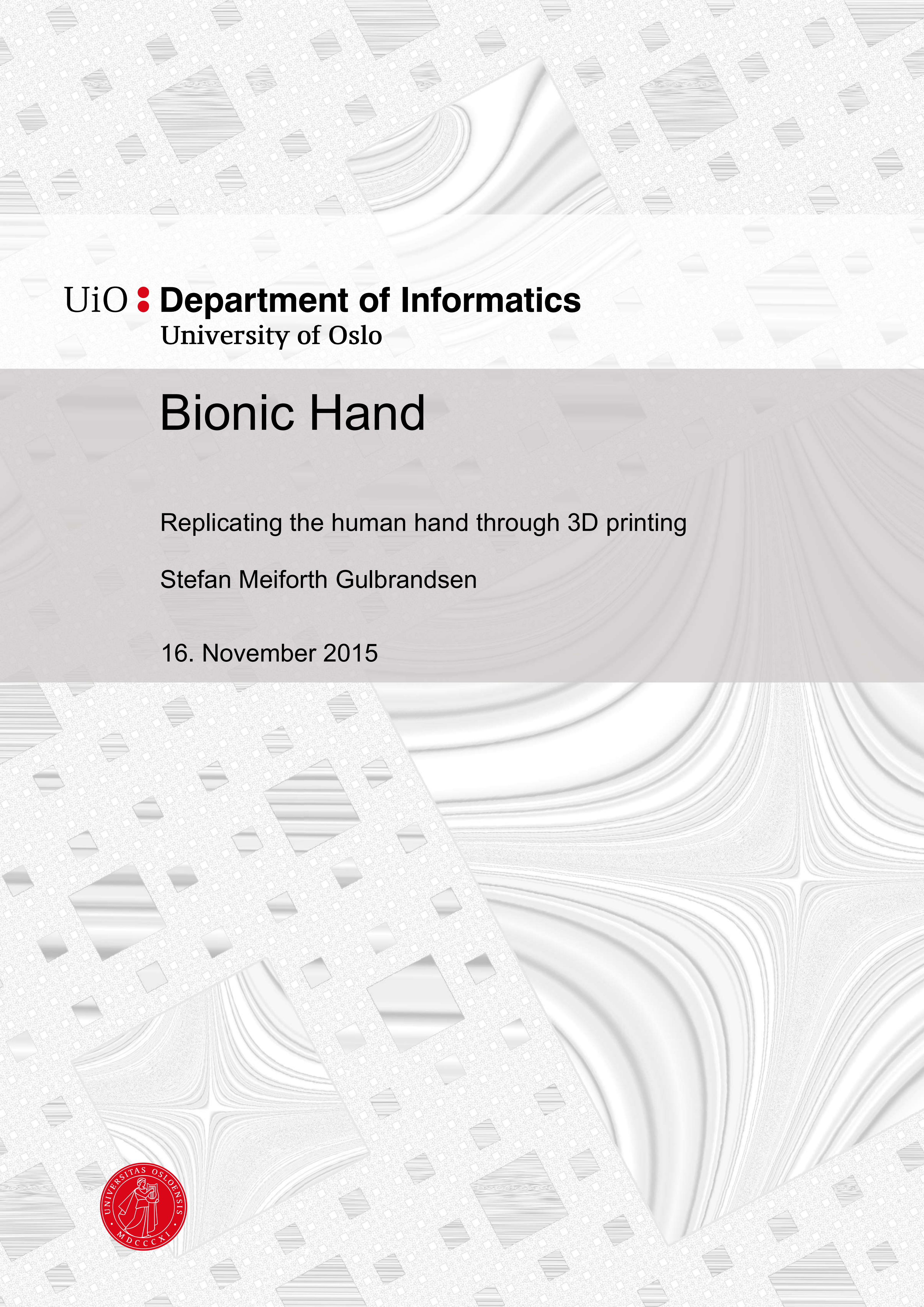

UiO : Department of Informatics
University of Oslo

Bionic Hand

Replicating the human hand through 3D printing

Stefan Meiforth Gulbrandsen

16. November 2015

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Stefan M. Gulbrandsen

Department of Robotics and Intelligent Systems (ROBIN)

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Abstract

Bionics, the application of biological theory in nature to engineering. The most complex machinery in the world can be seen every day. Walking to school, standing behind the counter at your local supermarket and you may even wake up beside one moving 40 or so different components to greet you in the morning. I'm off course talking about the human body.

This thesis explores the boundaries of one of the most advanced multimaterial 3D printers today. By creating a human hand with its ligaments, tendons and bone system it shows just how far it is possible to push technology towards developing biologically inspired prosthetics and robotics. By doing so, inspiring others to create more natural looking and less power consuming prosthetics.

Acknowledgment

I would like to thank my supervisor Mats Høvin. He gave me the freedom and control I needed to create the thesis as I wanted.

I would like to thank Medscape Drugs & Diseases for helping me both with great sites to get information on everything related to the field of medicine and for being really helpful so close to my deadline with procuring what I needed.

I would like to thank BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan, for sharing an extensive database of 3D models for different components of the human body.

Lastly I would like to thank my girlfriend, Giedre Bertasiute, for not only mental support through the entire project and for putting up with me these last couple of weeks, but also for supplying me with what she had of anatomy experience from her own studies to become a nurse.

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Glossary

3D Three-dimensional
3DSMax 3D Studio Max
ACT Anatomically Correct Testbed
CT Computerized axial Tomography
CNC Computer Numerical Control
Extrinsic (of a muscle, such as an eye muscle) having its origin some distance from the part which it moves.
DARPA Defence Advanced Research Projects Agency
DIP Distal Interphalangeal
FDP Flexor Digitorum Profundus
FDS Flexor digitorum superficialis
IK Inverse Kinematics
MP Metacarpophalangeal
MPL Modular Prosthetic Limb
NURBS Non-uniform rational B-Spline
PIP Proximal Interphalangeal
Percutaneous pertains to any medical procedure where access to inner organs or other tissue is done via needle-puncture of the skin
RAPHaEL Robotic Air Powered Hand with Elastic Ligaments
ROBIN Department of Robotics and Intelligent Systems
SUBD Sub Division
TAH Total Artificial Heart
UTS Ultimate Tensile Strength

Chapter 1.

Introduction

What kind of technology is being developed today, and how far have the leading industries gotten in creating the new and improved limb 2.0? There is an overwhelming amount of research and data within the field of medicine and robotics, but how advanced is the field of bionics? Is there enough cooperation between the fields or could they both have profited further with a better synergy between the two?

This document tries to answer the previous question in a short and concise way with literary studies, simulation and testing, with focus on the human hand. Literary studies to understand why certain choices has been made. Simulation to see how research made in one field benefits the other. Testing to see how closely we can replicate biology of the human body with the printer of one of the leading manufacturers of production three-dimensional (3D) printers.

1. 1. Motivation

The implementation of 3D printing and computer numerical control (CNC) machining in biology is a relatively new and exciting field of study. Organs are being printed and robotics are becoming more and more lifelike. Still, we see the development of advanced robotic limbs with motors and actuators. So the question arose, “Is it possible to create something as close to biology as possible, to create a prosthesis that would integrate with the human body in the most natural way?”

Robotic limbs and prosthesis are mainly constructed with bolt joints, motors and actuators, components you will not normally find in the human body. Every new product is lighter and better, and effort is made to make robotics more realistic looking. If what is being created is meant to help people with disabilities or create robots that are indistinguishable from humans, are engineers and medical professionals cooperating in a way that enables them to create prosthetics that adapt to human physiology?

Biologically inspired prosthetics without all the high end, expensive electrical components. Prosthetics that are operated in a more natural and comfortable way could help with issues like:

- Stigma
- Adaptability
- Power consumption
- Cost

1. 2. Goal

The goal of the thesis is to investigate just how far fields like medicine, robotics and bionics has progressed in the development of prosthetics and robotics. Researching biology and robotics while modelling, testing and prototyping new solutions in 3D and comparing it all to the human physiology. Nature has created the magnificent body that is man through millions of years. This thesis will explore the possibilities of replicating this.

With a focus on the human hand with its tendons, ligaments and bone structure this thesis will explore existing research on: implants, biomaterials, prosthetics and CNC machining/3D printing.

It will explore the capabilities of, the multimaterial 3D printer Objet500 Connex, herby referred to as the Objet. It will create the components of a human hand as close to biology as possible on the Objet. The materials available for the Objet are not biological. The materials from the Objet will therefore be compared to actual materials used within the field of medicine and prosthetics.

Upon the completion of the thesis it can prove as both, an element in further research with regards to bionics, and printing on the Objet. It can also be valuable in regards to other fields of study within biology, medicine and engineering.

1. 3. Outline of thesis

This thesis is divided into 8 chapters, each going into detail in their respective fields.

- Chapter 2: Background: explains some basic anatomy with regards to the human hand. It also details basic knowledge about biological 3D printing, prosthetics and already existing technology.
- Chapter 3: Creation of an artificial human hand. A review of literature and proof of concept: contains an in depth explanation of the possibilities of prototyping artificial organs, tissue and components of the hand. It compares different research and choices the industry has made up to today with regards to further development of humanoid like robotic and prosthetics.
- Chapter 4: Tools: explains what tools have been used to procure the results. It explains why some basic choices were made early on and what techniques were used in the creation process of the thesis. It also explains the creation of the testing rig used to test materials in Chapter 6.
- Chapter 5: Practical creation of an artificial human hand: is a step-by-step process in creating artificial organs and tissue from the human hand on the Objet.
- Chapter 6: Material testing: is an in depth look into the capabilities of the materials printed with one of the most advanced multimaterial printers of today, the Objet, as the basis.
- Chapter 7: Discussion and Conclusion: is a discussion of the work done, the conclusion and possible future work.

Chapter 2.

Background

This chapter gathers and explores some of the primary research fields towards implanting engineered components into the body or replace existing ones. It explains the theory that forms the backbone of the thesis and gives short examples to better understand the separate fields. It will also explore some technologies that already have biology as its inspiration and what materials out there that are readily available for bio engineering. It will also describe some biology with focus on components from the human hand to give a better understanding of material presented in later chapters.

2. 1. Anatomy of the hand

It is not easily done, the creation of a fully functional copy of the human hand with the push of a button. In order to do so, a need to understand each organ in the hand is crucial. This chapter will focus on the most crucial organs and components in the hand that makes a hand move like it should.

2. 1. 1. Bones

Bone is the organ that support and protect the organs in the body. It produces the red and white blood cells and store minerals, insulin and fat. It also detoxifies the blood removing and storing foreign elements and later gradually releasing them in smaller portions.

The bones in the hand are connected to each other with ligaments and are moved by tendons connected to muscles in the forearm and smaller muscles inside the hand. Bone is a type of dense connective tissue, which connects and support other organs (bones). The bones are also what constitute most of the toughness of the hand [1].

2. 1. 2. Articular Cartilage and the joint

Cartilage is a flexible connective tissue. It can be found in many areas of the body like joints, ears, nose, airways and the ribs. The focus of this chapter is the Articular Cartilage found on the end of bones that make up joints. Articular Cartilage is very hard. It is not as hard as bone but still harder than muscles, and has low surface friction. This enables easy bending of the fingers, since the two end parts of the bone glide on the surface of each other. Hyaline Cartilage has no blood vessels to supply regenerative factors and therefore suffers from poor regeneration. The wearing down and injury of articular cartilage in joints is one of the main reasons for joint pain in the US [2].

The cartilage, same as with bones, acts as shock absorbers [3]. Each joint in a straight line increase the shock absorbing effect and even though the bone is the primary dampener, the cartilage can take a lot of impact stress. The joint is also encapsulated by synovium and synovial fluid, Figure 2.1. The synovium is a thin membrane only a few cells thick deciding what can and cannot get through to the inner joint where the synovial fluid acts as shock absorbent and lubrication of the joint [4].

