The Hybrid Finger:
Combining Nature with Technology into a 3D Printed Finger for a Hand Prosthesis with Minimized Assembly

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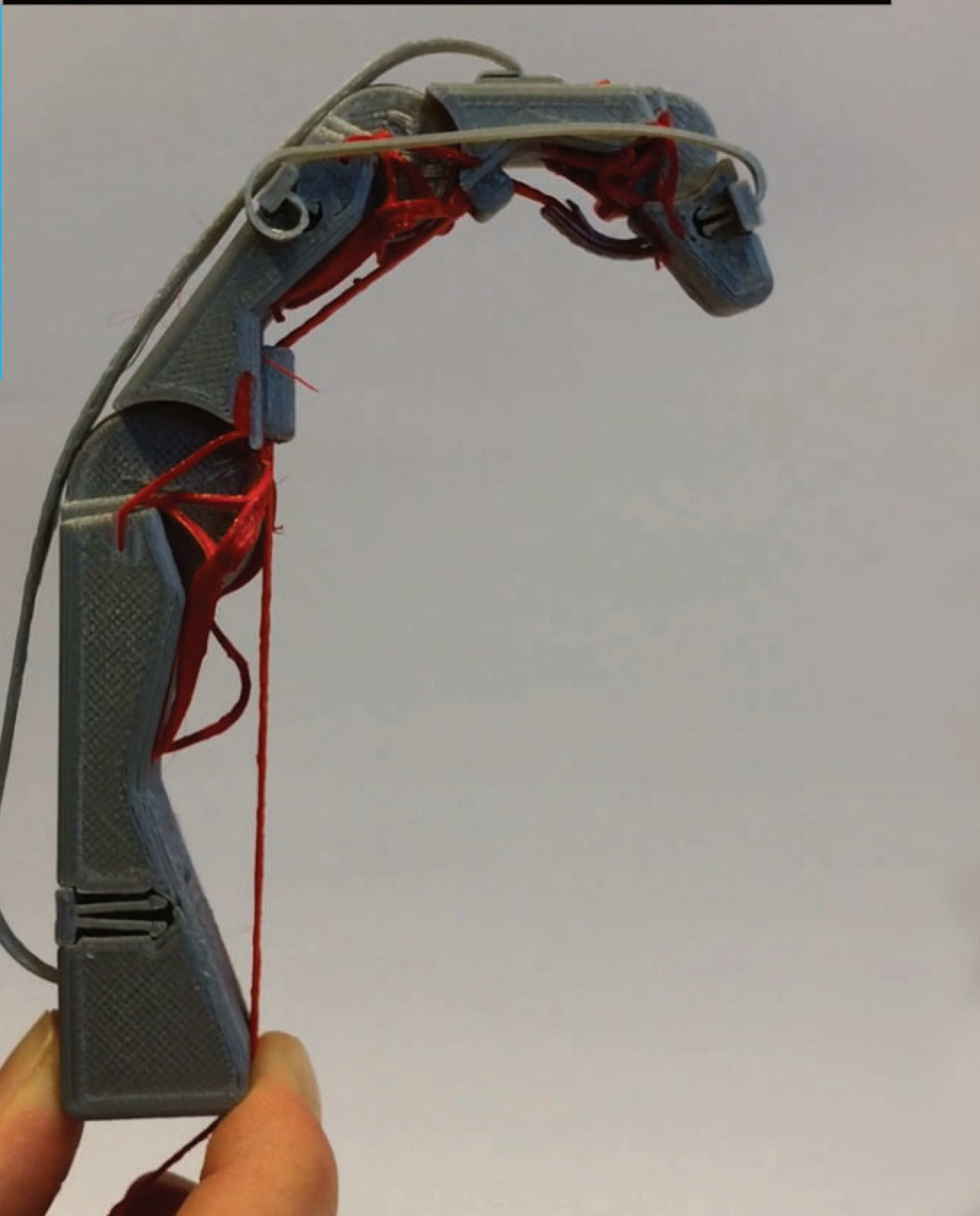

The Hybrid Finger
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by

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Preface

I have always enjoyed to make, build and create things. For example, I liked to play with LEGO instead of dolls when I was a young girl. I liked to create things with LEGO to make the life of the tiny LEGO puppets better, such as building a beautiful house. This shortly represents my interest in technology as a means to improve quality of life of all people. Not only for the people around me here and now, but also for the people of the future, and for people in less developed countries in the world. This is my motivation to become an engineer.
Improving quality of life is also my motivation to design a finger for a hand prosthesis for use in low-income countries. Even though I may have contributed only a bit to an actually used product, I am proud to be part of it. I want to thank some people for supporting me to finish my Master in Mechanical Engineering. Thanks to all of my supervisors: Paul, Gerwin, Juan and Costanza. Thanks for helping me to finish this project with a functional prototype by sharing your knowledge on design and prosthetics and for thinking along with me. Ik ben enorm blij met de hechte band die ik met mijn familie heb: bedankt dat jullie altijd voor me klaar staan en in me geloven. Goof, ik kan je niet genoeg bedanken voor alle liefde, steun en hulp die je me geeft! Ik kan niet wachten tot we op reis gaan later dit jaar. Al mijn lieve vrienden en schoonfamilie: bedankt voor de gezelligheid, interesse en af en toe wijze raad.

Merle Celine van der Kroft
Rotterdam, 16 januari 2018

Contents

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Merle van der Kroft

January 25, 2018

Abstract

Access to prosthetics is very limited to many potential users, while the need is high. There are two main reasons for this that both are related to the production of prosthetics: the lack of skilled people and high costs. Minimized assembly production using 3D printing could be a solution: no training is required, assembly takes only a short amount of time and cheap materials can be used. Besides, 3D printing is a good method for customization. Therefore, this study proposes a 3D-printed finger for a body-powered hand prosthesis with minimized assembly. The design approach is the following. First, the human finger anatomy is studied. Then, a stylized version of the human finger is made that includes only the functions required for the prosthesis. Finally, the design principles of the stylized finger are evaluated and structurized. Based on the design principles, a finger for a prosthetic hand is designed and a prototype is developed. The prototype is produced with an Ultimaker 3 using a rigid and a flexible material in one print. The evaluation of the prototype shows promising results. The finger is suitable for a hand prosthesis that can perform an adaptive power grip and a pinch grip. The mass of the finger is 17 grams, which makes the finger comfortable to wear. An actuation force of only 16 N is required to fully bend the finger. Minimized assembly and cheap production are achieved: only four assembly steps are required and the material costs are only 1.68 euros per finger. In conclusion, the prototype shows a promising step in the direction of a hand prosthesis that is affordable, functional, body-powered, and has minimized assembly.

1 Introduction

1.1 Prosthesis Production

Currently only 10 percent of people have access to assistive technologies according to the World Health Organization. In over 75 percent of low-income countries, there is no prosthetics training program [1]. However, in these countries the highest prevalence of disability-related health conditions is found.
Upper limb deficiency is such a condition. Someone with an upper limb deficiency misses a part of the upper limb, for example the hand. Numerous types of hand prostheses exist to compensate for the missing hand. However, there are many potential users that do not have access to them. There are two main reasons for this that both are related to the production of prosthetics: the lack of skilled people and the high costs [1].
We first provide background information on minimized assembly of prostheses using 3D printing and different types of prostheses, before coming up with a problem definition and a goal.

1.2 Minimized assembly of Prostheses using 3D Printing

Minimized assembly production is a production method in which no training is required and assembly time is short. This can reduce the costs of a prosthesis drastically. 3D printing is pointed out as a feasible technique for production of minimized assembly mechanisms [2]. Mechanisms that are produced with 3D printing can easily be customized which is desirable for prosthetics. Besides, cheap materials can be used in a 3D printer reducing the costs even further. Hence, minimized assembly production using 3D printing is a feasible solution for affordable prosthetics.

1.3 Types of Prostheses

Hand prostheses can be categorized by controllability and by the source of power. On the one hand there are passive prostheses that can not be actively controlled. There is no source of power in this type of prostheses. On the other hand there are active prostheses that can be activelty controlled. Two sources of power for active prostheses can be distinguished: external power, and body power.
Among users, non-functional gripping is indicated as one of the main reasons for rejection of a prosthesis [3]. This explains the high rejection rate of passive prostheses, that have a very limited functionality: 39 % among adult users [4]. The comfort of a prosthesis is another main reason

for rejection of a prosthesis. Externally powered prostheses usually have a higher mass due to for example the battery that is included in the design, making the proshtesis uncomfortable to wear. The body-powered hand can have a function grip, while being lightweight. For this reason this study proposes to design a body-powered hand prosthesis.

1.4 Problem Definition

It is desirable that the proposed hand prosthesis is body-powered, that it has minimized assembly, and that it has a functional grip. A functional grip can be achieved by making the fingers of the hand prosthesis adaptive. For this reason, we focus on the design of a finger of a prosthesis. On the one hand, existing functional fingers for body-powered hand prostheses have a long assembly time. For example the SHARP hand [5] or the Cyborg Beast [6]. On the other hand, existing minimized assembly fingers for body-powered hand prostheses are not adaptive. For example the FA3D hand [7]. Hence, no finger for a body-powered hand prosthesis exists that has minimized assembly and has a functional grip.

1.5 Design Approach

Existing bio-inspired designs of fingers for adaptive hands have a functional grip, namely an adaptive grip [8], [9]. Therefore, the design of the proposed finger is bio-inspired. We study the anatomy of the human finger because we assume that it has been optimized by thousands of years of evolution. We make a stylized version of the human hand in which we include only the components with functions that are required for the prosthetis finger. We use the design principles of the stylized finger for the design of the prosthesis finger.

1.6 Goal

The goal of the study is to design and develop a prototype of a bio-inspired finger for a hand prosthesis that:

- is body powered
- is produced with 3D printing to minimize assembly
- has a functional grip

1.7 Outline

Section 2 presents background information on anatomy of the human finger. In Section 3 a stylized version of the biological finger is proposed. Section 4 presents the design principles of the the stylized biological hand. Section 5 presents the design requirements. Section 6 presents the finger that is designed following the design principles and explains the production of the prototype. The prototype is evaluated in Section 7. The paper concludes with a discussion and a conclusion in Sections 8 and 9.

In this paper a color scheme is used so that it is easy to distinguish the different components of the finger. Figure 1 shows a drawing of a finger with all the components that are included in this paper. Table 1 is the legend for the colors used in Figure 1. Also names for axes, directions and movements are used consistently throughout the whole paper. Figure 2 defines the names of the axes and of the directions along the axes. Figure 3 defines the names of the movements that the fingers can make.

Figure 1: The finger including all the components used in this study. The colors are defined in Table 1. The Figure is adapted from [10].

Table 1: Legend of the colors of the finger components in Fig. 1.

Color	Biological name of Component
	Bone
	Accessory collateral ligament
	Palmar ligament
	Proper collateral ligament
	Flexor Pulley sheets
	Extensor sheets
	Flexor Digitorum Profundum
	Flexor Digitorum Superficialis
	Central band of Extensor Digitorum Communis
	Lateral bands of Extensor Digitorum Communis
	Lumbrical muscle and Interosseus muscle

2 Anatomy of the Human Finger

2.1 Scope

The construction of the human finger is studied for design of the construction of the prosthetic hand: the bones and the joints and the ligaments that connect them. The components for movement control of the human finger are studied for the transmission and actuation design: the muscles and tendons and the pulleys and sheets that guide the tendons. There are also other components in the human finger, such as nerves, veins and joint capsules. They are out of the scope of this work because they are not relevant for the design of the finger for a body-powered

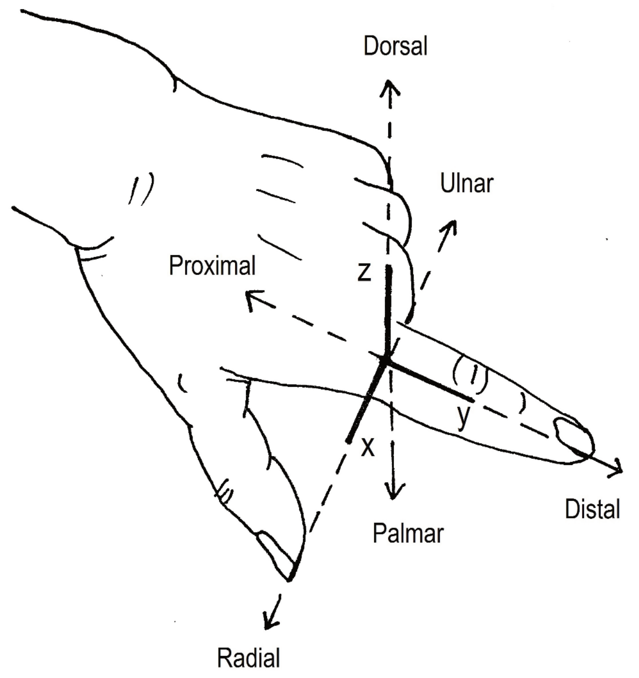


Figure 2: Definitions of the x-axis, y-axis and z-axis used in this paper with respect to the human finger. The names used to indicate directions along the axes are also indicated.

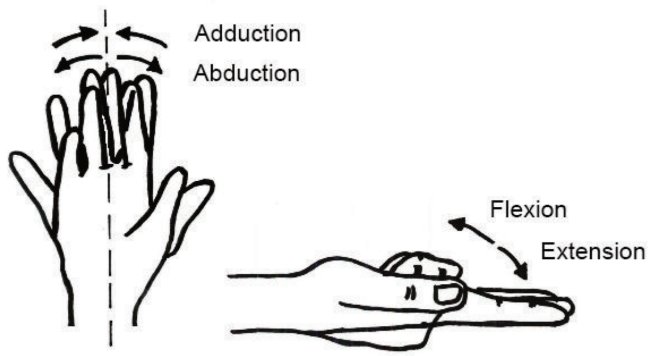


Figure 3: Definition of the movements of the human finger, adapted from [11]

hand prosthesis.
In the human finger the construction of all four the fingers is the same, but the actuation and transmission mechanism is not: the index finger and the little finger can move independently while the middle finger and the ring finger can not. We do not require independent movement of the fingers, so the middle finger and the ring finger of the biological hand are studied. During the anatomy study simple 3D models were created to better understand and visualize the components and the working principles of the human finger. The models can be found in Appendix A.

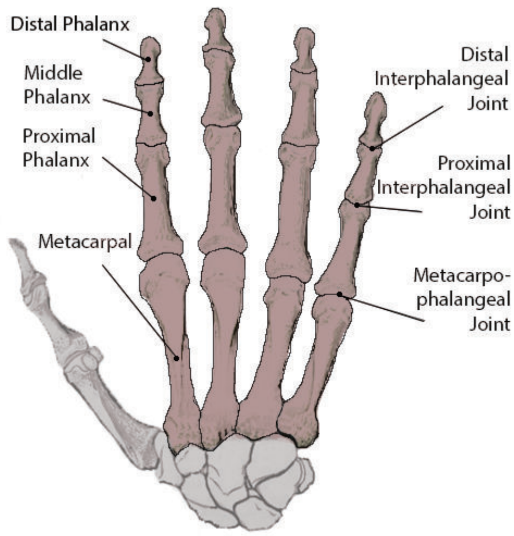


Figure 4: Drawing of the bones in the human hand. The four fingers are highlighted. Colors are as defined in Table 1. Adapted from [12].

