedings</th>
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**Figure 1:** New Ultralight Anthropomorphic Hand

**Figure 2:** Overview of the TAKO-Flyer

**Figure 3:** Concept of TAKO-finger

**Figure 4:** Prototype for the TAKO gripper (3-fingered 15DOF system is adaptively controlled by only one single motor.)

**Figure 5:** TAKO Flyer

**Figure 6:** NEW SALE Pneumatic Hand


[21]
[22]

Fluid Hand

ZJUT Hand

1 Non-thumb’s tip; 2 Top segment; 3 Joint I; 4 Middle segment; 5 Screw; 6 Joint II; 7 FPA; 8 Bias segment; 9 Joint III; 10 Pipe connector; 11 Joint IV

Fig. 6 The non-thumb of robot hand

Newer version of [18]
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Seesaw mechanism like the 2003 TUAT hand [13]

Dale Artificial Hand (1946)

![Lopez Hand](image)

Cables: 6, 18, 7


![Octopus Hand](image)

Figure 4.17: La main Octopus pour une prise en deux temps : extraction par dépression, puis stabilisation par un mécanisme sous-actionné à trois doigts.


![Herder Force Directed Design hand](image)

Glove used to return to stretched finger position (plus additional springs to counteract deformation glove material)

![Rolling joints](image)

Figure 3a. Design of a two-phalanx finger: 1, distal phalanx; 2, proximal phalanx; 3, middle joint; 4, finger bone; 5, major tendon; 6, minor tendon; 7, proximal tendon; 8, cylinder; 9, small plate; A, B, and C, anchors attachment point; a, angle between metacarpal and proximal phalanges; and b, angle between proximal and distal phalanges.
**Non-rigid Compliant**

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<tr>
<td>[37] NC  DC</td>
<td><img src="image2" alt="Festo Fin Grasper" /></td>
<td>Festo, <em>Bionictripod 2.0</em>, retrieved from <a href="http://www.festo.com">http://www.festo.com</a>.</td>
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</tbody>
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Festo, Bionictripod 2.0, retrieved from [http://www.festo.com](http://www.festo.com).

Non-rigid Pneumatic/Hydraulic

Octarm

[39]
NP
DP

[40]
NP
DP

[41]
NP
DP

[42]
NP
DP

Air pockets are filled with air for closing motion.
Ligaments are used for open position as steady state.

RAPHaEL (Robotic Air Powered Hand with Elastic Ligaments)

AMADEUS

Gas-actuated hand

Torsion springs: Distributed compliant
No tendon, tube inflated, torsion springs flexes back
Non-rigid Tendon


Imperial Hands permits easy adjustment of finger prehension force with the use of a screwdriver.
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**Carrozza Soft Hand**

**Fig. 3.** Structural scheme of the endoskeleton.

**Fig. 4.** Prototype of the finger.

**Bologna U.C. Finger / Gloveless endoskeletal hand**

**Ciocarlie Data-driven Optimization Hand**

**Doshi Yeh LeBlanc (1998) The design and development of a gloveless endoskeletal prosthetic hand**
Passive mechanical adaptation SDM (Shape Deposition Manufacturing) mechanisms are simultaneously fabricated and assembled.


Pringle Artificial Hand (1919)