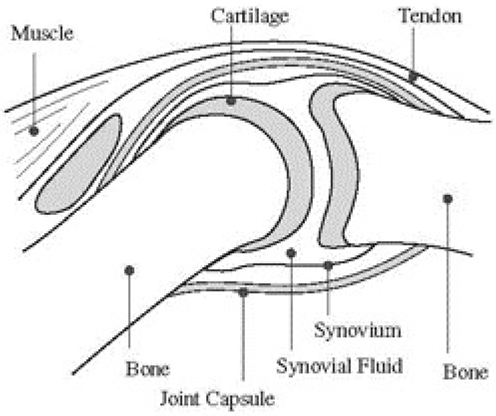

Figure 2.1 Finger joint with names of components.

2. 1. 3. Ligaments

Ligament is the tissue that binds bone to bone, Figure 2.2 and Figure 2.4. Ligaments are similar to tendons as they are both made of connective tissue but ligaments can stretch more since it contain more elastic fibres. The ligaments in the finger stabilize the joints during movement and also determine how much the joints can move a certain way. Normally several ligaments work together in defining the range of motion for a particular joint. People without 100% effective ligaments usually suffer from impeded movement or joint dislocation [5].

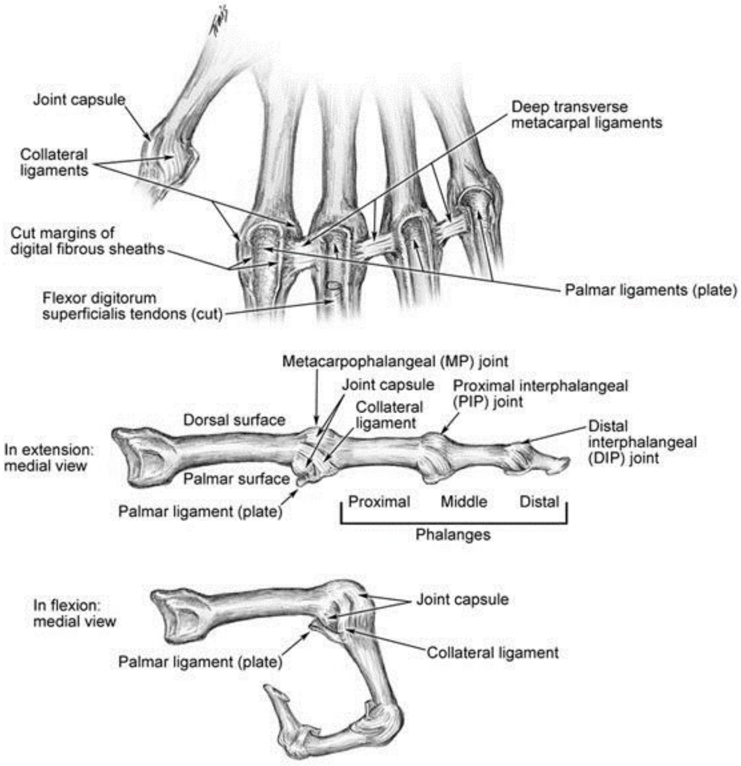

Figure 2.2 Ilustration of ligaments in hand [62].

2. 1. 4. Tendons

Tendons are bands of connective tissue that usually connect muscle to bone, Figure 2.3 and Figure 2.4. The control and movement of bones is achieved by flexing and relaxing the muscles in the forearm so as to transform force to tendons connected to the bone. Tendons are tough but still stretch a small amount. This is so sudden stretching of the tendon do not damage or rupture it [6].

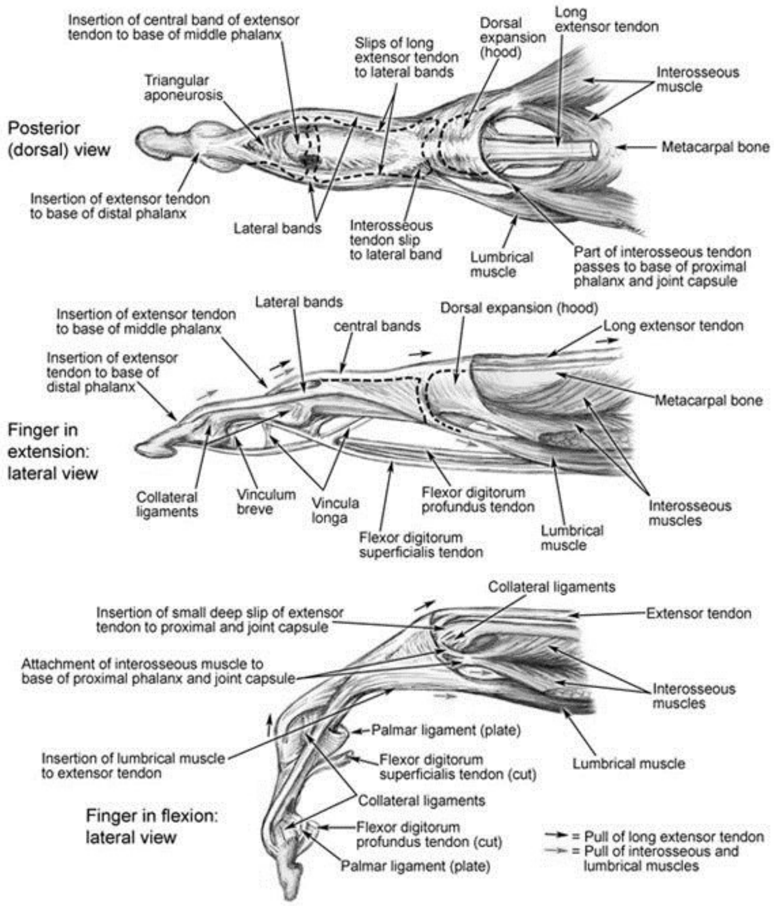

Figure 2.3 Illustration of tendons in finger [63].

2. 1. 5. Skeletal Muscle

Muscles is a band of fibrous tissue that has the ability to contract. The contraction produces force and motion on the organ the muscle is connected to or part of, see Figure 2.4. There are three types of muscles, but the main focus for this thesis is skeletal muscles used to move bone. Muscles main power source is the burning of fat and carbohydrates. The force the muscle can exert is proportional to its physiological cross-sectional area [7].

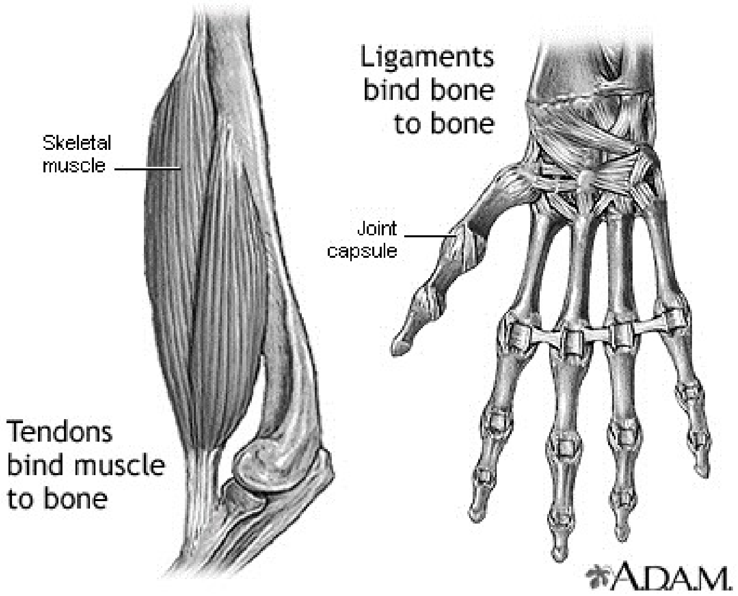

Figure 2.4 How tendons and ligaments bind muscle and bone [2].

2. 2. Medical tools and components

There are several tools and components that can be used when implanting or connecting artificial components in the human body. This chapter explains some of the typical definitions of such and some of the tools used in medicine for the creation of artificial organs and prosthetics.

2. 2. 1. CNC Machining

CNC machining is the process of using rotary cutters to remove material. When a person is in need of replacing bone, CNC machining can be utilized to create an implant from a suitable material such as titanium or certain plastics. When special surgery equipment for a custom procedure or parts for implants is needed, these can be developed with pinpoint accuracy. The shape of the tool or implant often needs to be optimized for a single person and the utilization of 3D models and CNC machining enables rapid development of such custom tools. CNC machining is a fast growing industry within the field of medicine.

2. 2. 2. Implants

A medical implant is a device manufactured to be implanted into the body. It could be grown or manufactured in a lab or come from a donor. It can replace a missing biological structure, e.g., implants for hip replacement or knee replacement. Assist a damaged biological structure, e.g., a pacemaker. Enhance a biological structure, e.g., breast implants. Implants can be permanent or temporary. Implants such as hip replacement are considered permanent while screws to repair broken bone are considered temporary. The risks of medical implants include infection during implanting to reactions leading to rejection of the foreign material in the body. The field of medical implants is a strong growing field with robotic components getting smaller and smaller to the point where tiny robots can move through blood vessels and medical tools that can be inserted through the tiniest incisions.

2. 2. 3. Prosthetics

Prosthesis is an artificial device that replaces a missing body part. The need for replacement can come from an accident, illness, wear and tear or birth defect. It is meant to have the same functionality as the body part it is replacing, or as a cosmetic replacement. They can be removable like that of most prosthetic arms and legs or they can be permanent like a testicle or tooth. The type of prosthesis can vary depending on if only a part of the affected area is missing or if an entire limb is missing. If the patient can function at almost full capacity with a missing extremity cosmetic replacement or physiotherapy to adapt to the new physiology is often a viable choice. Prosthetics also serves as an emotional recovery tool. The loss or injury of a limb can often lead to mental scarring. A cosmetic prosthetic can help a patient adapt to a sudden change in appearance and its ability to function.

2. 3. Medical 3D Printing

Additive manufacturing or three-dimensional (3D) printing is the process of creating a 3D structure, layer by layer, from a 3D model. Medical 3D printing uses additive manufacturing to create medical devices or organs with a customized 3D printer loaded with inorganic or organic materials for use in the body.

Standard 3D printers have become a valid aid for surgeons in both the diagnosis of illnesses and in the treatment of different physiological disabilities and defects. Normally a doctor must plan a surgery after opening up a patient but exact models of organs printed beforehand enables better planning and preparation. It also reduces risk of infection and hypothermia since the organs of the patient does not need to be exposed over a longer period of time. On the other hand, printers with the abilities to print organic matter lets researchers and medical professionals create organic tissue and even organs.

There are mainly three types of 3D Bioprinters, inkjet, Microextrusion and laser-assisted [8].

2. 3. 1. 3D Modelling

3D modelling is the process of creating three-dimensional models, or surfaces, from mathematical formulas using a specialized software. This can be done by the specific ordering of a collection of points in 3D space. The points are connected by lines that in turn can represent surfaces. The higher density of lines and surfaces the more detailed an object becomes, as illustrated by Figure 2.5. 3D modelling is used by a wide variety of fields from engineers and medical professionals to artists and laymans as a tool for visualisation and construction. The 3D model is still only a ordering of bytes in a computer. By including actual physical parameters a blueprint for an actual physical copy of the 3D model in the software can be created with the use of a 3D printer.

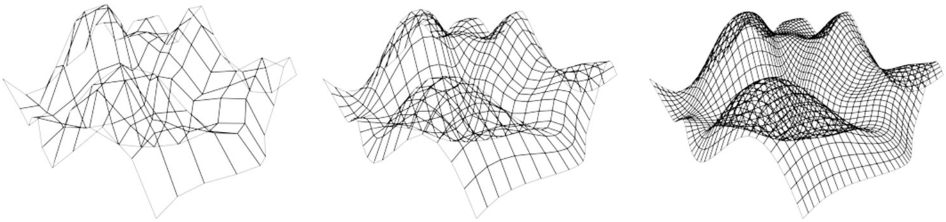

Figure 2.5 Meshsmoothing with 0, 1 and 2 iterations.