2.2 Bones and Joints

The human finger is constructed by bones and joints. As we are interested in the construction of the finger, this subsection gives a description of the bones and joints in the finger. Figure 4 shows the four bones of the human finger that can be considered the rigid bodies of the finger. Working from proximal to distal, the bones of each finger are named the metacarpal (MCP), the proximal phalanx (PP), middle phalanx (MP) and distal phalanx (DP). The three phalanges together form the finger while the metacarpal is inside the palm of the hand. Joints allow the four rigid bodies to move relative to each other. The joints are named the metacarpal (MCP) joint, the proximal interphalangeal (PIP) joint and the distal interphalangeal (DIP) joint as indicated in Figure 4.
There are two different types of joints in the fingers: the ellipsoid joint and the hinge joint. The degrees of freedom (DoF) and the components that stabilize the joint are characteristic to each joint type. Table 2 lists their characteristics.
The hinge joint exists of a convex surface on the proximal side and a concave surface on the distal side in the x,z-plane that can slide along each other. Rotation about the x-axis only is allowed by this shape of the joint. The ellipsoid joint exists of a convex surface on the proximal side and a concave surface on the distal side in both the x,z-plane and the y,z-plane that can slide along each other. Rotation about both the x-axis and the z-axis are allowed by the shape of the ellipsoid joint.
There is a rim along the convex surface and and a groove along the concave surface along the joint surfaces of both the hinge and the ellipsoid joint. This prevents translation along the x-axis.

Table 2: Main characteristics of the finger joints: Name of the joint, Type of joint, Degrees of Freedom (DoF) of the joint, Components that stabilize the joint [11],[12].

Name	Type	DoF*	Stabilization
MCP joint	Ellipsoid	1. Flexion/extension 2. Adduction/abduction	1. Ligaments 2. Extensor hood of Extensor Digitorum Communis 3. Intrinsic muscles
PIP joint	Hinge	1. Flexion/extension	1. Ligaments
DIP joint	Hinge	1. Flexion/extension	1. Ligaments

*Only actively controlled DoF are included in the table. The MCP joint has one passively controlled DoF: rotation along the long axis.

2.3 Ligaments

Ligaments connect the bones to each other. The main function of the ligaments is to stabilize the joints. The range of motion of the bones is restricted by this stabilization. Figure 5 indicates three types of ligament that can be distinguished: the proper collateral ligament, the accessory collateral ligament and the palmar plate. The movements that the different ligaments restrict are characteristic to each ligament and are listed below.

1. The palmar plate is a foldable sheet that is located at the palmar side. It stabilizes the joint by preventing hyperextension of the PIP and DIP joint. Hyperextension is defined as rotation along the x-axis in the dorsal direction. In the MCP joint about twenty to thirty degrees of hyperextension is allowed.

2. The proper collateral ligament is located on both lateral sides. It is attached eccentricly. It restricts translation along the y-axis: abduction and adduction. At the MCP joint this rotation is restricted to about twenty degrees when the MCP joint is straight. Due to the eccentric attachment, the tension in the ligament increases as the MCP joint flexes and as a result the abduction and adduction is further restricted. At the PIP and DIP joints it is less diagonally attached than in the MCP joint so that abduction and adduction are restricted already in a straight joint. Next to the restricting of abduction and adduction the proper collateral ligament also restricts the degrees of flexion in all three joints to about ninety degrees due to the increasing tension in the ligament.

3. The accessory collateral ligament is located on both lateral sides. It originates from the centre of rotation of the proximal side of the joint and it attaches to the palmar plate. It has the shape of a fan so that the distance from origin to attachment is constant [10].

2.4 Muscles and Tendons

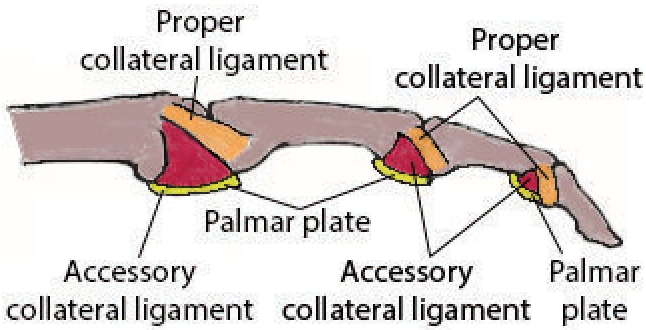
2.4.1 Type of Muscles

The muscles are the actuators of the finger and the tendon transmits the force of the muscle to the bones of the finger. Both the ring and middle finger have the same muscles and tendons anatomy.
There are two types of muscles: extrinsic muscles that originate in the forearm and intrinsic muscles that originate in the palm of the hand. The intrinsic muscles do not have their own tendons: they attach to the tendons of the extrinsic muscles. Figure 6 shows all the muscles in the human finger. Table 3 lists the characteristics of the different muscles.

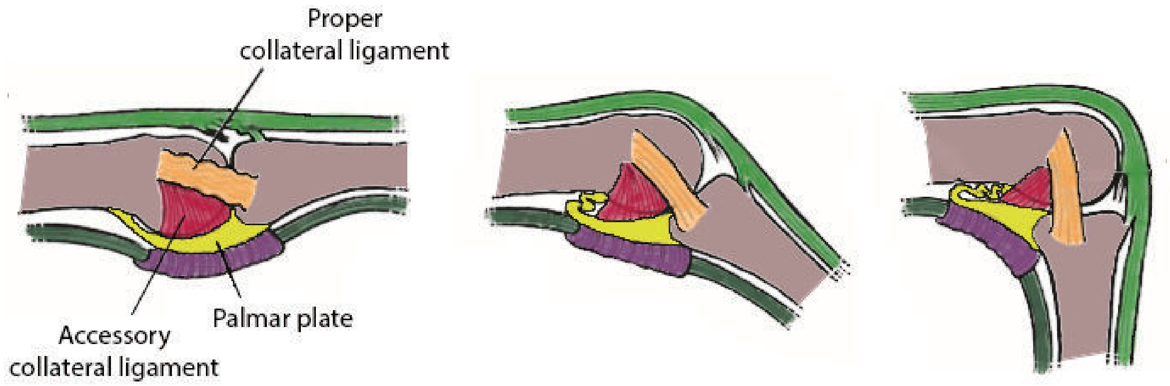
2.4.2 Actuated Degrees of Freedom

Flexion and Extension
Two muscles are mainly responsible for flexion of the whole finger: the FDP and the FDS. The FDP is the main flexor. The FDS helps if the force that the FDP exerts is not high enough, for example when there is an external force exerted on the finger. The FDP cannot flex each finger independently due to the FDP tendons arising from a common tendon in the forearm. The FDS can flex each finger independently. The intrinsic muscles help to flex the MCP joint via their attachment to the extensor hood.
The central slip of the EDC is mainly responsible for extension of the MCP joint. The lateral bands of the EDC help to extend or flex the PIP and DIP joint depending on the location of the band with respect to the joint's center of rotation. The intrinsic muscles help to extend the PIP joint and DIP joint via their attachment to the extensor tendon.

Adduction and Abduction
We name the thumb finger 1 and we work in ulnar direction to the pink being finger 5. The dorsal interossei adduct the MCP joint in finger 2-4 and abduct finger 3. The palmar interossei abduct finger 2, 4 and 5 [11], [12].



(a) An overview of the ligaments in the whole finger



(b) From left to right: joint with ligaments in a straight finger, joint with ligaments in a slightly bent finger and joint with ligaments in a fully bent finger. Tendons and pulleys are included in this figure.

Figure 5: Schematic drawings of the ligaments in the human finger. Colors are as defined in Table 1. The Figures are adapted from [10].

Table 3: Characteristics of the finger muscles: Muscle Type (extrinsic or intrinsic), Actuated DoF, Origin of tendon (extrinsic muscles) or muscle (intrinsic muscles) and Insertion of tendon(extrinsic muscles) or muscle (intrinsic muscles) [11],[12].

Muscle	Type	Actuated DoF	Origin	Insertion
Flexor Digitorum Superficialis (FDS)	Extrinsic	Flexor of PIP & MCP	Forearm	Base of MP
Flexor Digitorum Profundus (FDP)	Extrinsic	Flexor of DIP, PIP & MCP	Forearm	Base of DP
Extensor Digitorum Communis (EDC)	Extrinsic	1. Extensor of MCP 2. Extensor of PIP and DIP (if the lateral bands shift to above the joint's center of rotation) 3. Flexor of PIP and DIP (if the lateral bands shift to under the joint's center of rotation)	Forearm	1. Base of MP 2. Base of DP
Lumbrical	Intrinsic	1. Flexor of MCP 2. Extensor of PIP & DIP	Tendon of FDP	Tendon of EDL
Dorsal Interosseus	Intrinsic	1. Flexor of MCP 2. Extensor of PIP & DIP 3. Ad/abduction of MCP	Lateral side of metacarpal bone	Extensor hood
Palmar Interosseus	Intrinsic	1. Flexor of MCP 2. Extensor of PIP & DIP 3. Ad/abduction of MCP	Lateral side of metacarpal bone	Extensor hood

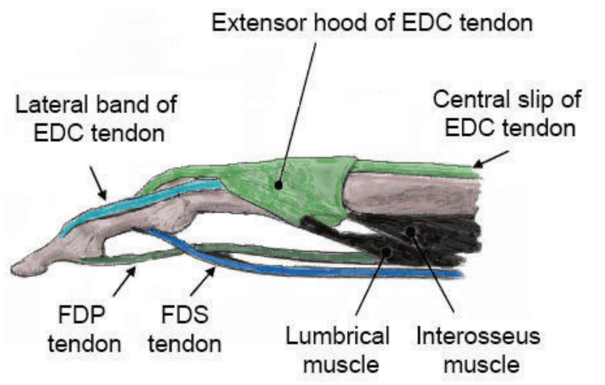


Figure 6: Schematic drawing of the human finger that indicates all the muscles in the human finger. Colors are as defined in Table 1. Adapted from [13].

2.4.3 Shape of Tendons

Flexion

Figure 6 shows the shape of the tendons. The insertion of FDP has a larger area than the insertion of FDS. This makes the insertion of FDP stronger. The FDS tendon has a superficial insertion increasing its distance to the PIP joint and thus increasing the moment arm around the joint. The FDP lies closer to the bone than FDS in the forearm, while FDP's attachment is more distal than FDS's. As a result FDP's and FDP's tendon cross. FDS splits and FDP goes through the split. In this way they cross symmetrically.

Extension

The EDC tendon has a notable shape in which three areas can be distinguished: the extensor hood, the central slip and the lateral bands (there is one band on both lateral sides). The intrinsic muscles insert on the tendons of the extrinsic muscles. The lumbricals and the dorsal and palmar interossei insert on the extensor hood. The extensor hood has an additional function: it stabilizes the MCP joint by wrapping around it.

The movement of the PIP and DIP joint are coupled mechanically by the central slip and the lateral bands of the EDC tendon. When PIP flexion is larger than DIP flexion, tension in the central slip is high, while tension in the lateral bands is low. As a result it is easier to flex the DIP joint than the PIP joint. When DIP flexion is larger than PIP flexion, tension in the lateral bands is high while tension in the central slip is low. As a result it is easier to flex the PIP joint than the DIP joint [14].

2.5 Pulleys and Sheets

The tendons are kept in place by pulleys and sheets. The extensor tendon needs to be kept in place only where it crosses the joints due to its flat geometry and the intrinsic muscles that help keeping it in place. The flexor tendons need to be kept in place all along the finger to ensure that the workline of the transmitted flexor muscle force is perpendicular to the joint centre of rotation [14]. In this way the force of the tendon has a maximized moment arm at the joint. Figure 7 shows the sheets on the extensor side that prevent the subluxation of the tendon. On the flexor side fibrous sheets wrap around the finger along the full length of the finger. They are strengthened at intervals by a series of elastic bands called pulleys, that are local thickenings of the sheet. Two types of pulleys can be distinguished: annular pulleys and cruciate pulleys. The former have a straight and flat geometry and they prevent tendon excursion during flexion. The latter are crossings of two narrow bands and they provide the flexibility for approximation of the annular pulleys during flexion while maintaining a continuous inforcement of the sheet [15]. Figure 8 indicates the organization along the finger: broader pulleys lie over the phalangeal shafts and narrower pulleys lie over the joint. In this way the risk of sheet buckling is minimized. Buckling can impede the tendons that pass through it. Also the flexor force workline is maximized by the organization along the finger.

The dynamics of the finger are enhanced by the pulleys

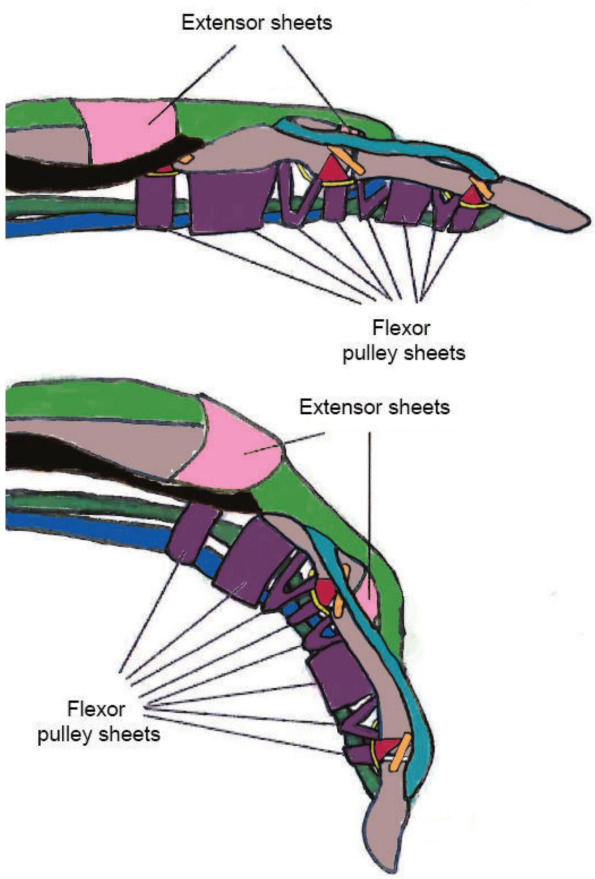


Figure 7: The finger in straight (top figure) and bend (lower figure) position with the extensor sheets and the flexor pulleys indicated. Colors are as defined in Table 1. The Figure is adapted from [10].

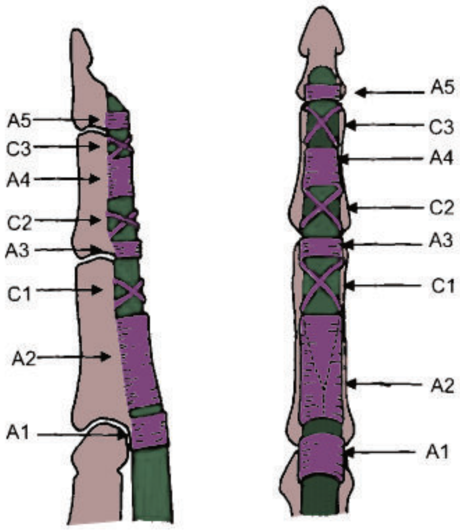


Figure 8: Schematic drawings of the pulley locations in the finger, left: lateral view and right: top view, A1 - A5 indicate annular pulleys, C1 - C2 indicate cruciate pulleys. Colors are as defined in Table 1. The Figure is adapted from [15].

being flexible. If the straight finger starts to flex, the moment arms at the joints are small which results in a fast bending motion with small torques at the joints. As the flexion angle increases, the pulleys starts to stretch out because the flexor exerts a force on it. The stretched pulley results in an increase of the moment arm. This results in the motion slowing down and the torques increasing. The movement is fast and torques are small when approaching an object and movement slows down and torques are high when forming a grip around the object [16].

3 The Stylized Human Finger

3.1 Components of the Stylized Finger

This Section proposes a stylized version of the human finger. Stylizing the finger is done in two steps: first the components of the biological finger with functions that are not required for the prothesis are excluded from the stylized version of the finger and second the characteristics of the finger components are pushed to their extremes. We exclude the following components to end up with a stylized hand:

1. The ellipsoid joint is excluded: all the joints in the finger are hinge joints. This type of joint has one DoF: rotation along the x-axis. In the prosthesis one degree of freedom per joint can be actively actuated as there is just one pulling cable for actuation. The finger still has an adaptive grip when the additional DoF of the ellipsoid joint is excluded.

2. Intrinsic muscles are excluded. The intrinsic muscles are required for stabilization of the wrist, for precision handling or for actuation of the additional DoF of the ellipsoid joint. The prosthesis has a fixed wrist, precision handling is not required and the ellipsoid joint is excluded. Fig. 9a shows the finger with only the extrinsic muscles.

3. The FDS is exluded, leaving the FDP as the only flexor. In biology the FDS is used when there is not enough force using the FDP alone. In the prostheses this is not a problem because the available force of the user's shoulder is transmitted through the single pulling cable. Adding another cable would not add force because it cannot be actuated. Figure 9b shows the muscles that are left after excluding the FDS.

4. The extensor sheets are excluded. Figure 9c shows the finger without the sheets. They are used to keep the extensor mechanism in place. In the prosthesis the chance of subluxation is very limited due to exclusion of adduction and abduction and pre-tension of the extensor cable.

3.2 Characteristics of the Stylized Finger

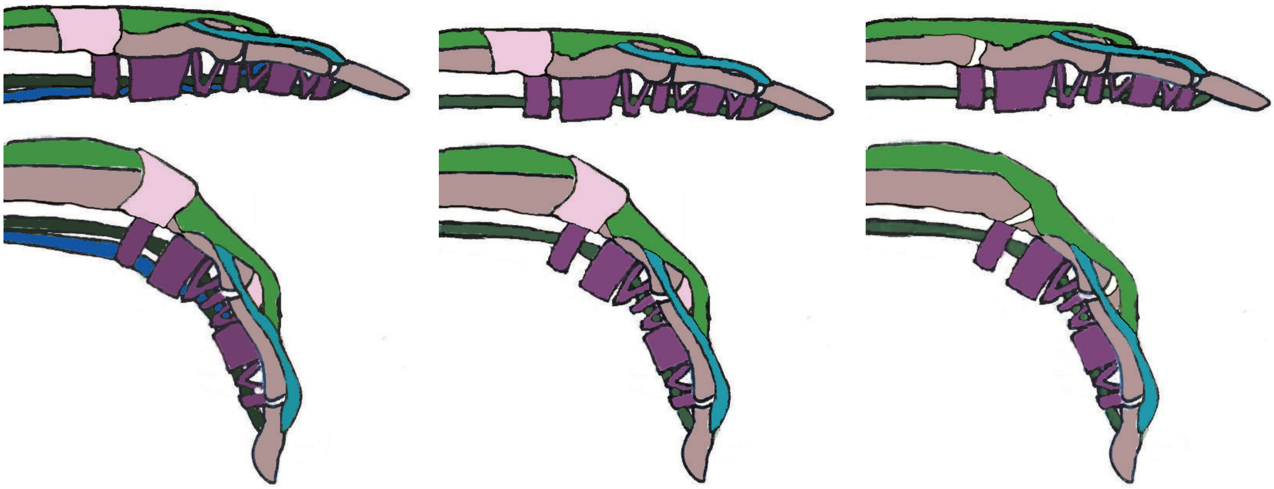
The material behaviour and shapes of the components of the stylized are pushed to their extremes. For example we assume that tissues are either fully stiff or fully flexible and that components have basic geometric shapes, which are squares, rectangles, circles and triangles. We explain one example of the characteristics of one component. The pulleys are a bit flexible so that the moment arm is increased with flexion angle as was explained in Section 2.5. However, if we push this characteristic of flexibility to its extreme the pulley tissue is either stiff or flexible: If the pulley would be fully flexible, the moment arm increases infinetly. If the pulley would be fully stiff, the moment arm is constant and the finger still has the adaptive grip that is required. Therefore, a fully stiff pulley is assumed. The basic shape of the pulley is a rectangle.

4 Design Principles

4.1 Shape Design

4.1.1 Introduction

In this Section the design principles of the stylized human finger are presented. The structure of this Section is according to the structure of the diagram in Fig. 11. It can be used as a design guideline: first the design principles of shape are described, then the design principles on kinematics and after that the design principles of torque transmission. From this section on, technical terms are used to describe the principles instead of the biological terms we used to describe the anatomy of a human finger. Fig. 12 shows schematic drawings of the design principles.



(a) Excluding the intrinsic muscles

(b) Excluding the intrinisc muscles and the FDS

(c) Excluding the intrinisc muscles, the FDS and the extensor sheets

Figure 9: Drawings of the finger in straight (top figures) and bend position (lower figures) showing the components that are left after each exclusion. Note that ligaments are not included in this drawing. Colors are as defined in Table 1. The Figures are adapted from [10].

The drawings help to explain the design principles.
We start with the design principles of shape: the shape of the bodies and the shape of the joints. We assume that the shape of the rigid bodies is adapted to withstand the bending moment of the load acting on the body. We assume that all joints are hinge joints as is described in Section 3.

4.1.2 Rigid Bodies

Principle 1.1.1 describes the shape of the whole finger. We assume the finger is a beam that is optimized to withstand the bending moment of a load that is applied in the middle of all three bodies in case of a power grip or at the end of the most distal body in the case of a pinch grip. Both load cases results in an increasing bending moment as Fig. 10a shows.
Principe 1.1.2 describes the shape of the most distal body. We assume that this body is a beam that is optimzed to withstand the bending moment of the load applied to it. The biggest bending moment on this body occurs when a pinch grip is applied. In case of a pinch grip a force is exerted at the end of the body. Fig. 10b shows the bending moment as a result of this load.
Principle 1.1.3 describes the shape of the other rigid bodies. We assume that these bodies are a beams that are optimized to withstand the bending moment of the load applied to it. The biggest bending moment on the bodies is when a power grip is applied. Fig. 10c shows the bending moment of the bodies for this load case.

4.1.3 Joints

Principle 1.2.1 describes the shape of the joint that allows rotation along the x-axis only. Fig. 10d shows how a convex surface at the proximal end of the joint and a concave surface at the distal end in the x,z-plane can slide along each other to allow this rotation.
Principle 1.2.2 describes the shape of the joint that prevents translation along the x-axis and the z-axis. Fig. 10e shows the groove along the concave surface and the rim along the convex joint surface that fits in the groove. The rim and groove can also slide along each other so that rotation along the x-axis is still allowed, while preventing translation along the x-axis and the z-axis.

4.2 Kinematics Design

4.2.1 Introduction

The principles of kinematics design make sure the bodies movement is restricted to 90 degrees of palmar rotation along the x-axis, no other rotations and no translation along any axis. First, we limit the DoF and then we limit the range of motion. Note that the shape of the joints already limits the DoF to rotation along the x-axis and translation along the y-axis and the z-axis. Fig. 12 shows the components that are required for the Kinematics Design principles.

4.2.2 Degrees of Freedom

Principle 2.1.1 describes a fan-shaped sheet connected to a foldable sheet. Together they prevent translation along the y-axis. The fan-shaped sheet on both lateral sides of the joint originates in the center of rotation of the convex part of the joint and attaches to a foldable sheet on the palmar side connected to both bones on either side of the joint.

4.2.3 Range of Motion

Principle 2.2.1 limits rotation to the palmar direction. To this end, the foldable sheet on the palmar side is connected to the bones on either side of the joint.
Principle 2.2.2 limits the rotation to 90 degrees. One sheet is attached on both lateral sides of the joint. The sheets originate dorsal from the center of rotation of the convex side of the joint and attach palmar from the center of rotation of the concave side of the joint. The sheets are loose in a straight joint and tight in 90 degrees bending.

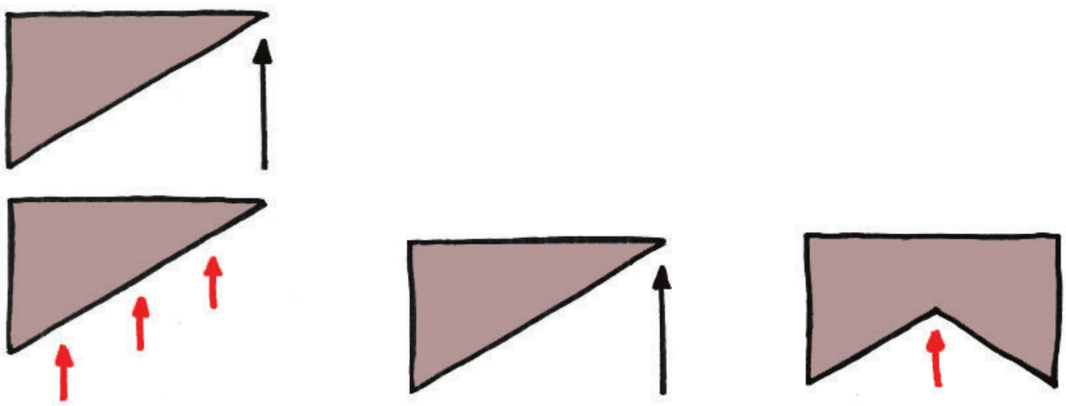
4.3 Transmission Design

4.3.1 Introduction

Actuation is required to rotate the bodies. Muscles are the biological actuator which are outside the finger, so the actuation principles are outside the scope of this study. However, the mechanism that transmits the actuation force to the finger is within the scope. The transmitted actuation force exerts a torque on each joint. The torque is distributed over the joints and optimized at the individual joints.

4.3.2 Torque Distribution over the Joints

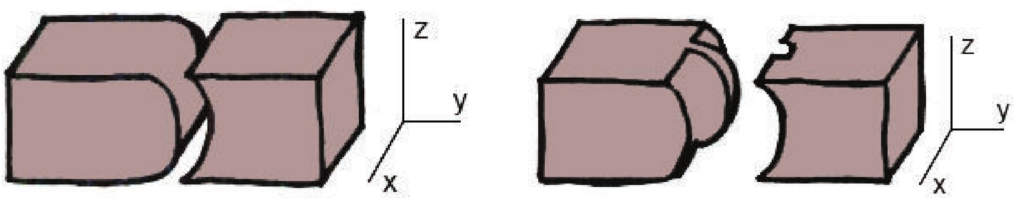
Principle 3.1.1 describes the mechanism for underactuated bending the finger. Multiple sheets are mounted on the rigid bodies and on the palmar sheet. The sheets wrap around the cable that is used for bending, creating a pulley system. The pulley system is shown in Fig. 7 an 12.
Principle 3.1.2 describes the mechanism for underactuated extending of the finger. The extensor mechanism has attachment points at each of the rigid bodies. The multiple attachment points of the extension transmission are illustrated in Fig. 6 and 12.
Principle 3.1.3 describes the mechansim that links the rotation of the DIP and the PIP joint. Two lateral sheets attach on both lateral sides of the DIP joint and one central sheet attaches on the dorsal side of the PIP joint to couple the rotations of the joints due to the spring-like behaviour of the three sheets. When the DIP joint bends the tension in the lateral bands increases while there is relative laxity in the central band. PIP bending is now easier than DIP bending. When the PIP joint bends, tension in the central band increases and the lateral bands are unloaded. DIP bending is now easier than PIP bending.



(a) Bending moment of the load of a pinch grip and a power grip.

(b) Bending moment of the load on the most distal body.

(c) Bending moment of the load on the other bodies.



(d) The convex and concave surface of the joint.

(e) The groove and rim shape in the joint. Right: top view, left: 3D view.

Figure 10: Drawings of the design principles of the rigid bodies (top figures) and of the joints (bottom figures). Colors are as defined in Table 1. A red arrow indicates a force exterted in case of a power grip, a black arrow indicates a force exerted in case of a pinch grip.

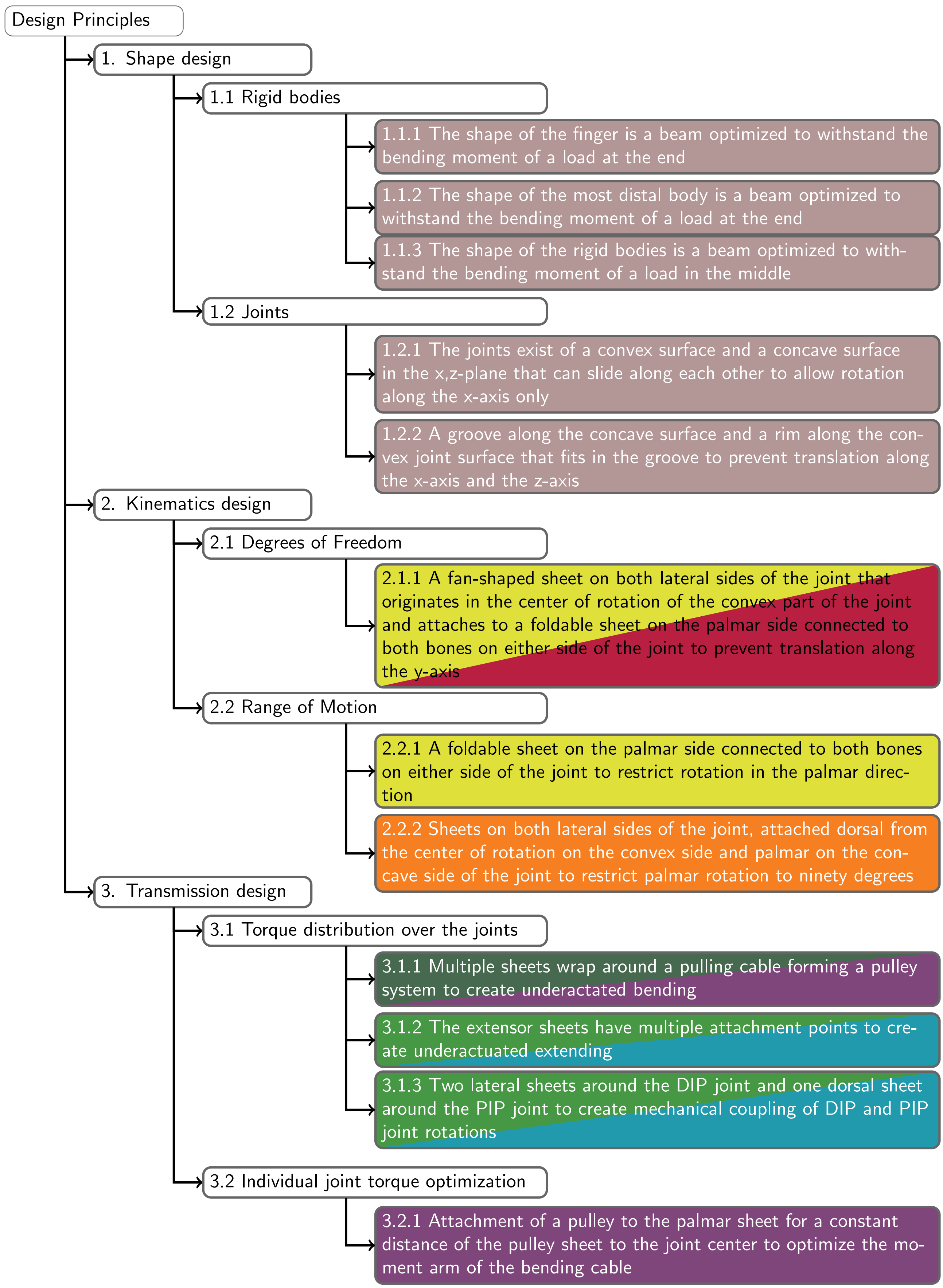


Figure 11: Diagram of the design principles of the stylized human finger. The colors of the node indicate the components that belong to the design principles. The colors of the components are defined in Table 1.