2. 3. 2. Inkjet bioprinting

Inkjet bioprinters, Figure 2.6, are the most commonly used types of printer, stemming from the standard office and household printers. They function by either heating the print head to force exact volumes of organic material on to specific areas on a print surface or with pulses formed by piezoelectric or ultrasound pressure. This enable pin point printing of materials such as enzymes and living cells.

2. 3. 3. Microextrusion bioprinter

Microextrusion bioprinters, Figure 2.6, use pneumatic or mechanical dispensing systems to extrude a continuous beads rather than exact volumes of matter. These are common because of their relatively low price. Mechanical systems have smaller, more complex components, providing better special control but reduced maximum force.

2. 3. 4. Laser-assisted bioprinter

Laser-assisted bioprinting, Figure 2.6, utilises the principles of laser-induced forward transfer [9] to eject biomaterial by superheating of a material, i.e. titanium or gold, coated with a thin layer of liquid film with biomaterial to propel a vapour pocket onto the print surface. The nanosecond laser heats the material to a gas-plasma state so a vapour pocket is formed by conduction at the metal liquid interface. When the vapour pocket expands a liquid droplet is ejected from the film.

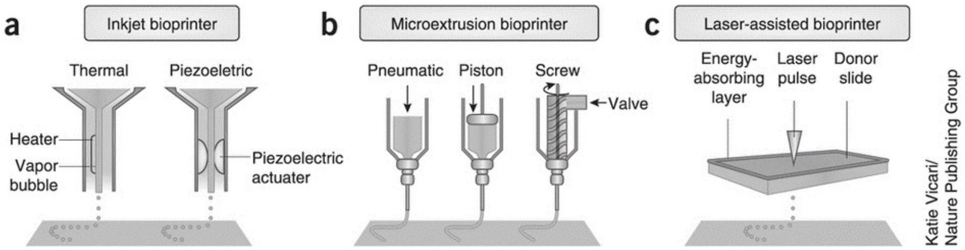

Figure 2.6(a) Thermal inkjet printers electrically heat the printhead to produce air-pressure pulses that force droplets from the nozzle, whereas acoustic printers use pulses formed by piezoelectric or ultrasound pressure. (b) Microextrusion printers use pneumatic

2. 4. Human Machine Interface

The human machine interface (HMI) has always been the greatest challenge within the field of medicine and prosthetics. Controlling a multi-input system with multiple degrees of freedom (DoF) with maybe just a few muscles left in, e.g., an amputated arm or leg can be a challenge.

Bionic reconstruction [10] is some of the latest research towards giving people with impaired movement in their hands, the ability of interaction back by replacing the defect hand with a robotic limb that interfaces directly with a patients nerves. This is a more natural approach compared to interfacing man and machine since it utilizes nerves already used for controlling limbs, and is also becoming more of the norm since it enables more sensory input for controlling the prosthesis.

2. 4. 1. External

External Human Machine Interface is an interface that utilises external sensors to acquire input to a robotic actuator or prosthesis.

2. 4. 2. Osseointegrated

Osseointegrated interface is when the interface connects directly to the bone in the remainder of the missing limb. This gives the user a more familiar and natural way of operating the prosthesis since the prosthesis reacts and responds more like a natural limb.

2. 5. Existing technology

DEKA Integrated Solutions Corporation and The Applied Physics Laboratory (APL) at Johns Hopkins University may be two of the names most people working within the fields of bionic think of when mentioning robotic arm prosthetics. It would not be unusual to count on them being the ones who has gotten closest to biology in creating copies of human arms. Still, when researching tendon driven robots, artificial robotic muscles and artificial ligaments for robotic joint movement they are not the ones that normally pop out. Systems like the ACT hand or RAPHaEL seem to have gotten much further in regards to biological similarity than the strongly funded alternatives.

2. 5. 1. DEKA arm

The DEKA arm, Figure 2.7, uses electromyography [11] to record electrical activity produced by skeletal muscles. These signals are converted to 10 powered movements. The price tag, 100k dollars [12], alone is enough reason to research alternative ways of prosthetics development.

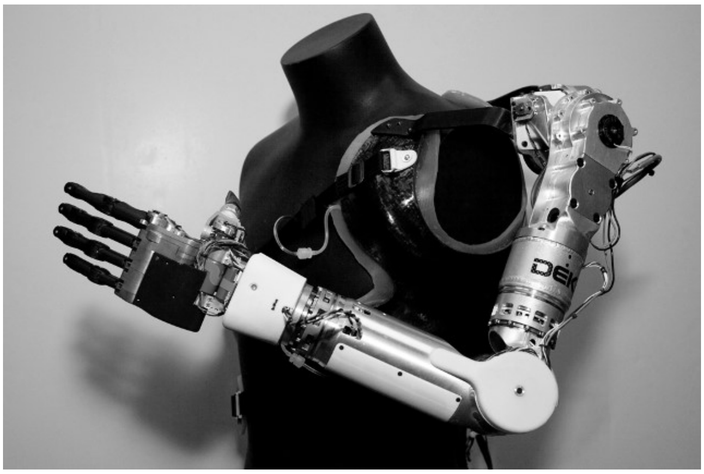

Figure 2.7 The DEKA arm holds a lightbulb, demonstrating its dexterity [66].

2. 5. 2. MPL

John Hopkins University APL with its modular prosthetic limb (MPL) prosthesis, Figure 2.8, funded by the Defence Advanced Research Projects Agency (DARPA) has maybe the most biological inspired robotic limb when it comes to functionality. With an extensive amount of motors and sensors the MPL tries to function like a normal hand focusing on somatosensory [13]. The MPL is probably the polar opposite of what this thesis tries to accomplish. Except for the fact that it looks like a hand, every joint is controlled by servos and it is filled with electronics and sensors.

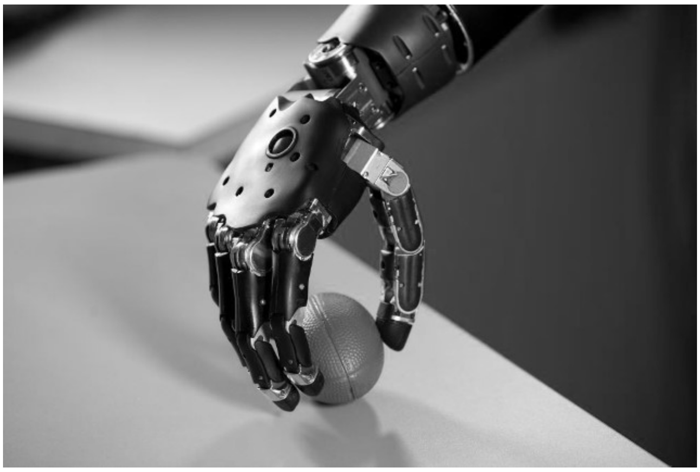

Figure 2.8 DARPA funded APL arm [67].

2. 5. 3. ACT Hand

The anatomically correct testbed (ACT) hand, Figure 2.9, is an anatomically correct bone system with a hinges instead of ligaments for joint rotation, developed to mimic the active and passive dynamics of the human hand with a tendon-driven structure [14]. This is the closest you can get to an anatomically functioning hand. This is also the technology most similar to this thesis with regards to actually mimicking biological behaviour.

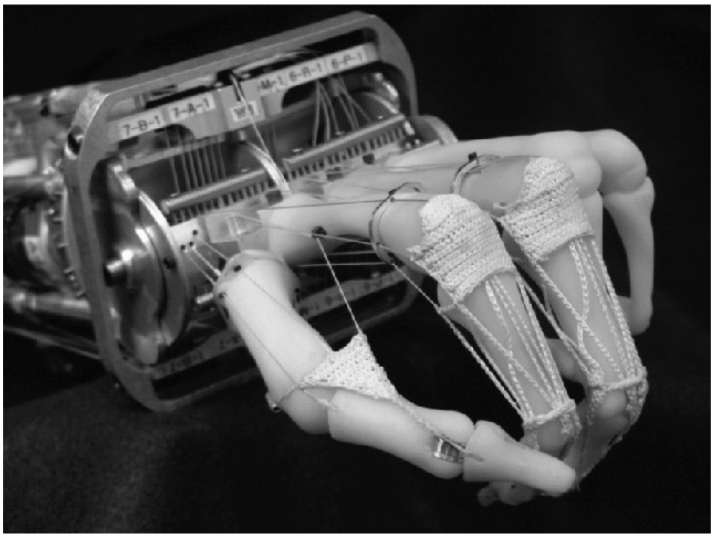

Figure 2.9 Anatomically correct testbed hand [14].

2. 5. 4. RAPHaEL

RAPHaEL, Figure 2.10, short for Robotic Air Powered Hand with Elastic Ligaments, is an air powered robotic hand with elastic ligaments. This makes it unique in the sense that it does not need any motors or actuators, and the grasping force is easily adjusted with air pressure force [15]. The use of elastic ligaments is similar to the way normal ligaments function and show similarities to artificial joint replacement technology, Chapter 3. 5.

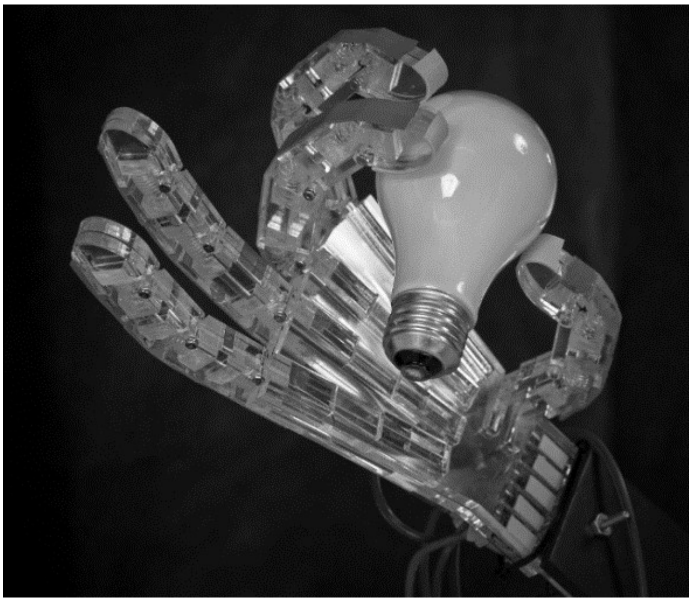

Figure 2.10 RAPHaEL hand holding lightbulb [68].

Chapter 3.

Creation of an artificial human hand. A review of literature and proof of concept.

The hand consists of 14 phalanges, 5 metacarpals and 8 carpal bones, Figure 2.2 and Figure 2.4. A total of 27 bones. These are controlled by 18 extrinsic finger flexors and extendors, and 17 hand instrinsics and thumb muscles. 35 muscles controlling the bones from inside the hand or from your forearm [16]. The bones are held together by at least 123 named ligaments and everything is encapsulated in fat, and tissue to make up the human hand [17]. All of these components are completely unique for each individual. Some individual may have more and some may have less of these components. The uniqueness of the joints and how everything is formed and where ligaments and tendons are connected is what makes every person different. One person may easily dislocates a joint while another has greater control of individual finger movement. This is also what makes creating each component of the hand tailored for an individual such an endeavour.

This chapter will detail the issues and solutions toward creating artificial organs for use in the human body or as a robotic limb, with focus on the human hand. It will step by step try and prove the possibility of creating something as intricate as the human hand with artificial components as close to biology as possible.

Creating a copy of the hand as close to biology as possible would be something that could potentially replace the hand and still function as the original. There for each chapter will also try and find an alternative that is as close to its biological counterpart as possible and that could or can be used in the human body.

3. 1. Complexity

It is a given that to create a fully functional hand you need to be able to create every single component within it. Organs like hearts, livers and lungs does not necessarily have to have a specific form or be made of a specific material since their functionality is not directly connected to their appearance, as illustrated in Figure 3.1. As long as a lung provides oxygen to the blood, a heart pumps blood through the body and a liver removes toxins and filter blood each of these could be of any shape, size or material as long as the it does not obstruct with the normal behaviour of the part of body it is implanted in.