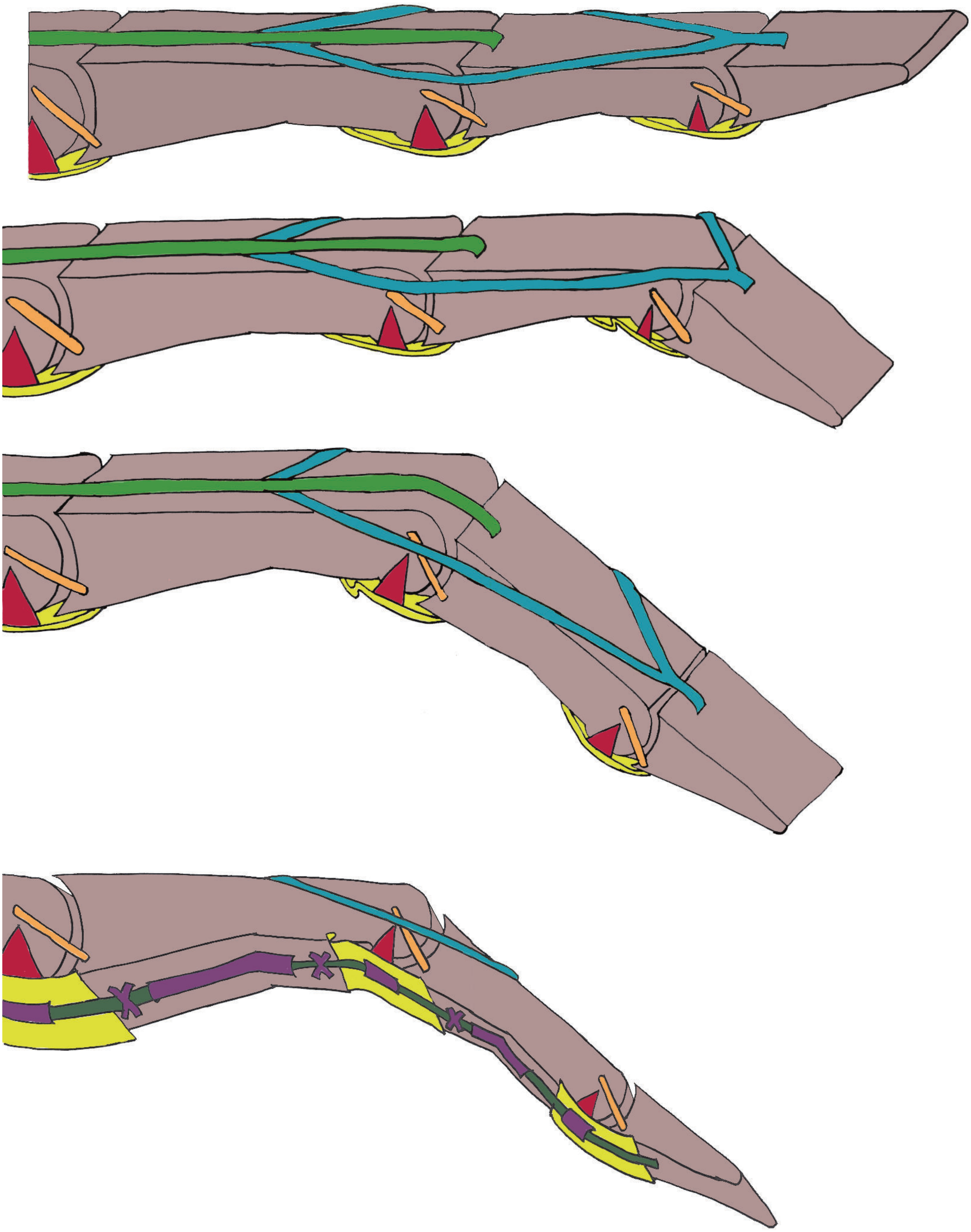


Figure 12: Schematic drawings showing all the design principles. Top figure to lower figure: a straight finger viewed from above, a finger with the DIP joint bent viewed from above, a finger with the PIP joint bent viewed from above, a finger with the PIP joint bent viewed from below. Colors are as defined in Table 1.

Table 4: Design requirements for the prosthetic finger

Category	Description	Requirement
Approach	Bio-inspired design	Biological design principles
Comfort	Mass	≤ 25 g
Control	Actuation force to fully bend finger	≤ 70 N
	Pinch force	≥ 30 N
Production	Minimized assembly	Assembly time ≤ 15 minutes

4.3.3 Torque Increase at the Individual Joints

Principle 3.2.1 describes how torque is optimized at the individual joints. Attachment of a pulley sheet to the palmar sheet ensures that the pulley sheets have a constant distance to the joint center. The moment arm and thus the torque of the pulling cable that goes through the pulley defined by this distance. Fig. 12 shows that the pulley sheets are attached to the palmar sheet.

5 Design Requirements

5.1 Design Approach

The functional requirements for the prosthesis finger are listed in Table 4. The approach used for the design is bio-inspiration. The design principles of the stylized human finger that are described in Section 5 should be used as a guideline for the design of the prosthetic finger.

5.2 Comfort

It is important that the prosthesis is light weight, as excessive weight is one of the main reasons for rejection of a prosthesis [4]. Chandler found an average mass of a human hand of 400.4 grams in six male cadavers [17]. If we assume that the four fingers are a quarter of the weight of the whole hand, then the mass of one finger should not exceed 25 grams.

5.3 Control

One way to control a hand prosthesis is via a shoulder harness. We assume that this device is used for the control of the hand and also for control of the proposed finger. The maximum actuation force a person can deliver by a shoulder harness is on average 280 N [18]. No fatigue occurs for repeated muscle action if the actuation force is at maximum 20% of the maximum actuation force [19]. Therefore, Ten Kate proposes that the desirable maximum acceptable actuation force for a hand is 56 N [5]. We assume that the actuation force to bend a finger is one quarter of 56 N, which equals 14 N. However, this is a wish, not a requirement. The requirement is that the total actuation force is one quarter of 280 N, which is 70 N. The pinch force used in Daily Life Activities is up to 30 N [20], [5]. This is also the requirement we use as the desired pinch force. The actuation force required for a 30 N pinch grip should not exceed 70 N which is the maximum force of a should for controlling one finger.

5.4 Production

Assembly of existing hand prostheses that are made using 3D printing easily takes 1.5 hours [21]. The requirement for the production is minimized assembly. This is defined as less than 15 minutes assembly time.

6 Design and Prototype of the Hybrid Finger

6.1 3D Printer and Material

The choice of the 3D printer for the prototype is limited by the printers that are available and easily accessible because a lot of prints have to be made during the design process to optimize the design for 3D printing with minimized assembly. Background information on the state-of-the-art of complex non-assembly mechanisms produced using 3D printing and on choosing a printing technique can be found in Appendix G.

The Ultimaker 3 was used for the final prototype which is a Fused Deposition Modeling (FDM) printer. In FDM a polymeric filament is heated and pushed through a nozzle to build the prototype layer by layer [2]. The prototype is printed in dual extrusion mode. Different materials are extruded through the two nozzles of the printer: PLA which is a rigid material and MPflex45 which is a flexible material. Material properties of PLA and MPflex45 can be found in Appendix C. The settings of the printer that are used for printing the prototype are listed in Appendix D. The general findings on 3D printing from the prototyping process are described in Appendix F.

6.2 General Notes on the Design

Before describing the design some notes are made that apply to the whole design. First, rigid components are made of PLA, components that require bending or folding are made of MPflex45 and components that require a spring-like behavior are made of PLA in a thin geometry. Second,

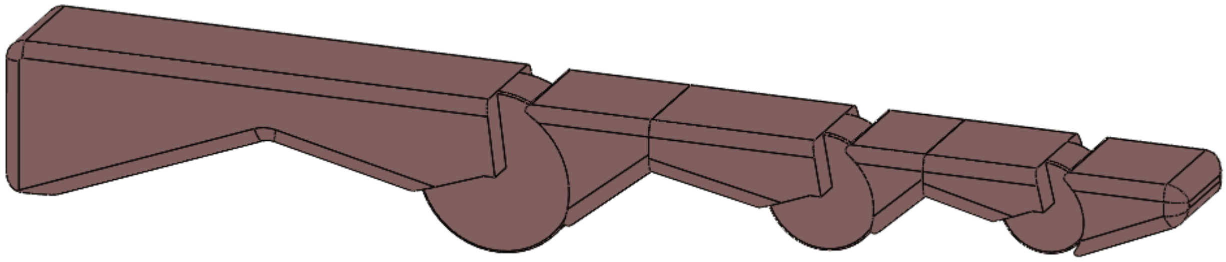
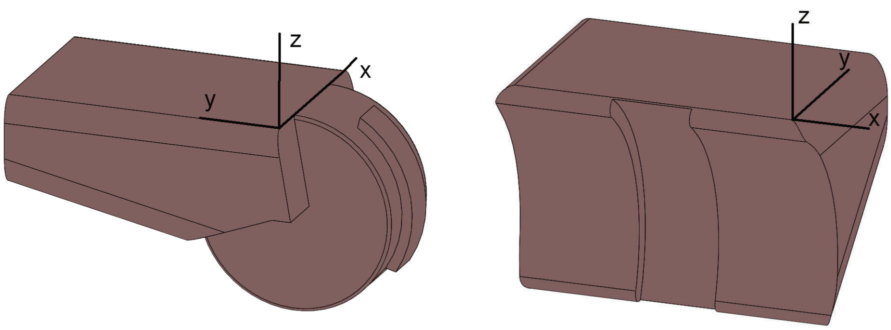


Figure 13: The design of the finger in SolidWorks showing only the components that belong to the shape design. Colors are as defined in Table 1.



(a) The rim.

(b) The groove.

Figure 14: The joint design of the finger in SolidWorks showing the groove and the rim. Axes as defined in Fig. 2 are indicated. Colors are as defined in Table 1.

the finger is printed lying on its lateral side to minimize the amount of support material. Third, the components in the design category are described first and then the main dimensions of the components are explained. Technical drawings including dimensions of the design can be found in Appendix E.

6.3 Design of the Finger

6.3.1 Shape Design

Fig. 13 shows the design of the finger including the components that belong to the shape design. The three rigid bodies have the shapes that are described in Principle 1.1.1., 1.1.2 and 1.1.3. Note that an extra body is added to the design: namely the most proximal body in the Figure. This is done so that is easy to hold the finger. The shape of this body is similar to that of the other bodies for easy designing.
The joints have a convex and concave surface as described in Principle 1.2.1. They also have the groove and rim of Principle 1.2.2. Fig. 14 shows the rim and groove in the joint design. The thickness of the rim and groove is 0.5 mm: in this way no support material is required between the groove and the rim. Support material would be unreachable in between the two components, so we prefer not to have it.
The rigid bodies and joints have the dimensions of the bones in the human finger that are listed in Appendix B. However, the dimension of the finger in x-direction is chosen as the width of the outside of the human finger because the skin, the veins etcetera that are present in the biological hand are not included in the prothetic hand. Also the joint thickness has the dimension of the outside of the joint in the human finger because the skin, the veins etcetera that are present in the biological hand are not included in the prosthetic hand. If the joint thickness increases, the moment arm of the bending and extending force around the joint increases. This is beneficial: less force is required to create the same bending or extending moment around the joint.

6.3.2 Kinematics Design

The three joints have the same components for kinematics design. Fig. 15 shows the design of the finger including these components. The design of both lateral sides of the finger is the same. The shape of the fan-shaped sheet of Principle 2.1.1 is adapted to make it more flexible. A cut is

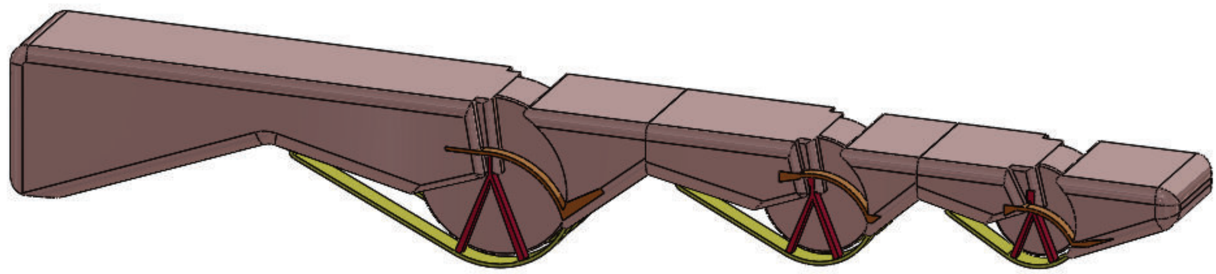


Figure 15: The design of the finger in SolidWorks showing the components that belong to the shape design and the kinematics design. Colors are as defined in Table 1.

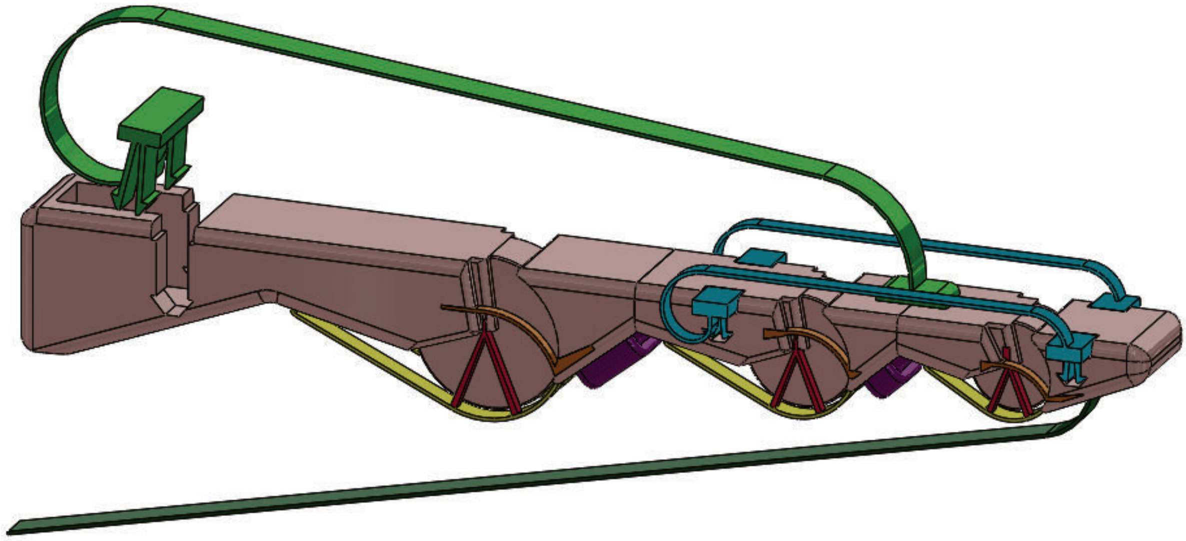


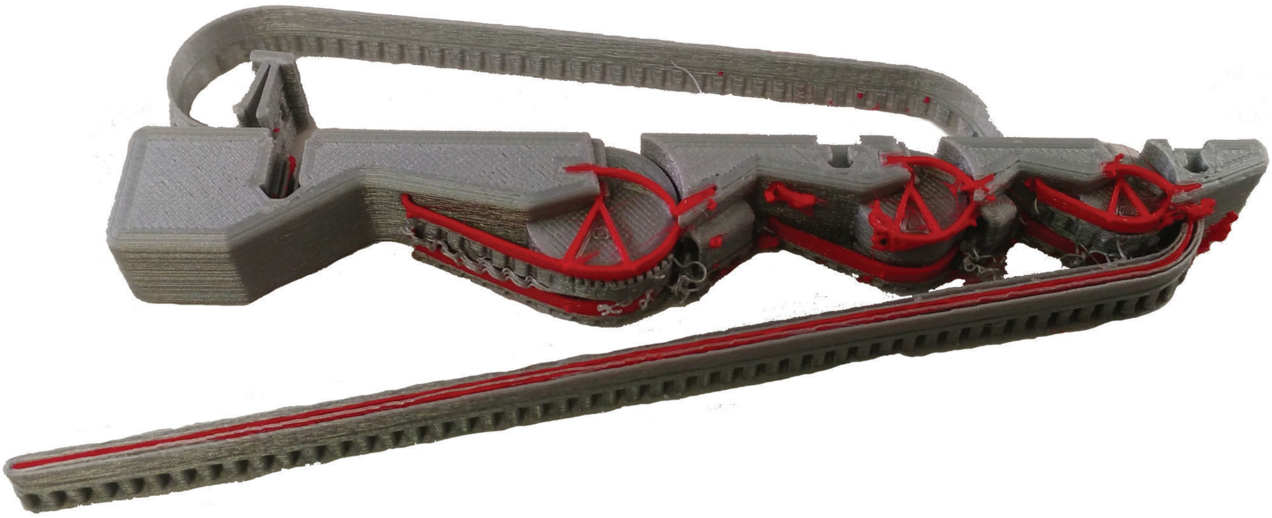
Figure 16: The full design of the finger in SolidWorks showing all components. Colors are as defined in Table 1.

made in the sheet, leaving only the sides of the fan-shaped sheet: just two flexures attached to the center of rotation of the joint. The flexures can bend around the x-axis. The palmar sheet of Principle 2.1.1 and 2.2.1 is also adapted to make it more flexible. Instead of one broad sheet, two narrow sheets are created by making a cut along the length of the sheet. The two sheets can fold along the x-axis. The eccentrically attached sheet of Principle 2.2.2 is loose in a straight finger and tight in a 90 degrees bend due to its curved geometry.

The dimension in x-direction of the convex part of the joint is decreased, so that there is enough space for the kinematics components to fit within the outer dimensions of the finger, while the joint can still withstand forces in x-direction. The thicknesses of the kinematics components are minimized: a thickness of 0.5 mm is used in the y,z-plane so that flexibility around the x-direction is maximized. A thickness of 0.5 mm is the smallest dimension that can be printed: this is equal to one line of printed material. The location of the palmar sheet is chosen such that the fan-shaped sheet can attach to it, while the palmar sheet is still overlapping with the convex part of the joint, so that it prevents bending in the dorsal direction by mechanical blocking. The attachment point and the radius of the curve of the eccentric sheet of Principle 2.2.2 is found using trial and error and is different for each joint.

6.3.3 Transmission Design

Fig. 16 shows the design of the finger including all components: the shape design, the kinematics design and the transmission design components. The system of pulley sheets is adapted. Only the broad pulley sheets of Principle 3.1.1 that are mounted on the rigid bodies are included in the design. The sheets named A2 and A4 as Fig. 7 indicates are included. It was not possible to print the other sheets due to the flexible material in combination with the used printing direction and the small dimensions of the cruciate pulley sheets and the narrow pulley sheets. The pulling cable is attached to the most distal body. It is printed next to the finger instead of through the pulleys as Fig. 16 shows. This reduces the amount of support



(a) The prototype with the support material before assembly.

(b) Lateral view of the prototype.

material and avoids that the pulleys sheets and the pulling cable melt together. The extensor mechanism of Principle 3.1.2 exists of three separate parts. The printing direction that we use makes the biological geometry hard to replicate. We do not have an actuator for extending the finger, so the extensor mechanism needs to work as a restoring force. One central spring spans both the MCP and the PIP joint. It extends both joints when the bending force is removed. Two springs, one on both lateral sides of the finger, span the DIP joint. They extend the joint when the bending force is removed. The central spring is attached to the middle body. When it is printed it is not attached to the palm. This reduces the amount of support material around the spiral of the spring in the palm. The spring is manually attached to the palm using a snap fit. A gap is made in the palm for spiral of the spring and the snap fit. The lateral springs are printed separately. They are connected to the finger with snap fits. This reduces the amount of support material. Cuts are made in the bodies for the snap fits. The three springs also function as the joint rotation linking system of Principle 3.1.3.

The pulling cable has a maximized dimension is the x-direction that fits in between the palmar sheets where it crosses the joints. The thickness of the cable is 0.5 mm so that the outer dimensions of the finger are not increased and to maximize the flexibility of the cable because is needs to bend around the joints. The pulley sheets are adapted to wrap around the pulling cable. All three springs of the extensor mechanism are 0.5 mm thick to maximize the flexibility of the spring. The x-dimension of the central spring is chosen so that the rigid body around the gap for the spiral of the spring is still strong: 5 mm. The x-dimension of the lateral springs is half of the x-dimension of the central spring: 2.5 mm.

6.4 Prototype Production

The SolidWorks files need to be exported to .stl files to open them with Cura, which is the software of the Ultimaker 3. Since we have two materials to print, we need to make two separate .stl files to open in Cura: one with all the components that need to be printed with PLA and one with all the components that need to be printed with

Table 5: Summary of the evaluation of the prototype.

Category	Description	Requirement	Evaluation	Fulfillment
Approach	Bio-inspired design	Biological design principles	Most design principles are used	Partially
Comfort	Mass	≤ 25 grams	17 grams	Yes
Control	Actuation force to fully bend the finger	≤ 70 N	16 N	Yes
	Pinch force	≥ 30 N	3 N	No
Production	Minimized assembly	≤ 15 minutes	3 minutes	Yes

MPflex45. When the files are openend in Cura and the materials are defined, we merge the two files into one part. We print the lateral bands separately so we also need to import them in Cura. We use the printing settings that are listed in Appendix D. Cura automatically generates support material according to the settings and generates a .gcode file that can be saved on a usb-stick. We insert the usb-stick in the Ultimaker 3 and start the print. Hair spray is used on the build plate so that the print is fixed to it. The printing time is 6:58 hours. Figure 17a shows the prototype when the print is just finished with all support material. Then we remove the support material. This takes 15 minutes with a needle nose plier. We assemble the central extensor band, the two lateral bands and we put the pulling cable through the pulleys. We lubricate the pulleys and the bending cable with basic kitchen oil to end up with a working prototype. This takes about 5 minutes. Fig. shows the fully assembled prototype.

7 Evaluation of the Prototype

7.1 Design Approach

This Section evaluates the final prototype. The results of the evaluation are summarized in Table 5.
In the category of approach we evaluate whether the components that are described in design principles are present in the prototype and whether they have the working principles that are described in the design principles.
All components of the design principles on shape design are present. Fig. 17b shows the shapes of the rigid bodies and joints. Fig. 22a shows that a small translation along the x-axis is possible. In a straight finger translation occurs at the MCP joint if a force of 4 N is exerted on the Proximal phalanx, at the PIP joint if a force of 1 N is exerted on the Middle phalanx, at the DIP joint if a force of 2 N is exerted on the Distal phalanx. We measured the forces using a Chatillon LG-100 spring balance. Fig. 18 shows the test set-up. If the finger is bend the tension of the extensor springs keeps the joints closely together. The rim and groove of 1.2.2. should be deeper to prevent the translation in the straight finger. However, there is no support needed in the current design between the two components but if we increase the thickness of the rim and joint there is support material needed between the rim and the groove that we can not reach.
Fig. 17b shows the fan-shaped sheets and the eccentrically attached sheet. Fig. 22b shows the palmar sheets. So all components of kinematics design are present in the prototype. Translation along the y-axis is prevented by the fan-shaped sheets and the palmar sheets. Dorsal rotation is prevented by the palmar sheets. The eccentrically attached sheet that is also shown in Fig. 17b bending should be restricted to ninety degrees. This can be tested by measuring the Range of Motion of the joints. The Range of Motion(RoM) of each joint is measured with a drafting

Figure 18: The test set-up to measure the forces exerted at the phalanges when translation in the x-direction occurs.

Figure 19: The test set-up to measure the actuation force to bend the finger.

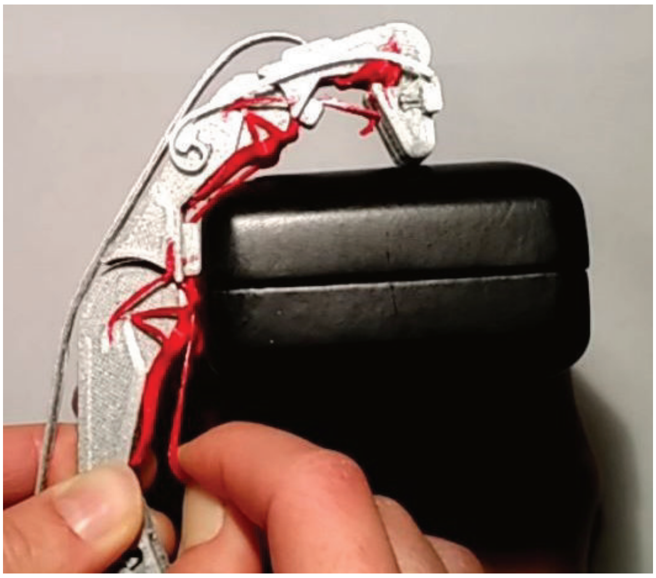


Figure 20: The prototype performing an adaptive grip.

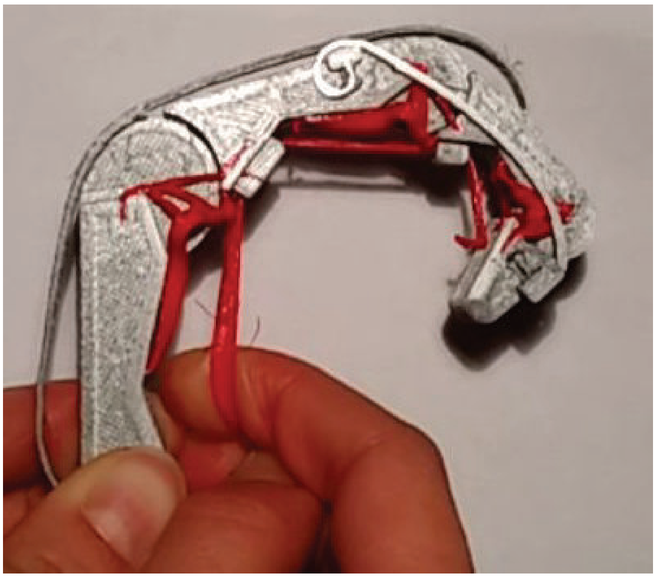
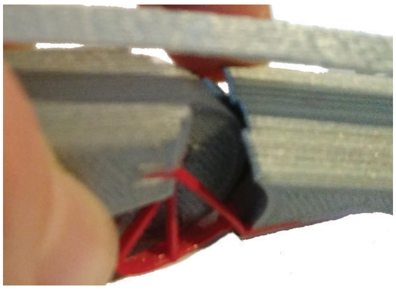


Figure 21: The bent prototype.

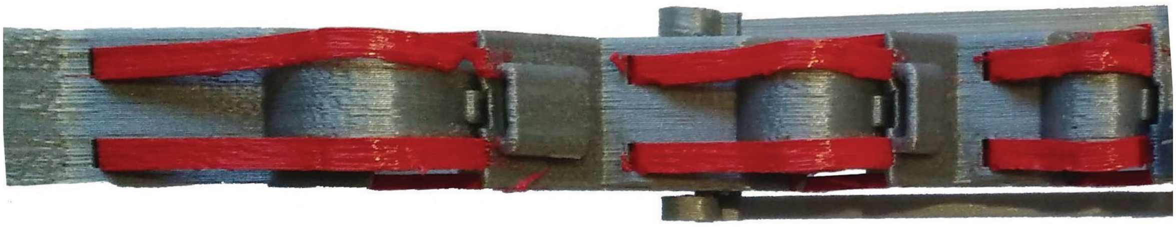
triangle for each joint. The RoM of the MCP joint is -15 to 115 degrees, the RoM of the PIP joint is -10 to 110 degrees and the RoM of the DIP joint is -10 to 110 degrees. We can conclude that bending is not restricted to ninety degrees.

Fig. 22c shows the pulley sheets and the pulling cable that create a pulley system for underactuated bending. All the elements from the design principle are present, except for some of the pulley sheets as we explained in Section 6. Fig. 20 shows that the finger can perform an adaptive grip resulting from the pulley system. Note that the DIP joint bends before the PIP joint bends. This is due to the small moment arm of the PIP joint, that is a result of the dimensions of the Middle Phalanx. Fig. 17b shows the extensor mechanism. It exists of three parts instead of one part that has multiple attachment points, making the working principle different from the underactuated extension as described in design principle 3.1.2. However, the prototype has the additional requirement on the extensor mechanism to act as a restoring force. The three parts together forming the extensor mechansim couple the rotations of the DIP and the PIP joint, so design principle 3.1.3 is fulfilled. However, it is easier to bend the DIP joint than the PIP joint in all joint angles, so we conclude requirement 3.1.3 is partially not fulfilled. The pulleys that should be mounted on the palmar sheet are not included in the design so the components of design principle 3.2.1 are not present in the prototype. However, the moment arm of the pulling cable is defined by the radius of the joint, so the joint thickness can be adapted to optimize the moments of the individual joints.

In conclusion, most components of the design principles are present in the finger. The transmission working principles in the proposed finger are different from those de-



(a) Picture of the prototype showing translation in the x-axis around the rim and groove in the joint.



(b) Picture of the prototype showing the palmar plates.

(c) Picture of the prototype showing the pulling cable and the pulleys.

Figure 22: Pictures of the prototype showing different components.

scribed in the design principles. We conclude that the requirement on using biological design principles is partially fulfilled.

7.2 Comfort

The mass of one finger is 17 grams. This is less than the requirement maximum mass of 25 grams so this requirement is fulfilled.

7.3 Control

The actuation force to bend the finger was measure using the test set-up shown in Fig. 19. The fully bend prototype is shown in Fig. 21. The actuation force to bend the finger is 16 N. This is less than 70 N so the requirement is fulfilled. It was a wish to have an actuation force that maximum 14 N to prevent fatigue of the muscles. This wish is not met. However, keep in mind that 16 N is required to fully bend the finger, in Daily Activities the finger is most of the time nog fully bend, so that less force is required. To get an idea of the actuation forces to bend the finger partially, the actuation forces to bend each individual joint 90 degrees is also measured. The forces are measure by blocking the joints that should not bend, leaving only one joint able to bend. An actuation force of 8.5 N is measured for bending the MCP joint, an actuation force of 12.5 N is measured for bending the PIP joint and an actuation force of 6 N is measured for bending the DIP joint.
A maximum pinch force of 3 N can be applied the finger bends in the dorsal direction. The requirement on pinch force is not fulfilled.

7.4 Production

To fully assemble the finger, four assembly steps are required. The central spring of the extensor mechanism need to be attached to the finger using a snap fit connection. The two lateral springs of the extensor mechanism need to be attached to the finger using two snap fit connections and the pulling cable need to be put through the pulleys. The assembly can be done in 3 minutes, so the requirement is fulfilled.

8 Discussion

8.1 Minimized assembly using 3D Printing for Production of Prosthetics

The goal of the study was to design and develop a prototype of a 3D printed bio-inspired finger for a body-powered hand prosthesis with minimized assembly. We use 3D printing for minimized assembly production because it is a feasible solution for minimized assembly production of prostheses, to solve the problem of the need for trained personnel, long assembly time and high costs. All that is needed to produce the finger is a usb-stick, a 3D printer, a plier to remove support material after printing, some kitchen oil and a short manual about the production process. The production process is easy and so it requires no training. This assembly time is also very short: 3 minutes only. The material costs are also low: only 1.68 euros per finger. This is very low if we compare it to other 3D printed hand prosthesis, of which the costs range from 5 to 500 dollars for a hand [22]. The 3D printer that is used costs approximately 3900 euros which may look like an investment quite big compared to the material costs. But if we compare this to the costs of customzing prosthesis using conventional production methods, it is very reasonable. Another note should be made on 3D printings. It has not yet been developed into a very reliable production method. There quite are a lot of factors that influence the results of the print, such as 1) environmental factors, like temperature or the printer being placed on an uneven surface, or 2) factors inside the printer, like leveling of the build plate or moist in the material. Knowledge about 3D printing is required to minimize the influence of these factors on the print so that no failure occurs, so we might eventually need trained personnel after all. 3D Printing prosthetics with minimized assembly is a step in the right direction towards affordable prostheses due to the low costs and the easy production process, but general knowledge about 3D printing is required for a reliable production.