Organs like bone, ligament and tendons on the other hand has to have a certain size and shape [18]. They also need to be of a specific composition for the human body to move in a natural and familiar way. The movement of a finger is proportional to how a bone is shaped, how the size and strength of ligaments restrict movement and how tendons are fastened to the bones to activate movement. Since bones, ligaments, tendons and muscles are used to transfer movement and exert force they have to be of a strong material that can withstand excessive strain. The type of material and material structure will also impact weight, which consequently will impact movement.

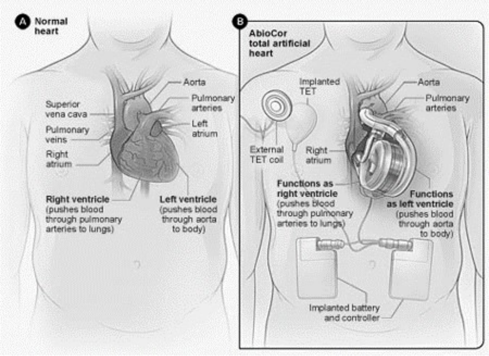

Figure 3.1 Left, normal structure and location of a human heart. Right, an AbioCor TAH and the internal devices that control how it works [56].

3. 2. Organ model

As stated in Chapter 3. 1. the organs in the hand need to have a certain form so with that in mind, a blueprint of the organ would be a natural first step when creating a copy of an organ. Obtaining a blueprint can be done in a number of different ways. In Chapter 2. 3. 1. it is mentioned that 3D models can be used as blueprints to create actual physical objects. How detailed such a 3D model is on the other hand depends mainly on the method of obtaining such blueprint. In the next sub chapters two methods of obtaining a blueprint of an organ is detailed.

3. 2. 1. Scanning

An ideal solution for obtaining a blueprint of an organ is obtaining an exact copy. This can be achieved with different scanning techniques that produce 3D models. One of the newest and most up to date methods for 3D scanning of organs is Revolution Computerized axial Tomography (CT) [19]. Revolution CT can produce a complete 3D model of the human body. This enables a doctor or engineer to extract a particular part (model) from the body to study and further edit.

The only downside to such a method of obtaining a blueprint is that you need to have an organ to copy. If the need for a blueprint is for purely scientific research, any person can be scanned for the blueprint. On the other hand, if a subject/patient is missing an organ or the organ is damaged in some way, a scan will not necessarily be the ideal solution since a damaged or missing organ would not give a complete blueprint.

3. 2. 2. Free form modelling

The alternative to scanning is free form modelling, but this is much more time consuming. With reference models from similar organs time consumed may shorten but it will still take longer and be an inferior solution to the process of scanning. If the purpose of the model is to create an organ in the arm or leg, a copy could be scanned from a healthy limb with the method from the previous chapter, and then mirrored. If the subject has perfect symmetry in their body it could be used straight away, but would most likely have to be modified.

3. 3. Bio compatibility

For artificial organs to be implanted in the human body, the body must accept the foreign object. If the materials in an organ where to be rejected by the hosts immune system, severe complications such as infection and loss of organ function could arise [20] [21] [22] .

For this not to happen when creating artificial organs, rejection possibilities must be considered. There is mainly two ways of going about this. Organs can be replicated using biological materials containing a hosts own antigens so as not to be rejected. Organs can also be replicated using inorganic materials, materials not normally found in the human body, which produce low possibilities of rejection by applying different techniques to the structure or adding special materials to it.

3. 3. 1. Pure bio materials

Materials that are produced from a hosts own genetic structure would be an ideal solution to replicating organs. This produces no chance of rejection since the organ being created has the same antigens as the hosts and the immune system would not attack the foreign component.

3. 3. 2. Inorganic materials

Using materials not composed of a hosts own genetic structure in implants always carries the risk of rejection. The human immune system regards all foreign agents in the body as contaminants and will try to attack them to defend its host [20]. Several methods to combatant this rejection are continuously being researched, and even though none has succeeded in creating something that is completely safe from the “foreign-body reaction” there are some promising solutions being developed.

The use of special gels to encapsulate implants [23] hinder the body from detecting the foreign object. This enables the use of materials that normally would not be useable as biomaterials.

The use of surface modification [24] where different techniques are applied to change the surface of the implant so as to hinder foreign-body reaction is an approach that has been used for some time and is used today on most implants.

3. 3. 3. Combination

A third alternative is the use of scaffolding [25]. Scaffolding is, as the name implies, a method of creating a scaffold. This works as a biodegradable structure for a hosts own genetic material to grow into [26].

3. 4. Bone

In the previous two chapters (3. 2 and 3. 3) the possibility of acquiring a model of an organ and the existence of methods for creating materials for use within the body were detailed. A natural next step in creating a copy of the human hand as close to biology as possible would be to explore the possibilities of creating bone, either to use within the body or as a robotic component mimicking human physiology.

In 2009 a set of researchers created a method of bone creation by heating a block of wood until only pure carbon remains, and after several processing steps they wound up with carbonated hydroxyapatite that has the potential to be implanted and used as bone [27].

3. 4. 1. Semi organic bone

A lot of research into artificially creation of bone is focused towards medicine as ways of replacing damaged or missing bone from the human body, creating scaffolds through 3D printing that normal bone can grow into with the help of the body’s own regenerative abilities [26] [28] [29].

This process of bone creation does not give a fully functional organ without the help of the body’s own regenerative ability, but still shows that it is possible to create something with similar biomechanical properties as bone but without the bones own metabolic properties.

3. 4. 2. Artificial bone

Titanium alloys and ceramics are some of the most researched and used replacements for bone as an inorganic material [30]. In Chapter 3. 3. it is mentioned that material for use inside the body needs to have a certain biocompatibility, but as a copy of human bone used in a prosthesis or for robotics it does not necessarily need the same bioinert or metabolic properties. Any material with similar biomechanics cold be used and shaped to imitate bone in appearance. You would only need a 3D printer with the proper materials or a CNC machine.

3. 5. Ligaments

The ability to create artificial ligament is something highly sought after. The wear and tear or rupture of ligaments can lead to scar tissue forming at or around the damaged area, and this in turn can lead to decreased motion and flexibility of the joint. This propels development of artificial means of organ creation.

Extracting the exact biomechanical and kinematic properties of ligaments though is difficult. Previous results published has mostly been tests on cadavers (corpses) because of the difficulty of measurement on living human subjects [31].

Since the biomechanical properties of an artificial ligament need to be as close to the original as possible a lot of challenges arise from trying to reproduce material properties and is seen as “almost impossible to duplicate” [32]. Still there are materials today, within the field of medicine, used to replace damaged ACL ligaments in the knee, such as the LARS™ ligament [33]. The same ligaments could be modified and used to create artificial collateral ligaments in the fingers or to create anatomically correct prosthetics within robotics.

3. 6. Joint/Cartilage

In robotics, joints usually achieve their smooth motion either from ball bearings or servos. This assures smooth motion along a single rotary axis, but this is not how the joints in a human finger work, Chapter 2. 1. 2. Also consider a situation where a hand with its several joints were to exert an extensive force on another object. In a human hand the bone and cartilage acts as shock absorbers, see Chapter 2. 1. 2, but within a robotic hand controlled with servos, unless there is some dampening effect built into the functionality of the limb, the entirety of the force is exerted on the servo.

Within the field of medicine, when a joint gets damaged the damaged ends on the bone comprising the joints are removed, and an artificial joint is inserted into the bone where the removed ends meet [34]. This mimics the biology of a joint, but does not reflect the actual structure. Instead this approach could be merged with the bone creation process, Chapter 3. 4, to manipulate the ends of the bone at time of creation. For implants, the scaffolding technique [2] can be utilized to create cartilage to grow into. For implants, robotics and prosthetics, artificial alternatives like a composite osteochondral device [35] could be utilized.

3. 7. Tendons

As mentioned in Chapter 3. 5. and 3. 6. joints on robotic limbs and many prosthetics are normally servos. This eliminates the need for separate constructs for ligament, cartilage and tendons since the servo acts as support, provides smooth motion and provide force for movement. The problem with this is that robotic limbs and even prosthetics get a lot of components in the hand weighing it down. There is also an issue with size when each joint need its own actuator.

Bones in the hand are operated by tendons moved by muscles in the forearm, Chapter 2. 1. 4. Since the forearm is much larger than the hand and has room for more muscles this ensures a hand that is strong but light weight.

Replicating this in robotics is already being researched, but still in ways that only replicate the pulley system, where a tendon is fastened to each bone giving more degrees of freedom than an actual hand. Very few focus on anatomically correct constructs, Chapter 2. 5. 3. Most tendons and muscles are multi-articulate (i.e. each muscle and tendon controls more than one joint), see Figure 2.3. Fewer tendons and muscles means less actuators, less weight, less power consumption. The tendons of each finger are connected to each other, Figure 3.2, sharing the combined strength of all. Off course this also limits some degree of movement and which is why it is difficult to move only one finger separately from the rest without practice.

It is also easier for a user to adapt to an atomically correct prosthesis considering the human body has already evolved to control movement in such a way over the course of hundreds of thousands of years.

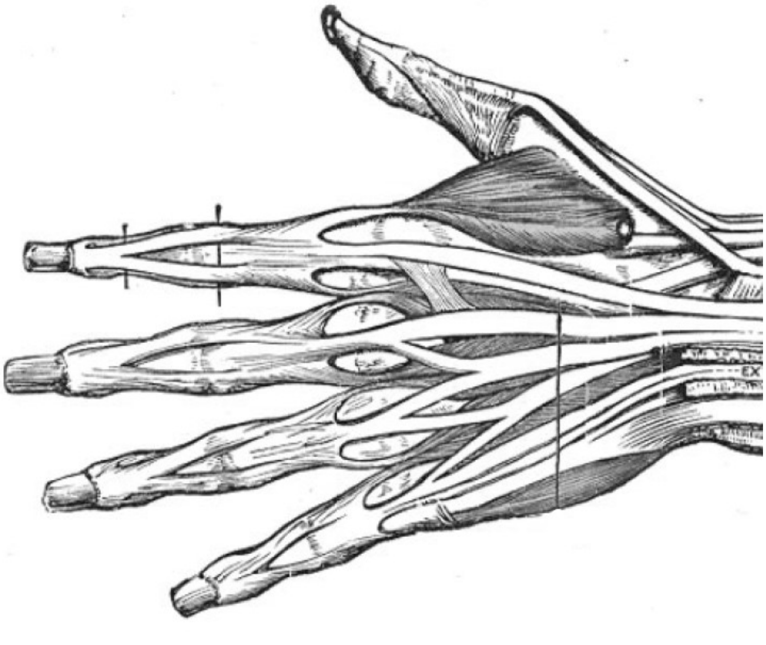

Figure 3.2 Tendons and muscles in hand.

3. 8. Muscles

Artificial muscles has existed for a long time. Making them function and act like the human counterpart though is something only achieved in recent years. When the need for more silent, lightweight, cheaper and smaller actuators arise, fields like medicine and robotics can benefit greatly from new and improved products.

Pneumatic or electroactive actuators are some of the products which mimic human muscles the most in ways of controlling movement. Pneumatic muscles resembles most skeleton muscles in the way that they both have a monotonically decreasing load-contraction relation. Both have to be set up antagonistically in order to get bidirectional motion, and both are able to control joint compliance [36].

With the right materials both pneumatic and electroactive muscles could be manufactured with 3D printing.

3. 9. Interface

In Chapter 2. 4. the issues interfacing with the human body is detailed. With a robotic limb, you only need to connect some wires for interfacing, but with actual organic tissue some issues can be challenging. Researchers are still mapping how the human body and minds work and how signals travels through our bodies.

The Swedish university Chalmers has developed a percutaneous osseointegrated interface [37]. This may well be the closest thing you can get to actually implanting artificial components in the body. Although right now it is only connecting the base of a prosthesis to what is left of bone in the arm, and connecting sensors to nerves and muscles, further development may enable seamless transfer from actual human skin to artificial skin with embedded sensors [38] [39] enabling both the feel and look of an actual limb.