8.2 3D Printing and Bio-Inspired Design

The human finger is assumed the perfect example for the proposed design, because thousands of years of evolution have optimized the human finger. However, when 3D printing is the production method, we question if this is a realistic assumption. A few differences between 3D printing and biology are pointed out. First, different materials are used. The biological design of the finger has been optimized for certain materials. The available materials for 3D printing are limited and the available materials have properties that are different from the properties of the biological tissues. This results in different design constraints, so that the optimal prosthesis design could be different from that in biology. Second, the growing direction is different. We used 3D printing to minimize assembly of the finger. When printing, the finger "grows" in one direction, namely in the printing direction. In biology the tissues can grow in any direction. Third, the constraints on dimensions are different. The minimal thickness that can be 3D printed is 0.5 mm. In the human finger however, tissues with smaller thicknesses exist. For example Sato *et al* finds an average thickness of the A2 pulley sheet of 0.27 mm [23]. Another difference between the dimensions is that in 3D printing there is a minimal gap size of 0.4 mm, while biological tissues can lie more closely to each other. Besides, dimensions in biology are optimized for the properties of the materials used, which are different in the prosthesis. Biology is a good starting point for the design. But a few iteration steps to optimize the design for the production process and material can further improve the design, because some contraints on the prosthetic finger are different from those in biology.

8.3 Recommendations

8.3.1 Design

The proposed finger shows a promising step in the direction of a minimized assembly hand. We recommend to make such a hand, which can be a combination of four bio-inspired fingers that are scaled to match the different finger lengths, a static or passively opposable thumb and a hand palm. We recommend to use an already existing technical design for the palm of the hand. Several techniques exist to make an adaptive mechanism for the pulling cable in the palm. We recommend the seesaw mechanism described in Appendix H because the pulling cable of the proposed finger can be connected to a palm with this mechanism.

We have some recommendations on the design and production process of the finger. We recommend to print the kinematics design components separately or to use a printer that is optimized for printing flexible material, because often one of these components failed during printing. We think that this is due to the use of support material between two flexible parts and the thin geometry. We also recommend to print the pulling cable separately and attach it later, because printing it fails. The solution of using a support of PLA on both sides of the cable, is not satisfying as the PLA melts together with MPflex45, which is explained in Appendix F. Removing the support damages

the pulling cable.
We recommend to adapt the dimensions of the central and lateral extensor springs to tune the coupling of the joint rotations. Due to limited time this has not been done yet. We recommend investigate the addition of pulleys to the palmar plate to increase the moment arm of the pulling cable without increasing the joint thickness.

8.3.2 Further Evaluation

We recommend to do basic user tests so that several user evaluation criteria can be adressed. Plettenburg defines the basic user requirements as cosmesis, control, and comfort [24]. For each requirement an example is given. First, the prosthesis now has a very technical look. We recommend to adapt the dimensions of the finger so that it fits inside a cosmetic glove to give it a look more similar to the human hand. If a glove is used, we recommend to protect the pulling cable and the extensor springs from touching the glove for example by printing a structure around them or making a groove in the finger in which they fit. Second, we recommend to further evaluate the control of the prosthesis. Third, we recommend to investigate the comfort of the prosthesis for example by testing the intuitiveness of control. Besides these three basic user requirements, we recommend to evaluate the durability of the finger because the durability of the material printed in the proposed configuration is unknown.

9 Conclusion

This study proposes a 3D printed adaptive bio-inspired finger for a body-powered hand prosthesis with minimized assembly. The finger is controlled by a single pulling cable. We studied the human finger anatomy and created a stylized version of it, that includes only the components that we need for the prosthetic finger. The design principles are of the stylized finger are evaluated and they are used as a guideline for the design of the Hybrid finger. A prototype is developed using an Ultimaker. With the dual extrusion mode two materials are used in one print: a rigid and a flexible material. The prototype shows promising results. The Hybrid finger has an adaptive grip. This makes the finger suitable for a hand prosthesis that can perform an adaptive power grip and a pinch grip. The mass of the finger is only 17 grams, which is comfortable for a user. An actuation force of 16 N is required to bend the finger. Only four assembly steps are required to assemble the finger in 3 minutes time and the material costs are only 1.68 euros. The prototype shows a promising step in the direction of an affordable hand prosthesis.

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Appendices

A 3D Model of the Human Finger

In order to better understand and visualize the construction of the finger and its movement in 3D, the simple model shown in Figure 23 was made. Cardboard represents the bones and postal elastic bands represent the tendons and the ligament.
It is hard to move the links of the cardboard model due to the irrealistic joint shape, so the second model shown in Figure 24 is made using more realistic materials. The CAD model of Galisky which is an MRI scan of the human finger bones is 3D printed with PLA using an Ultimaker 3[25]. Elastic band for clothing purposes are used to represent the A2 and A4 pulleys and collateral ligaments and a sheet of paper is used to represent the palmar ligament. Electric wires represent the flexor tendons.

Figure 23: Model of the human finger using cardboard and elastic band for post purposes. Top figure: lateral view, bottom figure: Top view.

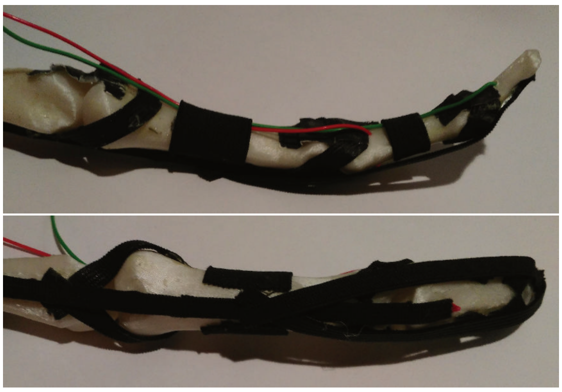


Figure 24: Model of the human finger using 3D printed bones and elastic band for clothing purposes. Top figure: lateral view, bottom figure: Top view.

B Dimensions and Mechanical Properties of the Human Finger

B.1 Dimensions of the Phalanges

The dimensions of the phalanges are listed in Table 7. Length is the dimension in direction of the y-axis as defined in Fig. 2. Relative lengths of the components were measured with ImageJ from Fig. 25. The real lengths were calculated from the real length of the proximal phalanx found in [26] and the relative lengths. The width of the finger was measured from the middle finger of the author. Width is the dimensions in the direction of the x-axis and thickness is the dimension in the direction of the z-axis. A few interesting things can be noted. The ratio between the thickness of a joint and the phalanx that lies distal to the joint is approximately 1.6 for all three joints. The ratio between the length of a phalanx and the phalanx that lies distal to it is approximately 1.5. Phalanx length and joint thickness are similar to those found in [27].

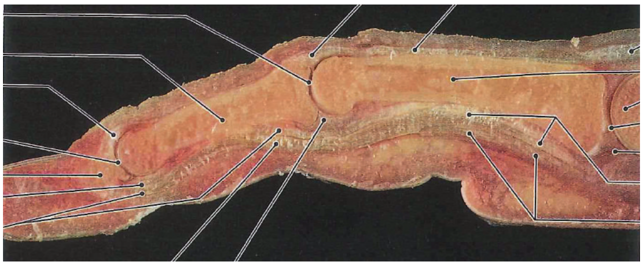


Figure 25: MRI scans of the human finger: sagital dissection.. From [28].

B.2 Length and Location of the Pulleys

Length of the pulleys are listed in Table 8 [15]. Length and location of pulleys vary between human.

B.3 Properties of Cortical Bone and Tendon

Mechanical properties of cortical bone and tendon are listed in Table 6.

Table 6: Mechanical properties of cortical bone and tendon. Bending properties of cortical bone from [29] and tensile properties of tendon of the human forearm from [30].

Component	**Area (mm^2)**	**Youngs Modulus (GPa)**	**Bending strength (MPa)**	**Ultimate stress (MPa)**	**Stiffness (N/mm)**
Cortical bone	35	15,2	170	-	-
FDP	9,89	1,31	-	95	104
FDS	9,97	1,288	-	115	112
ED	4,16	1,971	-	151	102

Table 7: Length of the bones in the human finger and of the outside of the human finger. Relative lengths of the bones were measured with ImageJ from Fig. 25. The length of the proximal phalanx bones was found in [26]. The outside dimensions were measured from the middle finger of the author.

Component	**Relative length**	**Length [mm]**
Proximal Phalanx, bone (length)	1,000	43,73
Middle Phalanx, bone (length)	0,682	29,82
Distal Phalanx, bone (length)	0,465	20,33
Proximal Phalanx, bone (thickness)	0,157	6,86
Middle Phalanx, bone (thickness)	0,127	5,55
Distal Phalanx, bone (thickness)	0,097	4,24
MCP joint, bone (thickness)	0,268	11,72
PIP joint, bone (thickness)	0,192	8,40
DIP joint, bone (thickness)	0,152	6,65
Finger outside (width)	-	16 mm
MCP joint, outside (thickness)	-	21.5 mm
PIP joint, outside (thickness)	-	15.7 mm
DIP joint, outside (thickness)	-	12.4 mm

Table 8: Length of annular pulleys, from [15].

Pulley name	**Pulley length (mm)**
A1	-
A2	17,4
A3	2,6
A4	6,4
A5	3,7

C Properties of 3D Printed Material

The mechanical properties of Ultimaker PLA and Makerpoint MPflex45 can be found in Table 9 and 10. However, these are the material properties of the material printed in a certain configuration. Ultimaker notes on the values listed in Table 9: "Properties reported here are average of a typical batch. The 3D printed test specimens were printed in the XY plane, using the normal quality profile in Cura 2.1, an Ultimaker 2+, a 0.4mm nozzle, 90 % infill, 210 ° C nozzle temperature and 60° C build plate temperature. The values are the average of 5 white and 5 black specimens for the tensile, flexural, and impact tests. The Shore hardness D was measured in a 7-mm-thick square printed in the XY plane, using the normal quality profile in Cura 2.5, an Ultimaker 3, a 0.4 mm print core and 100 % infill."

We tested the tensile properties of the components made with MPflex45. One is the pulling cable that is made out of MPflex45. The printed pulling cable which has a crossectional area of 5 mm by 0.5 mm breaks at 23 N pulling force. The actuation force required to fully bend the finger is 16 N which is less than 23 N. So we conclude that the material is strong enough.

The other is test is on the force needed to break the finger by pulling it longitudinally was measured using a Chatillon LG-100 spring balance. The sheets of MPflex45 break when we pull the finger in the longitudinal direction. The sheets at the DIP joint break at 33 N pulling force, at the PIP joint break at 39.5 N and at the MCP joint break at 64 N.

Table 9: Mechanical Properties of PLA from [31].

Property	Value	Unit
Tensile modulus	2346.5	MPa
Tensile stress at yield	49.5	MPa
Tensile stress at break	45.6	MPa
Elongation at yield	3.3	%
Elongation at break	5.2	%
Flexural strength	103.0	MPa
Flexural modulus	3150.0	MPa

Table 10: Mechanical Properties of MPflex45 from [32].

Property	Value	Unit
Tensile modulus	95	MPa
Tensile stress at break	24	MPa
Elongation at break	5.3	%

D Final Settings of the Printer

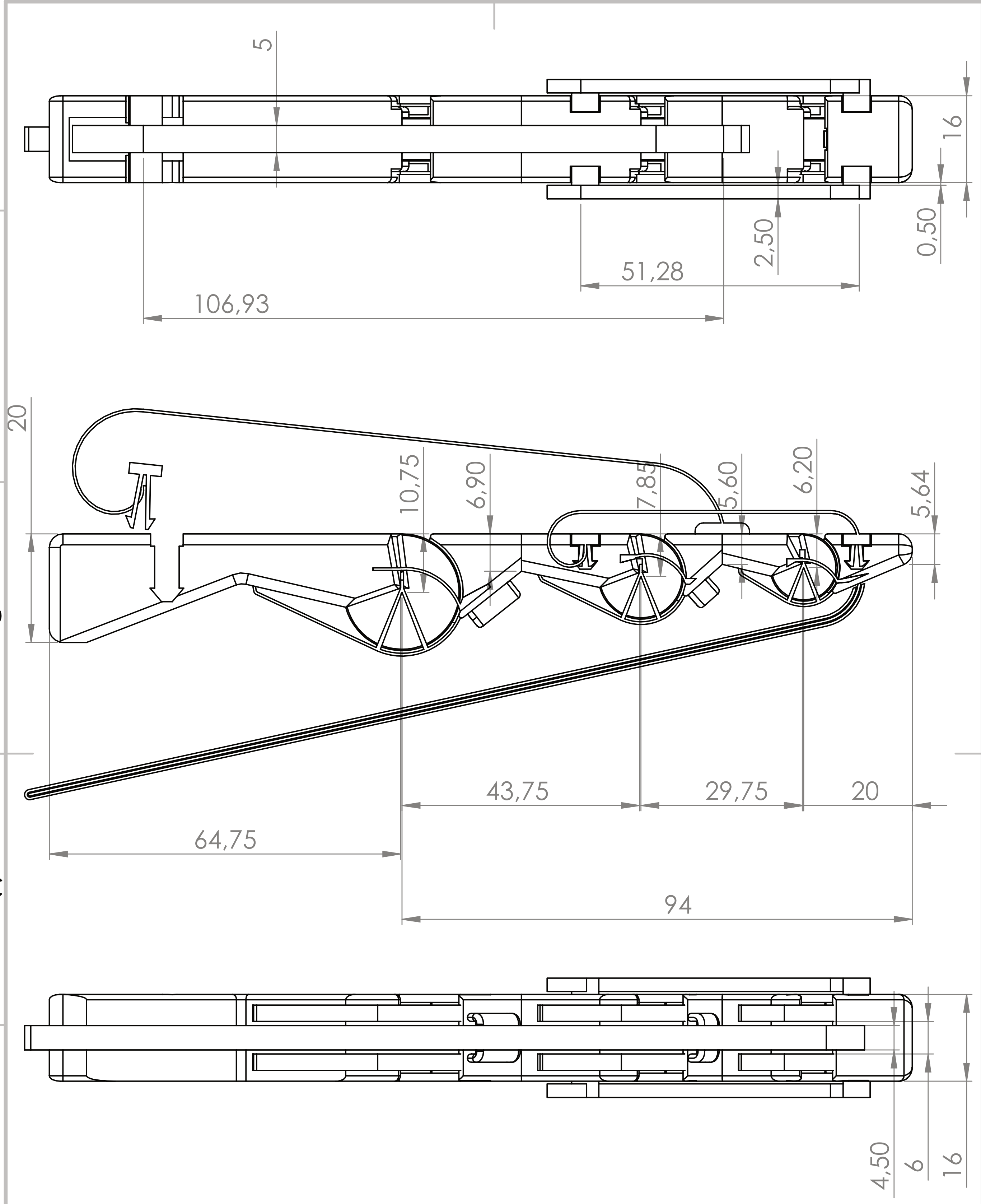
Table 11 lists the final settings for printing that are different from the standard settings in Cura.

Table 11: The final settings for printing that are different from the standard settings in Cura.

Category	Setting	Value
Quality	Layer height	0.2 mm
	Line width	0.4 mm
	Prime tower line width	0.8 mm
Shell	Standard Cura settings	-
Infill	Standard Cura settings	-
Material	Printing temperature	220° C
	Build plate temp	60° C
	Enable retraction	Off
Speed	Prints peed	15 mm/s
	Travel Speed	100 mm/s
	Initial layer speed	15 mm/s
Travel	Combing mode	No skin
Cooling	Enable print cooling	Off
	Minimum layer time	10 s
Support	Generate support	On
	Support material	PLA
	Support density	25 %
	Support Z distance	0.2 mm
	Support top distance	0.2 mm
	Support horizontal expansion	1.5 mm
	Enable support interface	On
Build plate adhesion	Build plate adhesion	None
Dual extrusion	Enable prime tower	On
	Prime tower size	20 mm
Mesh fixes	Standard Cura settings	-
Special modes	Standard Cura settings	-
Experimental	Standard Cura settings	-

E Technical Drawings of the Design

This appendix includes technical drawings including dimensions of the design of the whole finger, the mcp joint, the pip joint, the dip joint and the lateral sheets.



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Finger: view from top, view from side, view from below

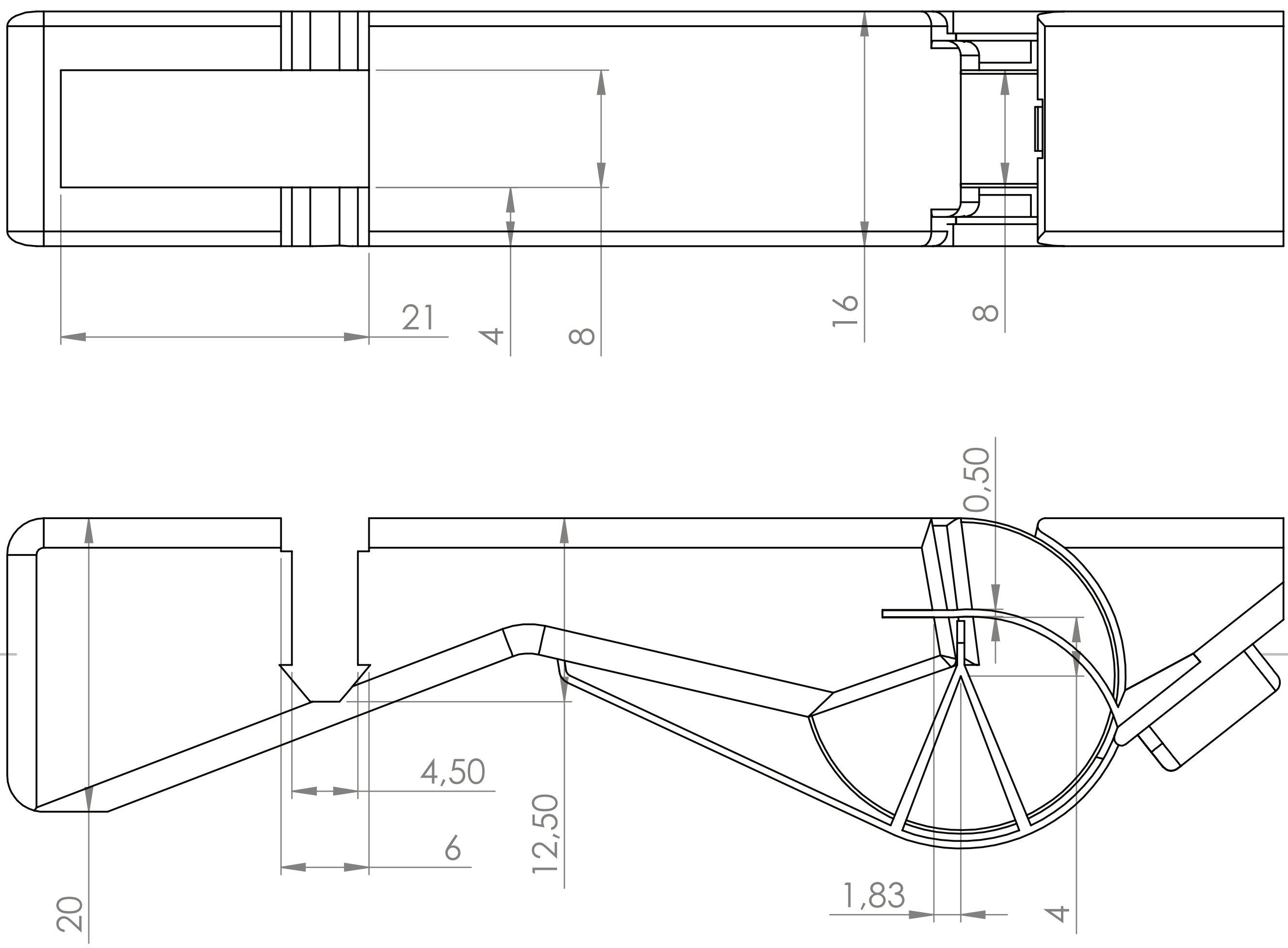
DWG NO.

Finger

A4

SCALE:1:2

SHEET 1 OF 1



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	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MCP joint: top view and side view

MATERIAL:

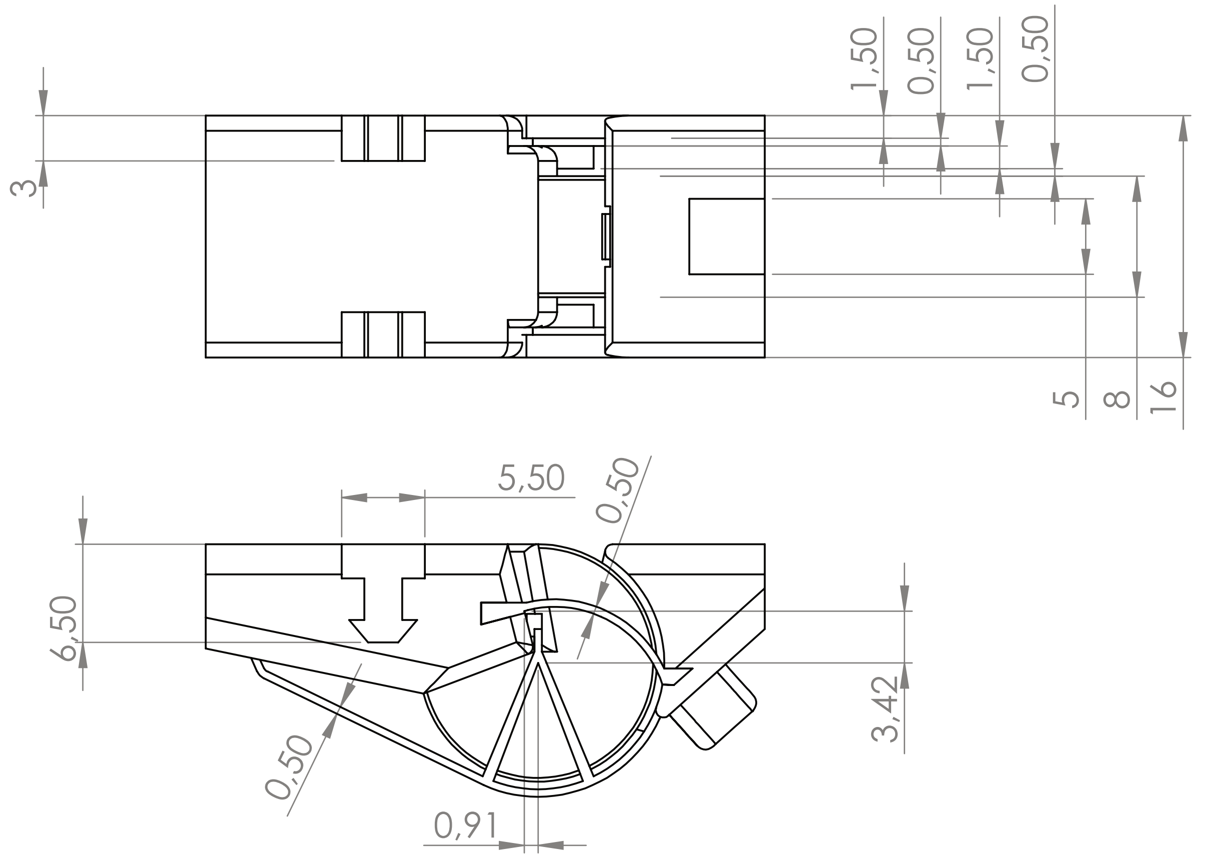
DWG NO.

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
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CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

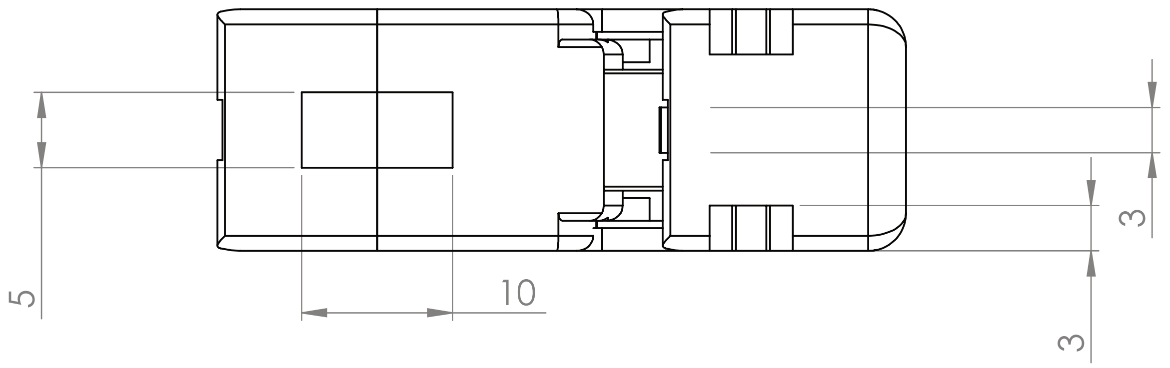
PIP joint: top view and side view

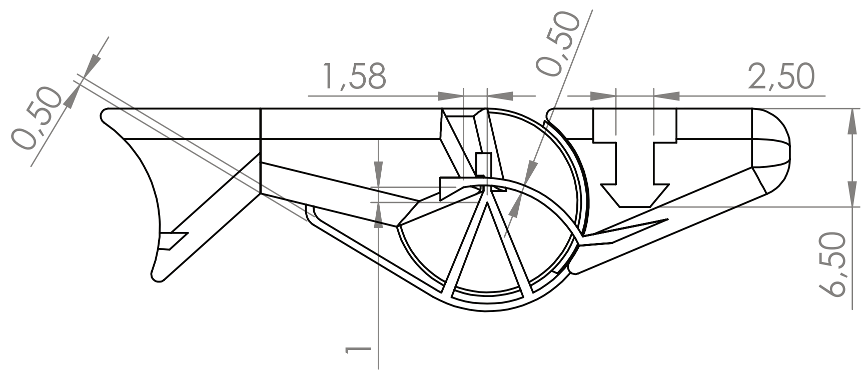
DWG NO.

A4

SCALE:1:2

SHEET 1 OF 1





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LINEAR:
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FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

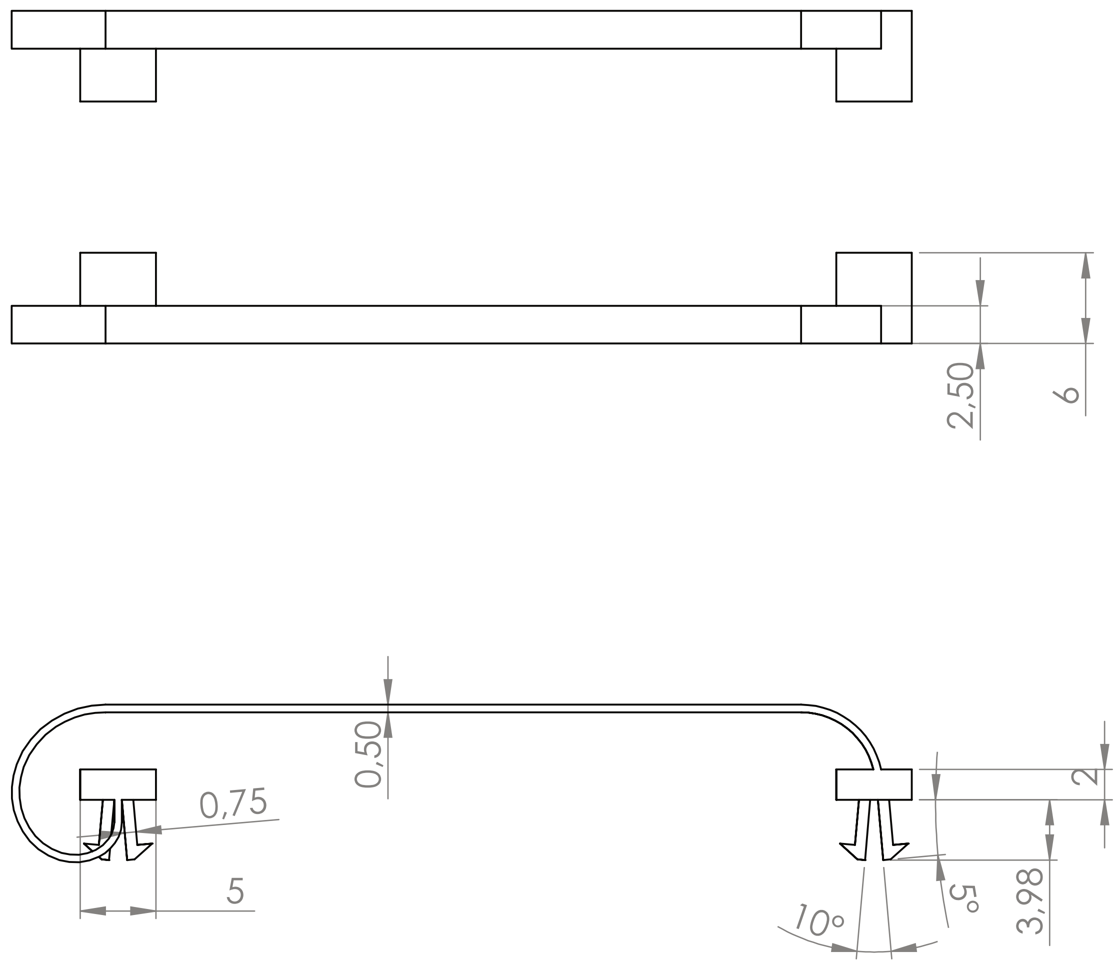
DIP joint: Top view and side view

DWG NO.

A4

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Lateral sheets: top view and side view

MATERIAL:

DWG NO.

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

F Findings on 3D Printing from Prototyping

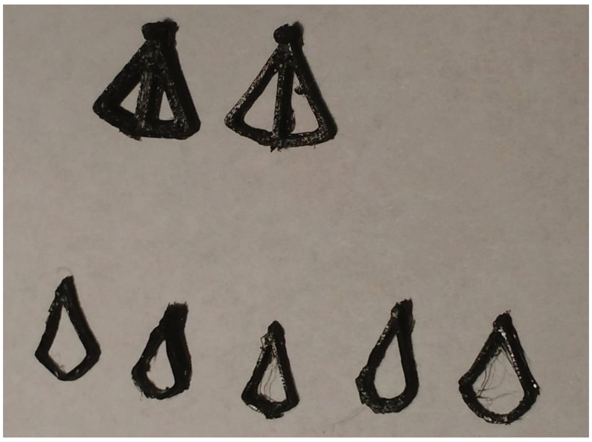
F.1 Introduction

In the prototyping process we tried different printers and materials to find a suitable combination. The experiences with each 3D printer are described chronologically and general findings are explained.