3. 10. Connecting components

In the previous chapters the possibility of creating each component in the human hand either with an organic or inorganic approach to production is presented. It is shown that most of these can be made almost identical to their biological counterpart. If we accept that now or in the near future all of these are plausible replacements for components in a living person, then we have proven that it is possible to create components as close to biology as we can get at least when it comes to appearance and biomechanical properties.

For all of these components to make up a hand though they need to be connected to each other. Reconnecting and repairing tissue is what medical professionals do every day when people are injured, need remodelling of tissue or in need of replacing an organ. If doctors can reconnect actual organic matter/tissue they should be able to do it with inorganic matter or artificially created organic matter in cooperation with engineers.

Chapter 4.

Tools

This chapter contains information on what hardware and software were used to create the prototyped components in Chapter 5. It will also contain information about why the selected tools were used and possible alternatives. Some limitations due to the specific 3D printer (Objet) used are discussed.

4. 1. 3D Modelling Software

To create 3D models for use in prototyping you need a 3D modelling software. When creating components with organic appearance, modelling with a sub division (SUBD) base modelling software is preferred for a more organic look of the components modelled. The alternative to SUBD based modelling would be non-uniform rational b-spline (NURBS) based modelling mainly used in engineering. NURBS based modelling gives the user more precise control of each point in a model, but can be hard to work with when organic shapes are needed.

4. 1. 1. Autodesk 3DSMax

3D Studio Max (3DSMax) was chosen as a modelling and simulation environment because it is fully featured with 3D modelling, animation, simulation and rendering possibilities and because of previous experience with this type of modelling environment. It was there for thought to be the best choice moving forward.

Modelling techniques

- **Mesh smoothing:** Mesh smoothing was used to smoothen irregular surfaces as illustrated in Figure 2.5. This also enables relatively crude modelling, focusing on the main properties of the object modelled, while the software smooths the surface of the model for a better look and surface finish.
- **Symmetrical modelling**: Symmetrical modelling is a pretty usual way to do 3D modelling. It works sort of like a virtual mirror. Editing done on one side of the mirror affects the model on the other side of the mirror. This speeds up the creation process and later, if needed, one can merge the symmetry modifier and continue with detailed modelling of each side without affecting the other.

Simulation techniques

- **Bones System:** A bones system is a linkage of "bones" to create a platform for animation. The joints of these bones behaves much like real joints does in the way that the link between these bones can be manipulated and constrained to behave in any way you want. These properties enables them to be used for more than just simulating how bone moves but can also be used to simulate how rope or other objects with bending motion behave.
- **IK Solvers:** An inverse kinematics (IK) solver enables IK to be applied to bone systems or other link like object to define rotation and position of all the links in a system based on a set of parameters. This can be used to simulate the movement of the bones in a finger, or how the ligament twist, turn and stretch.

4. 1. 2. Alternatives

There several alternative software for 3D modelling, but when choosing what software to do all the modelling and simulation on it was important to have a modelling environment with full SUBD support. Bio inspired modelling is best done with SUBD surfaces since there would be a lot of free form modelling. And a familiar working environment also enables faster development.

There are a lot of different 3D modelling environments but some of the popular alternatives with similar functionality as 3DSMax are:

- Maya [40]
- Blender [41]
- Rhinoceros [42]
- Silo [43]

4. 2. Engineering stress test machine

The material testing was done on a simplified tension testing machine, hereby referred to as the rig. The rig is a simplified version of standard tension test machines and was created through the course of this thesis with the sole purpose of the tests performed in Chapter 6 on the Objet. Details and technical drawings of the test rig can be found in Appendix B.

Engineering stress test is a measure of force needed to break the material. It is performed by mounting the material test piece between two clamps and stretching the material, while measuring the load force, until the material breaks.

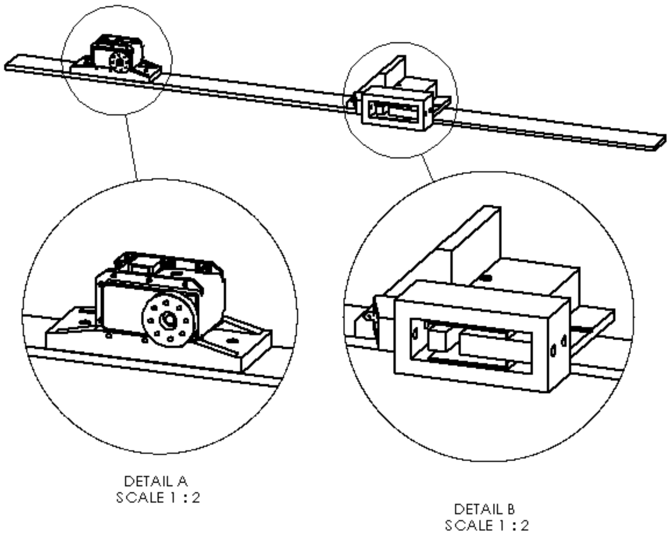

Figure 4.1 Dynamixel servo for pull force A, Load Sensor for load measurement B.

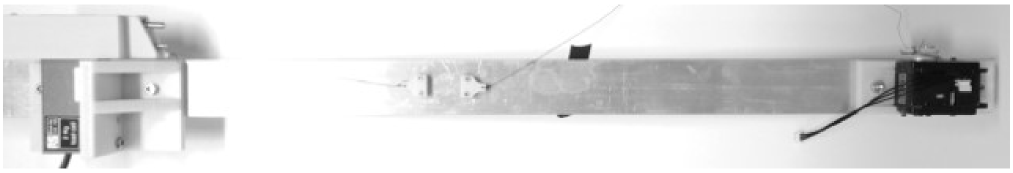

Figure 4.2 Engineering stress test machine, top view.

4. 2. 1. Components

The testing rig uses a Load Cell from Vishay Precision Group, Figure 4.3, combined with a strain gauge converter, Z-SG, to measure force with a sensitivity of$+ - 1\ mV$. The force applied to the material was created with a Dynamixel servo MX-106, Figure 4.4, with a stall torque of 8.4 Nm. For mounting the material to the load sensor and servo two clamps, Figure 4.5, was used.

The force sensor interfaced with an Arduino Mega board for serial communication with a computer. The computer was also set up with Processing for interface and control of the servo.

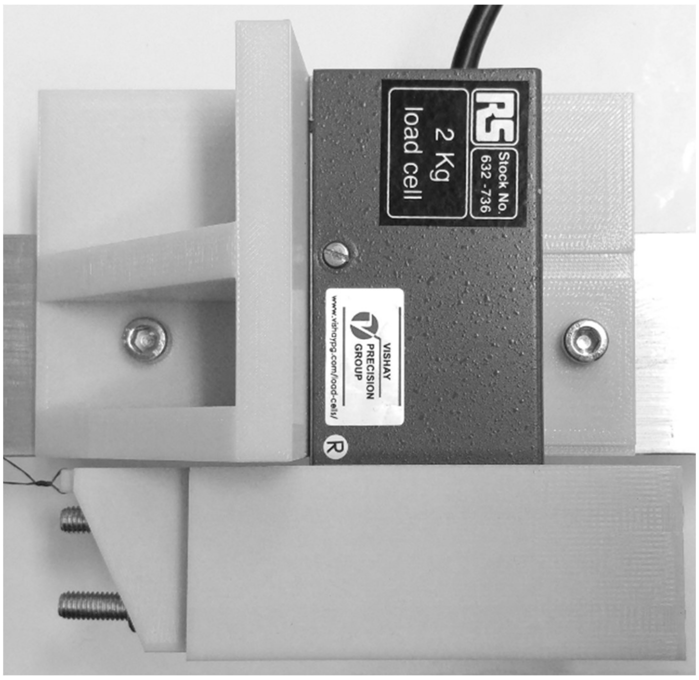

Figure 4.3 Load cell fastened to aluminium bar.

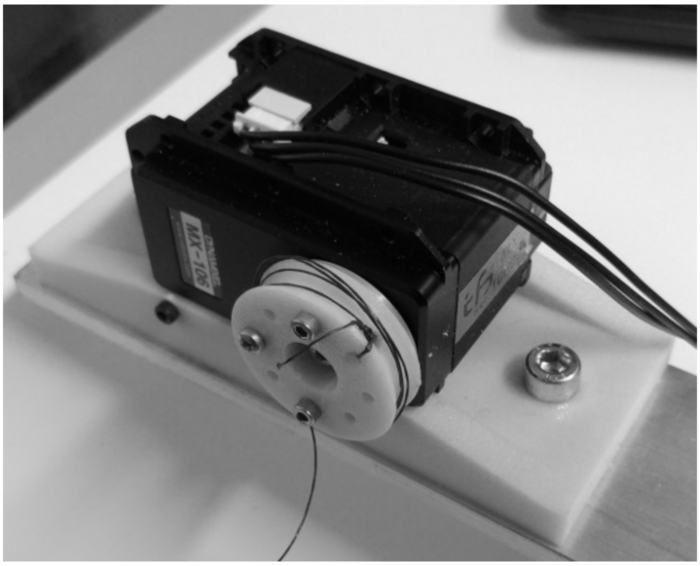

Figure 4.4 Servo fastened to aluminium bar.

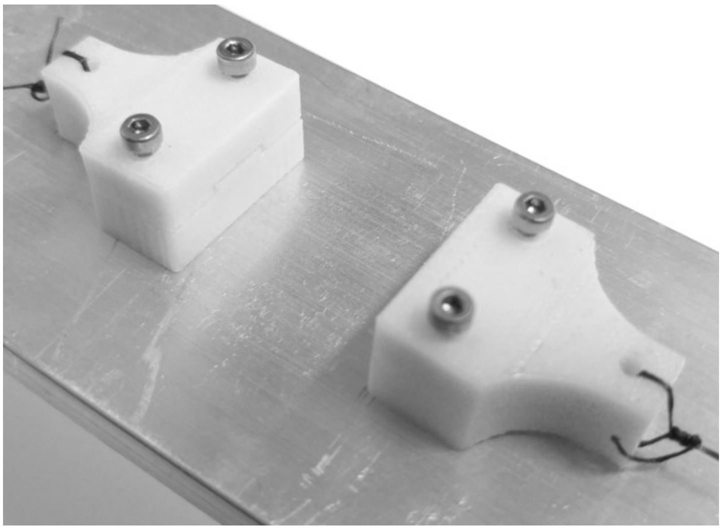

Figure 4.5 Clamps for holding onto the material piece.

4. 2. 2. Calibration

The strain gauge converter works by outputting the load 0-2 kg from the sensor with an output of 0-11 V. So not to fry the Arduino, a volt divider with R1 = 15 kΩ and R2 = 18 kΩ was created to reduce maximum output voltage from 11 V to 5 V with the formula:

$$V_{out} = \frac{R2}{R1 + R2} * V_{inn}$$

There was no calibration appendix with the manual for the strain gauge converter so a transformation matrix converting output to actual load was needed for obtaining correct data. Since the rig already had some weight from components needed to fasten test material to setup rig the output was adjusted to match its weight. Then weight almost equalling max output was loaded on the sensor and a linear vector containing about 1000 different points between "zero" weight and max weight were created for both the uncalibrated output data and actual correct weight. A function was then created returning correct output data from uncalibrated output data.

4. 2. 3. Testing

To make sure that all the calculations in the calibration of the sensor were correct, several objects with known value were weighed with the sensor. Because of the sensitivity of the strain gauge converter and calculations done to correct output data, the testing rig had an error of +-1 gram.

4. 2. 4. GUI

The test machine GUI, Figure 4.6, was developed with the use of the ControlP5 software for the processing environment [44]. It has controls for start, stop and reset of tests. Manual control of velocity. Backup and manual storage of test data. An output graph.