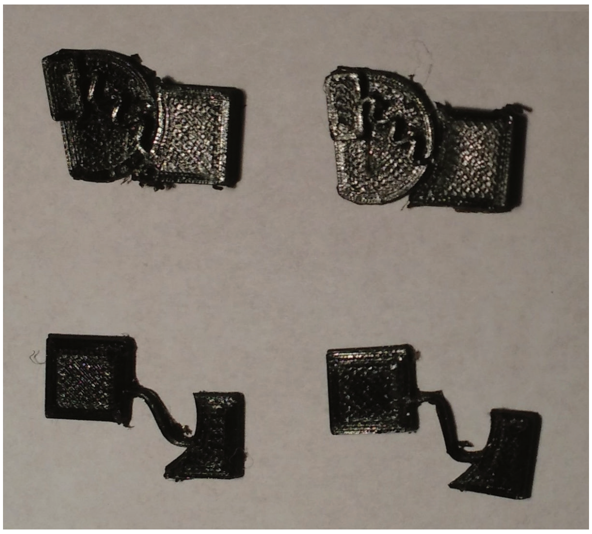
F.2 Ultimaker 3 with Nylon

The Ultimaker 3 was used with the material Nylon. The printing technique of this printer is Fused Deposition Modeling (FDM). Nylon is a standard material supported by Ultimaker and the printing settings are given by Ultimaker. Nylon is flexible in a thin geometry and it is rigid in a thick geometry. The findins from printing with Nylon are listed below.

- The build plate leveling needs precise adjustment. If the gap between the nozzle and the build plate it too big or too small, no material comes out of the nozzle.
- Nylon is sensitive to moist which causes air bubbles in the print.
- The flexible components need to be printed in several geometries to find the optimal geometry and dimensions for each component experimentally. Fig. 26 shows some examples of such experiments.
- Removing support material takes a lot of force because Nylon is very tough. Thin geometries in the print are easily damaged during the removal. A solution was found in printing the joint as two separate parts decreasing the amount of support required. Fig. 27 shows the two parts. After printing, the parts were put together manually.
- A lot of force was required to rotate the printed joint: it was concluded that Nylon is not flexible enough for the prototype.



(a) The fan-shaped sheet: the top samples have three flexures while the lower have only two. Thickness of the flexures and the geometry of the lower rounded flexure that connects the two straight flexures differ between the samples.



(b) The eccentrically attached sheet: top samples have a spring shape while the lower samples are bended flexures. Also the radii are varied.

Figure 26: Samples of components that were printed with different geometries and dimensions.

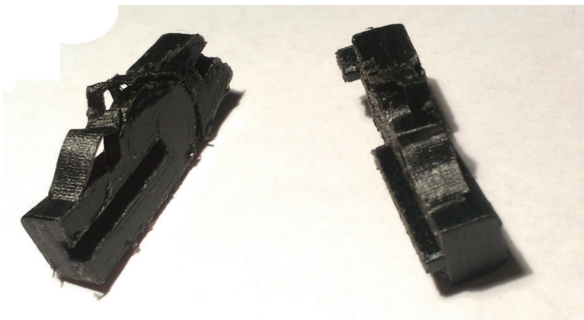


Figure 27: The two parts that together form the joint.

F.3 Envisiontec Perfactory 4 Mini XL with NanoCureR5

The Envisiontec Perfactory 4 Mini XL was used with the material NanoCureR5. The printing technique of this printer is Direct Light Projection. The personnel of the DEMO lab prints the parts with this printer. NanoCureR5 is a standard material supported by the printer and the settings for printing the material are given. The material is rigid in a thick geometry and it is flexible in a thin geometry. The material is very brittle in a thin geometry.

- The printing direction has no influence on the material behaviour. This is because the material of each printed layer is melted together with the other layers.

- The flexible components need to be printed in several geometries to find the optimal geometry and dimensions for each component experimentally. For example, the flexures were tried at several thicknesses to find a compromise between flexibility and brittleness. Unfortunately, the material was too brittle in any of the configurations. It breaked after about ninety degrees of bending, while a bigger bending angle is required for the prototype. Fig. 29 shows thin flexures that broke when bending the joint.

- The minimal gap size is approximately 1 mm which is about three times the minimal line width which is approximately 0.3 mm, otherwise the surface of the components is rough resulting in increased friction between the components. Fig. 28 shows the rough surface when a gap of 0.5 mm is used. This is disadvantageous compared to the Ultimaker 3 where the minimal gap size is approximately the equal to the minimal line width.

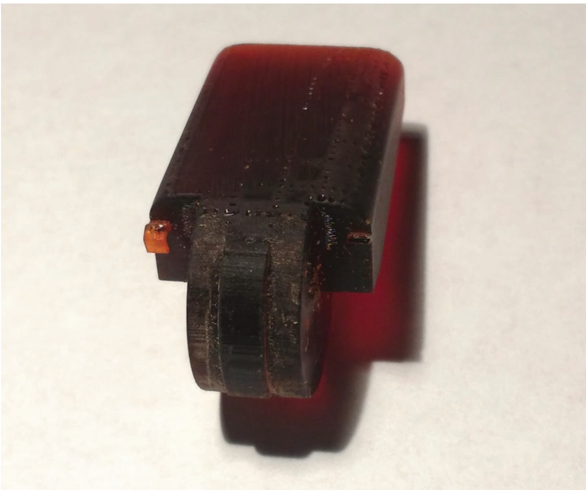


Figure 28: A sample that shows the rough surface when the gap size is too small.

F.4 Ultimaker 3 with PLA and MPflex45

The Ultimaker 3 was used in Dual Printing modus. In this modus it prints one part using two nozzles extruding different materials: PLA which is a rigid material and MPflex45 which is a flexible material. PLA is a standard material supported by Ultimaker and the printing settings are given. MPflex45 is a not a standard material supported by Ultimaker so the printing settings need to be found experimentally. PLA is rigid in a thick geometry and it behaves like a leafspring in a thin geometry. MPflex45 is flexible and the flexibility decreases with thickness.

Figure 29: A sample that shows flexures that broke due to bending.

- Support is printed in PLA because it is easier to remove than MPflex45.

- PLA is used for the components that required a spring-like behavior.

- Ultimaker 3 was able to print at the thin geometry required for the components with sprint-like behavior, but the Ultimaker 2 in the Student Workshop was not. Prints from the Ultimaker 2 had material wrapped unexpectedly one time while it had no wrapped material another time with exactly the same print and settings. Also the surface of the prints with Ultimaker 2 was less smooth which affects the quality of the print especially at a thin geometry.

- The flexible components need to be printed in several geometries to find the optimal geometry and dimensions for each component experimentally. This was also done when printing with Nylon, but when printing with MPflex45 not only the geometry and dimensions, but also the printer settings are part of the experiments. Print speed, temperature, retraction, support geometry, minimal layer time and cooling were found to be of big influence on the quality of the print. The final settings for printing with MPflex45 are listed in D.

- Printing flexible material is more challenging than printing rigid material. It needs to be printed at very low speed and it is very easily affected by changes in the settings like temperature, retraction and print speed.

- Printing MPflex45 is difficult in a thin configuration, because the nozzle easily moves the printed MPflex45 away from its printed position due to its flexibility so that the next layer of material is not printed on top of the printed layer. This results in an ugly print as Fig. 30 shows. There are a few solutions to this problem. First, the printing direction can be changed to minimize the use of thin geometries printed vertically. Instead the thin geometry can be printed as thin layers lying next to each other. Second, the time for each printed layer can be increased. If the material is not cooled completely it can more easily move when the nozzle pushes it, because it is even more flexible when it is hot. Third, support material can be printed on the side of the flexible part as Fig. 31 shows. The downside is that the flexible material and the support material melt together when the flexible material is moved by a push from the nozzle. They need to be separated afterwards which damages the print.

- When the two materials need to be printed on top of each other in a thin geometry there is even a bigger change that the next layer of material is not printed on top of the previous layer because they do not stick together very well. A solution to this problem is to increase the horizontal expansion of the support material.

- Preparing files for a dual print is more complicated than for printing with one material. First, separate files need to be prepared for each of the two materials. Second, the two materials do not stick together very well, so the shape of the components that need to be connected and are made of a different material need to be enclosed in one another. Fig. 32 shows such an enclosure. When designing the enclosure, it should be kept in mind that the flexible material prints at a very speed so it is prefered to use this material only when necessary.

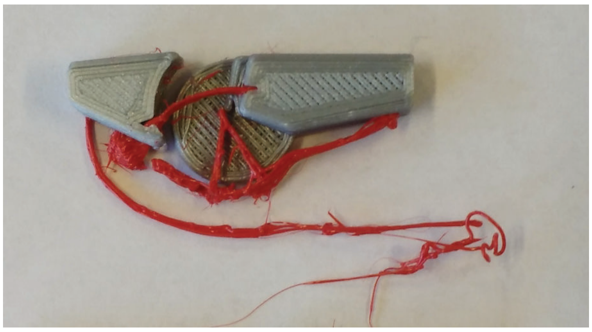


Figure 30: A sample that shows a thin configuration printed with MPflex45 resulting in a failed print. Red is MPflex, grey is PLA.

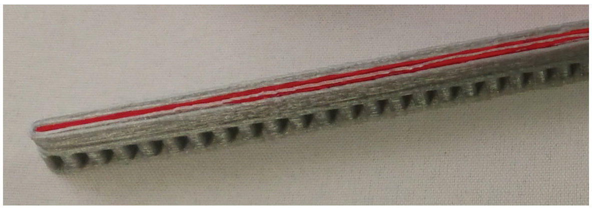


Figure 31: A sample that shows a side support for a thin configuration printed with MPflex45. Red is MPflex, grey is PLA. The two materials are melted together.

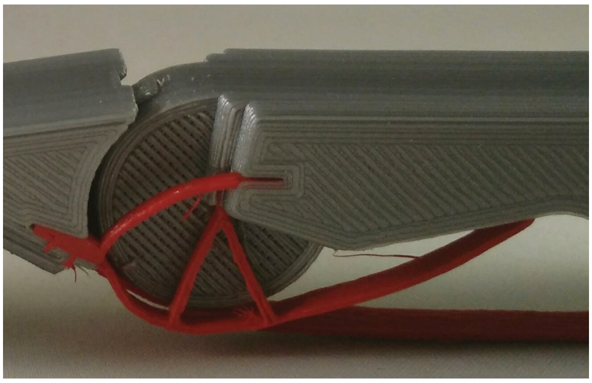


Figure 32: A sample that shows MPflex45 enclosed by PLA. Red is MPflex, grey is PLA.

G Additional Manufacturing of Complex Multi-Articulating Non-Assembly Mechanisms

Hand prostheses are complex mechanisms that require a long assembly time when using conventional production methods. AM is pointed out as a feasible solution to produce non-assembly complex multi-articulated mechanisms within a limited amount of time compared to conventional manufacturing methods [2]. When choosing an AM technique for prosthesis design, the different techniques can be assessed based on the following characteristics: costs, layer thickness, material options(properties), the need for a support structure, surface quality, the need for post-manufacture removing of material, options for multi-material printing [2].

As there are a lot of joints in a hand prosthesis, it is important that a joint can be manufactured with the choosen AM technique. Joints can be either rigid body or compliant joints. In rigid body joints, accuracy and layer thickness are very important because these two factors mainly determine the clearance between the bodies and the surface quality, which both can reduce friction and backlash [2]. In compliant joints, the deformation of flexible parts allow the joint to move. Clearance and layer thickness are not a major issue here, but material properties and geometric configurations are [2]. In AM printing orientation can be chosen so this leaves us with material properties as the main focus for choosing a printing technique. The problem is the properties these are hard to predict because a lot of techniques involve heating and pressurizing of the material, which both change the properties. Optimal geometric configureation can be found iteratively.

Compliant mechanisms can go around the low accuracy of the AM technique while still having the freedom to design complex structures. Numerous compliant mechanisms have been reported in literature. However, alternative techniques to deal with the disadvantages of the AM technique, like limited material choice, are upcoming [2]. One of them is metamaterial mechanisms. The internal microstructure of this mechanism is designed so that it can move in the desired way. For example, Schumacher et al created an algorithm that translates the varying desired elastic behaviour within an object into a 3D printable CAD model. [33].

H Adaptive Mechanical Hands

Underactuation is a principle that is used in numerous mechanical hands to use less actuators than DoF in mechanical adaptive fingers [34]. The output forces of two common underactuation mechanisms are analyzed [35]. Figure 33 shows drawings of the analyzed mechanisms. In both mechanisms a spring was added as a return mechanism. In this short review, the assumption is done that the spring force can be neglected in the analysis.

The first mechanism is the movable pulley from Figure 33a. This is a tendon based mechanism. The pulley is horizontally movable and can rotate around the axis perpendicular to the paper. The output forces are equal:

$$Fa_1 = Fa_2 = \frac{Fa}{sin(\alpha_1) + sin(\alpha_2)}$$

This result was expected due to the tension in the common cable being constant. However, it must be noted that the mechanical advantage (MA) of the system is dependent on α_1 and α_2:

$$Ma_i = \frac{Fa_i}{Fa} = sin(\alpha_1) + sin(\alpha_2)$$

The second mechanism is the seesaw mechanism from Figure 33b. This is a linkage based mechanism in which output force is dependent on the configuration of the arms that exert the output forces.

$$Fa_1 = b2 \cdot \frac{Fa}{c}$$

$$Fa_2 = b1 \cdot \frac{Fa}{c}$$

With

$$c = b_1 \cdot sin(\alpha_2) + b_2 \cdot sin(\alpha_1)$$

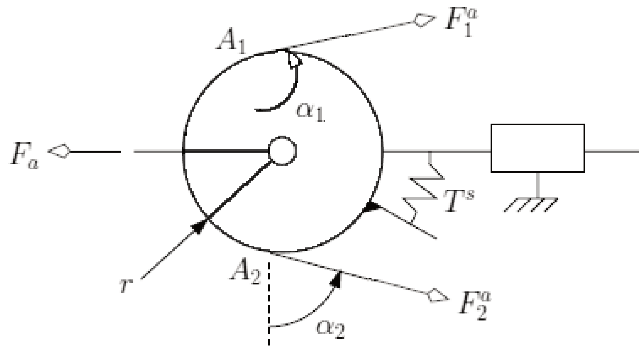
The mechanical advantage is dependent on length b_i:

$$MA_1 = Fa_1/Fa = c/b_2$$

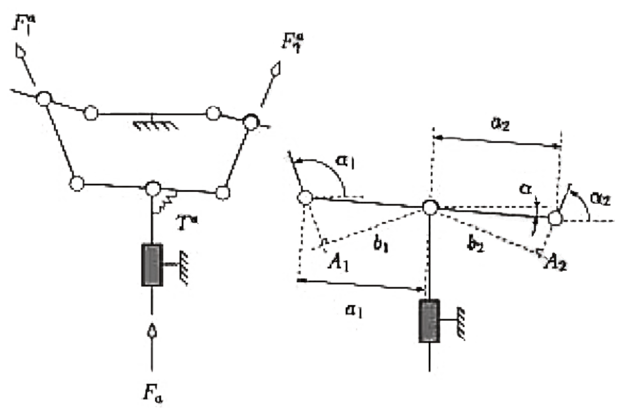
$$MA_2 = Fa_2/Fa = c/b_1$$

For application of underactuation mechanisms in grasping devices, a note must be made. For non-symmetric grasps non-isotropy of force can be desirable. The contact points of such a grasp are usually not symmetric with respect to the axis of the gripper. The contact forces are not equal if the actuation torque at the base of each finger is equal because of the asymmetry of the object. Also note that a priori information about objects that are to be grasped is usually not available so that we cannot design specifically for symmetric or non-symmetric objects.

Tendon systems generate friction along the tendon and they generally have a limited grasping force. In linkage mechanisms friction is generated mostly in the joints and they have a higher grasping force and thus linkage mechanisms are generally preferred when a high grasping force is required [36]. However, linkage mechanisms increase the thickness of the finger as compared to tendon-based mechanisms.



(a) The movable pulley mechanism



(b) The seesaw mechanism

Figure 33: Drawings of two common mechanisms to achieve underactuation and definition of the parameters used for analysis, from [35]