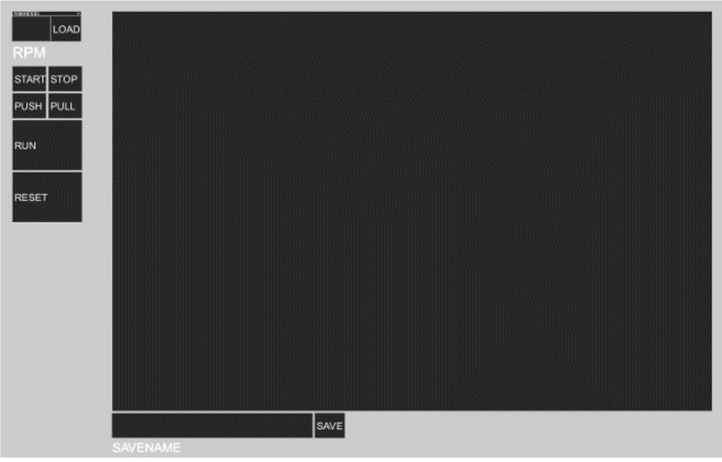

Figure 4.6 GUI for controlling test-machine and exporting test data. Controls (left), manual storage of data (bottom) and output graph (middle).

4. 2. 5. Difference from normal practise

Usually the percentile elongation is measured in parallel with the psi force needed to rupture the material piece when creating a tensile strength machine. This was not done in the process of testing for this thesis. This was because no tool was available for this purpose when creating the tensile strength testing machine and the creation of one was seen as too complex. The apparatus for measuring the percentile elongation is normally two clamps holding onto the test piece and a sensor measuring how these two points change in distance from each other when the material stretches. Because of the weakness in material strength and having to take this into consideration in the creation of an elongation measurement apparatus, the process was seen as to complex and not necessary enough for this thesis. Not necessary since the material testing was mainly done to get familiar with the material and demonstrate the drastic changes in material strength in different settings, Chapter 6.

For demonstration purposes a graph with data collected for material test in Chapter 6 is demonstrated, Figure 4.7, next to a standard tensile strength test graph, Figure 4.8, to show why the graphs were not included in the chapter. Since no length measurement tool was used engineering strain was not measured and the only data possible to gather from the test was the ultimate tensile strength (UTS).

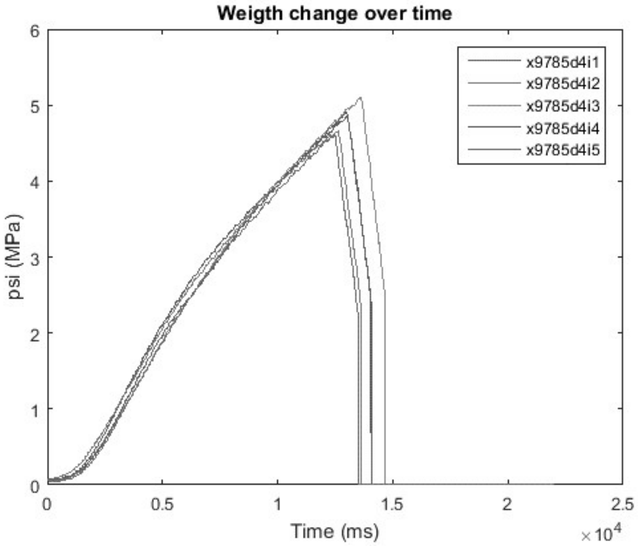

Figure 4.7 Demonstration of graph output from tensile strength testing of the 9785 material day 4.

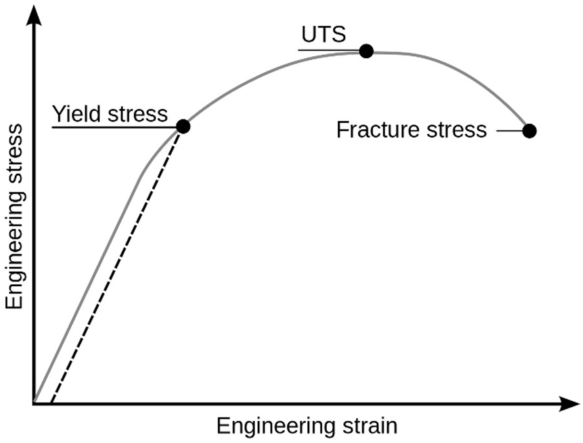

Figure 4.8 Standard format of tensile strength test graph.

4. 3. Tensile test piece

The material tests were done on a test piece following the standards of ASM International. Depending on what test was being performed it was sectioned up as illustrated in Figure 4.9.

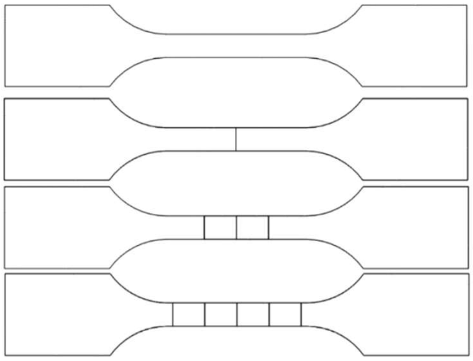

Figure 4.9 Test pieces top to bottom, single material, two materials, 4 materials, 6 materials

4. 4. Objet500 Connex

The Objet (Stratasys Ltd, Eden Prairie, Minnesota), is a Polyjet printer. It is a multimaterial printer able to print in a vast amount of different materials. This works by utilising two base resins in specific concentration and structure, so that it can produce a vast amount of different types of materials from varying combinations of the two.

The printer works by jetting photopolymer material with a layer thickness of 16 μm onto a printing surface, layer by layer. For each layer, the material is cured by UV lighting [45].

For each print every possible mix relations of the two bas erasing can be applied to several different models. The user is not restricted to using one mix for each print but can choose different parts on the same model to apply different mixes of materials or create several copies of the same model, each with different material mixes.

From what has been gathered, the Objet printers from Stratasys are the only production printers capable of printing in such a waste amount of different materials.

4. 4. 1. Materials

The materials used in creation process, Chapter 4 are listed below. A full list of specifications of materials can be found at Stratasys own website [46]:

- TangoBlackPlus FLX980/TangoPlus FLX930
- FLX-9740/9840-DM
- FLX-9750/9850-DM
- FLX-9760/9860-DM
- FLX-9770/9870-DM
- FLX-9785/9885-DM
- FLX-9795/9895-DM
- VeroWhitePlus

4. 4. 2. Issues

There are some issues with the printer though. When two objects in a print intersect, the meshes cross surfaces, the printer prioritise the object with the largest portion of material that is placed in material slot 1 of the printer, Chapter 5. 4. 3 iteration 3. This means that you will never be able to create one print with two objects that are created of the two different materials in slot 1 and 2 but need some of the material from the opposite slot inside its structure.

Another issue is that objects created from the same material printed to close to each other run the risk of blending meshes. Even though the 3d models had been looked over thoroughly and no intersecting of models was seen. This, of course, needs further testing since it cannot be verified if this is a hardware (printer) or software (3DSMax) problem.

4. 5. Advanced Objet Studio

Advanced Objet Studio is the software that is delivered with the Objet. It is the only software for interfacing with the Objet printer. Advanced Objet Studio is used for positioning, validation, material selection and printing on the Objet. The software is bundled with the Objet and no alternative exists.

Chapter 5.

Creating a hand on the Objet

Since a human hand is only several fingers put together, with relatively equal proportions, and just a difference of scale, the decision was made early on to focus on the creation of a single finger, the middle finger (Digitus Medius). After the initial research period it became apparent that each joint connecting the bones in the finger were relatively alike and the scope of creation was narrowed even further to focus on the PIP joint connecting the middle/intermediate phalanx and the proximal phalanx illustrated in Figure 2.2.

In order to create a human hand as close to biology as possible, by limiting the creation process to a single joint, if proven possible, the process could be replicated in the remainder of the joints of the hand.

At every step of the creation process, the main focus was to try to get as close to the actual size, appearance and mechanical properties of the actual organ or tissue.

Material names used in each step of the process is mentioned in Chapter 4. 4. 1. They will be referred to by their numbers, or names for materials without numbers.

5. 1. Reference models

As mentioned in Chapter 3. 2, a blueprint of the organ is a natural first step in the replication of an organ. Since this chapter is focused mainly on the possibility of creating an artificial hand as close to biology as possible it was decided that there was no need to produce models from scratch or acquire reference models from a subject. Reference models, Figure 5.1, of bone were gathered from BodyParts3D [47]. This saved both time and resources even though they had to be modified to some extent.

What was difficult to obtain were anatomically correct models of ligaments and tendons. With the help of reference pictures, Figure 2.2, Figure 2.3 and Figure 5.2, these where manually modelled.

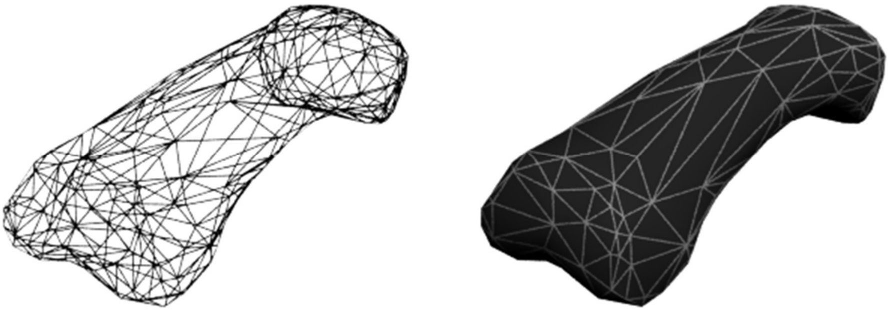

Figure 5.1 Scan of Proximal Phalanx of middle finger, a) see through wireframe, b) wireframe with blacked out faces.

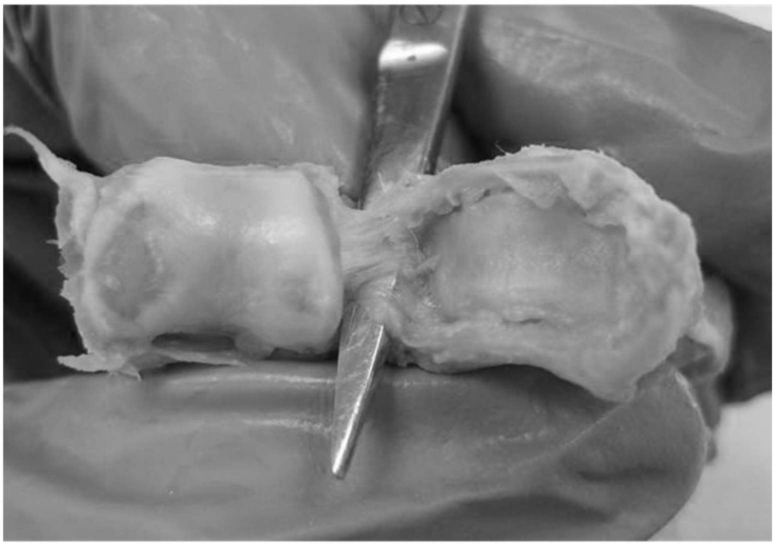

Figure 5.2 PIP joint with Proximal Phalanx left of cissor, and Middle Phalanx right of scissor. The colatteralo ligaments are marked with the scissor, with the porpper ligament above the accessory ligament [65].

5. 2. Bone

The reference 3D model can seem as though it can be used without modification. As detailed in Chapter 3. 6, reference models can be incomplete. In the case of a fully functional finger, bone consists of more than just bone tissue, Chapter 2. 1. 2. A layer of cartilage must be created on the surface of the bone where two bones connect as a joint. In order to simplify the modelling and printing process the bone and cartilage were modelled as a single entity. Since the low friction surface the cartilage provides was not needed for the printed model to be useful, using the same material for bone and cartilage was sufficient.

5. 2. 1. Modelling

Since the cartilage had to be modelled over the bone, rather than use 3D scans directly, the 3D scans were used as reference and cartilage modelled as a smooth cylindrical shape, Figure 5.3. Without overcomplicating things it is easier to work with the bone model when more intricate systems like ligaments and tendons are applied later on.

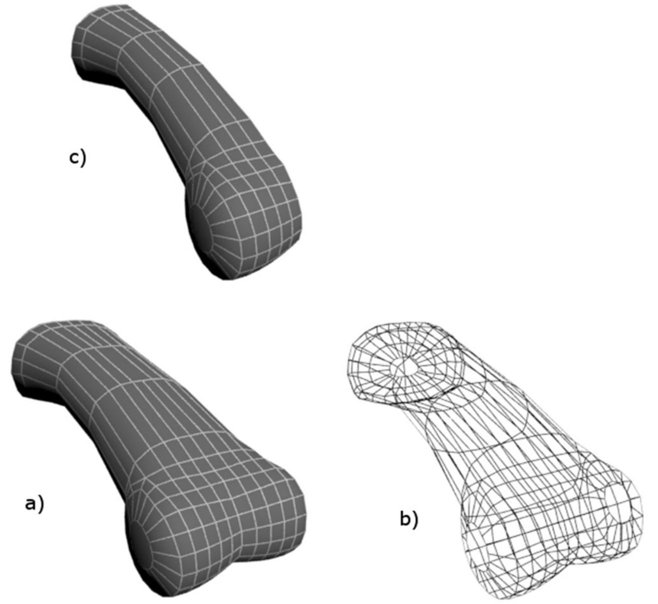

Figure 5.3 Model of the proximal phalanx with merged cartilage, a) coloured faces, b) wireframe, c) model without symmetry modifier.

5. 2. 2. Simulation

With the bone system described in Chapter 4. 1. 1. the movement of the middle phalanx connected to the proximal phalanx was simulated in 3DSMax to see if the modelling had been successful in shaping the ends of the bones to fit each other. In Figure 5.5 the model of bone is linked to the bone system so that movement of the bone system affects the movement of the bone, Figure 5.4. 3DSMax does not have the same physics as 3D modelling tools like SolidWorks so there is little to no collision detection other than checking when surfaces overlap. This makes it nearly impossible to get models with zero room in-between but because of how the Objet seem to have trouble with objects too close to each other when printed, Chapter 4. 4. 2, this works out ok.

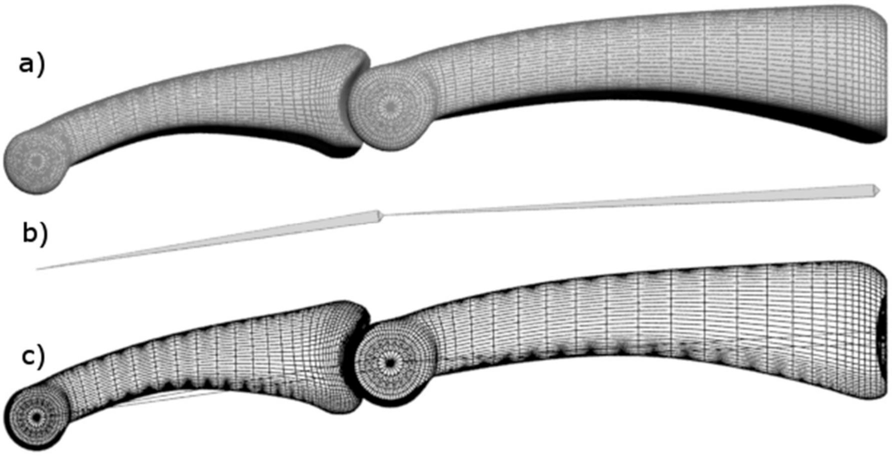

Figure 5.5 Modelled bones a), Bone System b), Modelled bones linked with bone system c).

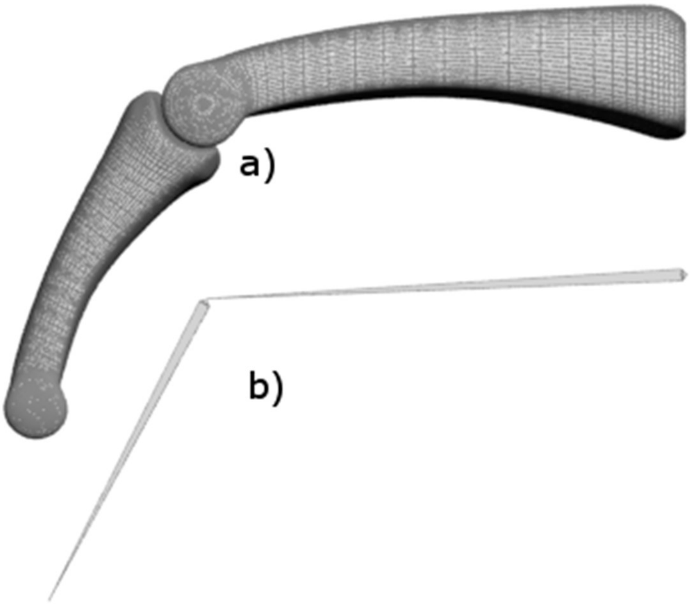

Figure 5.4 Bending bone system b) affects modelled bone a)

5. 3. Print

After a successful print of the joint portion of the proximal and middle phalanx in VeroWhitePlus material, Figure 5.6, they were fitted together to see if what was successful in simulation would be reflected in the actual print. With the Intermediate Phalanx moving smoothly along the surface of the Proximal Phalanx the print was seen as a success.

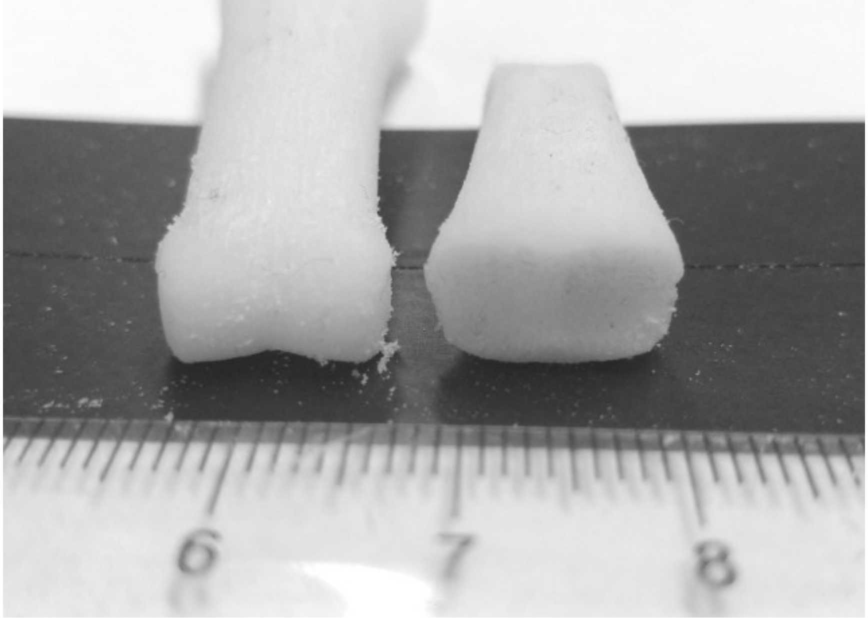

Figure 5.6 From left, Proximal Phalanx and Middle Phalanx PIP joint ends.

5. 4. Ligaments

Before creating the ligaments a lot of research went into figuring out its biomaterial and biomechanical properties. Most research material is medical texts and gross anatomy reference pictures without particularly specific references to dimensions, and since each individual is different some difficulty was experienced in figuring out the exact proportions of a ligament and how and where it connects to the bone in a joint or to other ligaments in the joint. Because of this some experimentation was done with regards to proportions.

5. 4. 1. Modelling

Since ligaments are bands of fibrous connective tissue and simple in appearance these can be modelled with relative ease, Figure 5.7. The idea was to create a model of the ligaments for the proximal interphalangeal (PIP) joint that could be easily scaled and refitted to the rest of the hands PIP joints and also the hands metacarpophalangeal (MP) and distal interphalangeal (DIP) joints. These joints are illustrated in Figure 2.2, Chapter 2. 1. 3.

Iteration 1

The main issue with printing a fully assembled joint is that a joint consist of more than one ligament. Each ligament has its own maximum stretch length at different rotary angles. No angle of the joint at print would give correct looseness or stretch of all the ligaments so data from the study: "In Vivo Length Changes of the Proximal Interphalangeal Joint Proper and Accessory Collateral Ligaments during Flexion" [31], was used to figure out what angle of rotation was closest to a sort of "middle ground" for all ligaments in the entire finger. The article only operated with angles of 0,30,60,90 and fully flexed, and among the angles used the closest to an ideal middle was 60 degrees. This would ensure that with some degree of looseness, all ligaments would stretch to a certain degree at their respective max stretch angles.

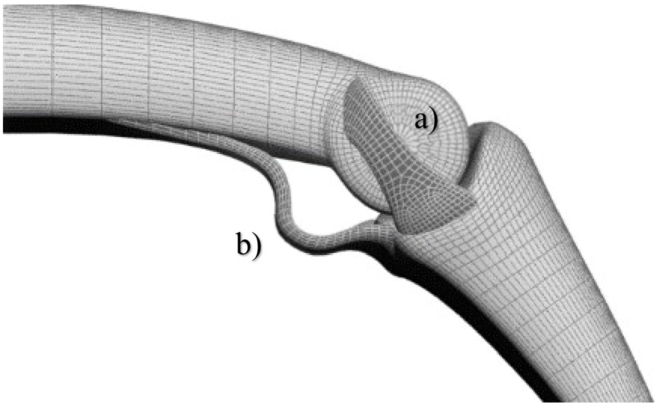

Figure 5.7 PIP joint connected with Collateral ligament a) and palmar ligament b).

Iteration 2

After failure to print a sturdy enough ligament, Chapter 5. 4. 3. iteration 1, and a shift in focus to material testing and getting better acquainted with the material, Chapter 6, it became apparent that to get a working joint a step back was needed and a simpler design of ligaments were explored. In order to try and preserve material integrity the ligaments were modelled with a uniform surface as “ropes” or “cylinders”, Figure 5.8. These “cylinders” were thicker than a normal ligament but this could prove to be an easier model for removing of support and handling and testing of the joint without damaging the ligament in the process.

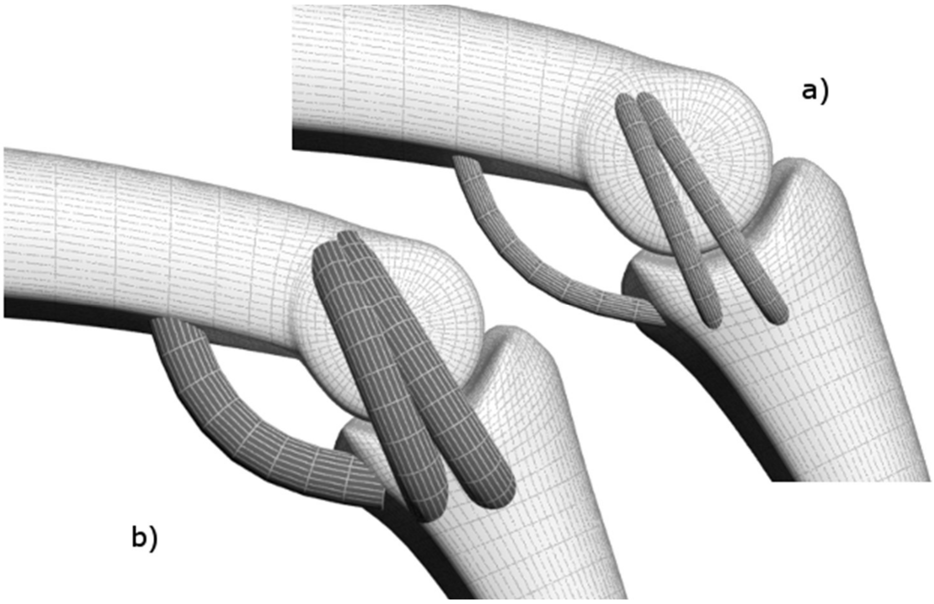

Figure 5.8 Second iteration of ligament test. Uniform circular ligaments with a) 1mm and b) 2mm thickness.

Iteration 3

After a semi-successful print, Chapter 5. 4. 3. iteration 2, of the uniform rope like joint, an attempt to mimic the stretch of normal ligaments was performed. Ligament has a wave like shape when relaxed and when the ligament stretch they straighten out until they cannot stretch anymore, Figure 5.9. In order to mimic this behaviour 0.5mm thin strands of VeroWhitePlus material, already tested to have the needed property, was embedded in a 1mm thick layer of TangoBlack+.

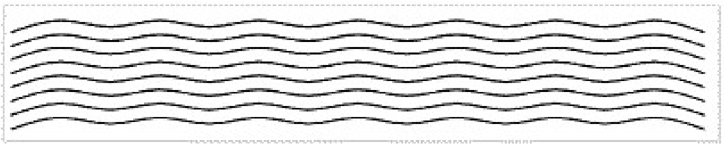

Figure 5.9 Top view of material piece with TangoBlack+, grey rectangle, and VeroWhite+, black wavy lines.

5. 4. 2. Simulation

When a model of the ligament has been modelled, with helper points attached to where ligament normally is connect to the bone, a bones system and IK, Chapter 4. 1. 1, can be created to simulate how ligament move. These helper points acts as anchors for the bone system restraining the endpoints to where the helper points are positioned, and by constraining what angles and movements the bone system can have the bone system starts acting like normal ligament.

Iteration 1

While comparing the model to actual human test data done on the length changing of ligaments in the pip joint [31] the ligament being simulated was adjusted until similar length specifications from the test data could be observed in the model.

5. 4. 3. Print

After confirming that the models where properly modelled without any defects that would affect print, and the simulation phase was done, the next step was printing.

Iteration 1

The printing of bone connected by ligament proved to be harder than anticipated. After print, when removing support, weakness in the elastic material was discovered. While removing support, the ligament band connecting the two bones would either get a rift and tear, or just break before all of the support material could be removed, Figure 5.10. Several semi-iterations were done, Figure 5.11, with adjustments to the ligament size, both in width, depth and in size of cross surface area where ligament and bone joins together.

When none of the attempts at ligament remodelling or different materials could solve the problem with tearing, focus shifted towards material strength and figuring out if the material printed from the Objet could actually support the strain put on it when the joint would move in a certain way.

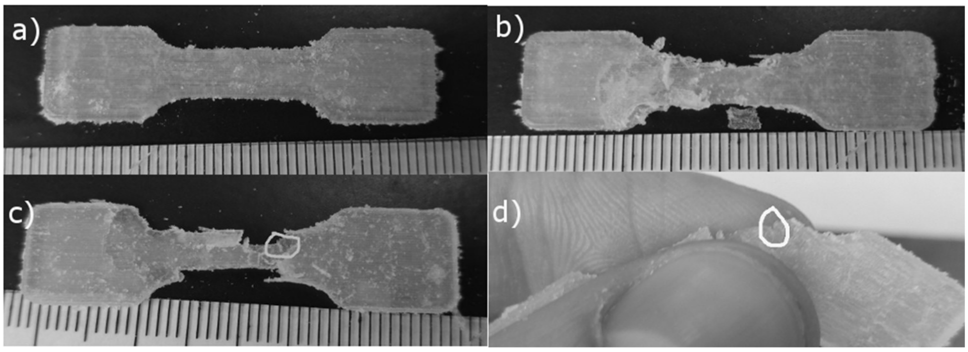

Figure 5.10 Steps a) through d) in removing support on a test piece with ligament size similar to iteration 1 of ligament modelling and printing phase. In c) and d) the typical rifts results from support removal in the material can be seen.

Figure 5.11 Three exemplars of bone print with ligaments.

Iteration 2

The print of the second iteration of ligament modelling, Chapter 5. 4. 1. iteration 2, was a semi-success. The ligament was printed in a 1mm and 2mm version, Figure 5.8, with “TangoBlack+” as material. Anny other material would be to stiff and be prone to tearing event with the size of 2mm.

The ligament, with thickness of 1 mm, was still frail and needed about an hour of work removing support for a single joint, and even after that there were still small chunks of support material on the ligaments making it difficult to see if they were deformed because of movement or because of the remaining support until they actually broke, Figure 5.12.

The 2mm version, on the other hand, could be cleaned almost perfectly in 10min. It could withstand rougher handling and even though deforming of the material could be seen when moving the ligament, Figure 5.13, it was not to a point where the ligament would rupture with simple movement.

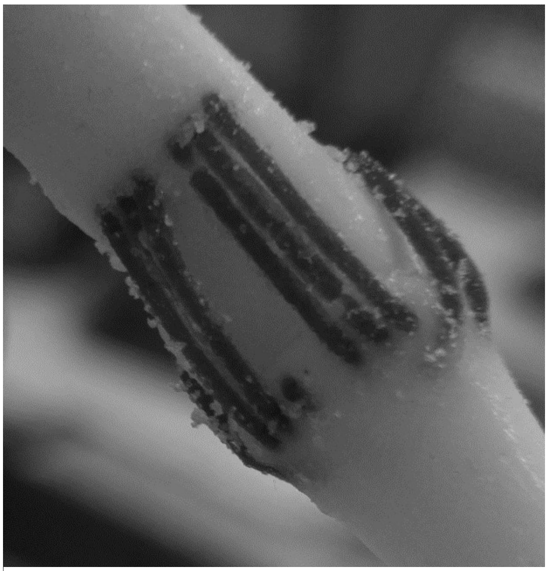

Figure 5.12 Joint 1mm with obvious signs of rupture.

Figure 5.13 Joint 2mm with small sign of rupture in one of the "cylinders" making up the palmar ligament.

Iteration 3

Trying to replicate the biomechanics of the ligament with the spring like pieces of harder material proved to be impossible to implement. After the first concept print the wavy pieces of VeroWhite where not printed inside the Tango material. It seemed as material submerged into another material on the Objet gets “deleted”. Even subtracting the shape of the curly pieces from the tango square, leaving empty space within the Tango material did not give any positive results.

5. 5. Tendons

Tendons acts much like rope. They function mainly by pulling on bone in strategic locations, which in turn makes the bone bend the way they do.

5. 5. 1. Modelling

Creation of tendons were done in a similar manner to ligaments, but with a stiffer material. This was done because the tendons needed to be pulled with a greater force than the ligaments in order to be able to move all the joints with a single tendon.

Iteration 1

When modelling the tendons the same issue with joints having to be printed in a bent angle was an issue. It made modelling a bit complex since the extender and flexor tendons, Figure 2.3 and Figure 5.15, would have to be modelled in a partially extended/flexed state. Another issue arose when modelling tendons. Because of the extra size of ligaments to combat the material strength the ligaments would get in the way of the tendon. Normally the palmar ligament, Figure 2.2, would lie close to the bottom side of the joint. Because they had to be modelled much larger than they normally would be, and it would be impossible to model them curled up, it was decided to split the palmar ligament in the middle to make room for the tendon to run through, Figure 5.14.

The tendon sheaths covering the tendon would also have to be modelled in a manner that did not hinder movement of the part of tendon that is not just a single cylinder. The two flexor tendons intertwine at one point, making it so that one tendon would have to be modelled a bit larger at this point creating a bottle neck if the tendons sheaths are not large enough to let it slip through. In the end the sheaths were modelled as small portions to not hinder too much movement in the joints.

Figure 5.15 From left, Tendons with white wireframe shaded, black see through wireframe with bones and lastly just black see through wireframe. The smaller bends along the tendons are tendon sheath.

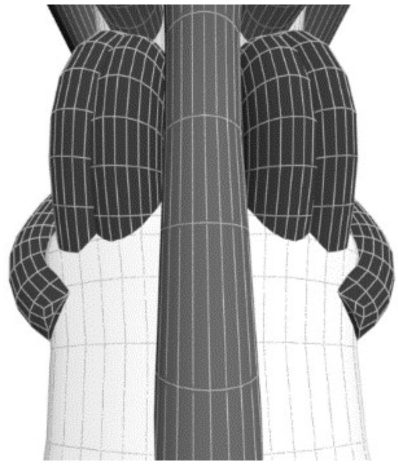

Figure 5.14 Tendon running up the middle in between the palmar ligament on the underside of the DIP joint.

Iteration 2

A second iteration of the tendons was created because of the problem with the sheaths and helper tendons in Iteration 1. The new Sheaths were modelled as 2 mm cylinders like the tendons. This would allow easy removal of support material and by placing them as close to the joint as possible, it was expected that this would give most of the same functionality of actual sheaths.

The helper tendons were removed in this iteration to see how the joints would behave and if removing them would show a lot of difference in functionality of the tendon.

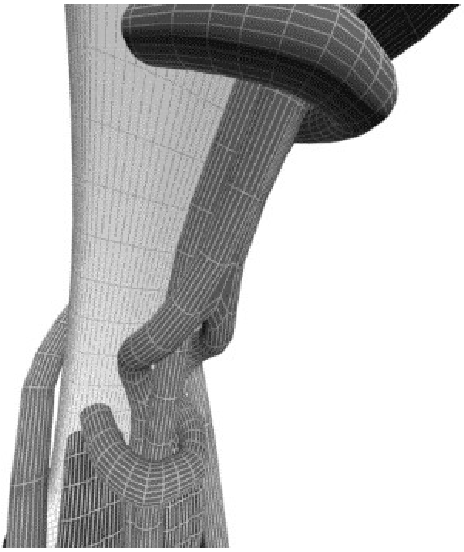

Figure 5.16 Tendons running through two cylinder tendon sheaths, top and bottom. The FDP tendon running through the FDS tendon in the camper chiasm.

Iteration 3

The third iteration was modelled with the finger fully extended, and with no tendon sheaths. This allowed the ligaments to be printed in a straight line and with possibility of room for helper tendons in between.

It was speculated that tendons modelled in a bent form would cause them to behave different than if they were modelled straight form but this would also mean that the ligaments had to be remodelled.

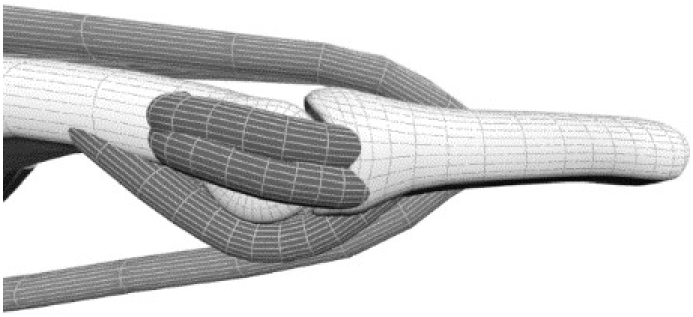

Figure 5.17 DIP joint fully extended.

5. 5. 2. Print

Iteration 1

The actual print of the tendons turned out ok for main tendons, but the helper tendons (Vincula Longa and Vinculum breve) made the joints stiff. It is next to impossible to create the helper tendons with the certain slack needed when the tendon is modelled as close to the bone as it is. This resulted in the joints getting stiffer movement or no movement at all since the main tendon is fastened on one side of the joint and the helper tendon on the other constricting the movement because of the stiffness in material.

After a couple prints with different materials the best material was found to be the 9885. This is pretty hard but still bends like it should and makes strong tendons that are easy to pull.

The tendon sheaths were printed in 9895. This gave them some flexibility in removing support but they would have to be modelled smaller or with gaps on next iteration because it was next to impossible to actually get all the way inside the tendon sheath with a tool to remove all the support. The portion of the tendons where the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS) intertwine (Camper chiasm), Figure 5.16, created a blockage hindering movement through the tendon sheath when the finger extends.

In the end the FDP tendon ended up ruptured because of this and the strain put on it while removing support, Figure 5.18.

Figure 5.18 DIP joint with ruptured FDP tendon.

Iteration 2

The second print with regards to tendon sheaths turned out to be a success, Figure 5.19. The new tendon sheaths worked great giving the needed functionality. They were printed in the same 9895 material as iteration 1. The small tubular shape gave them more flexibility and enabled easy removal of support.

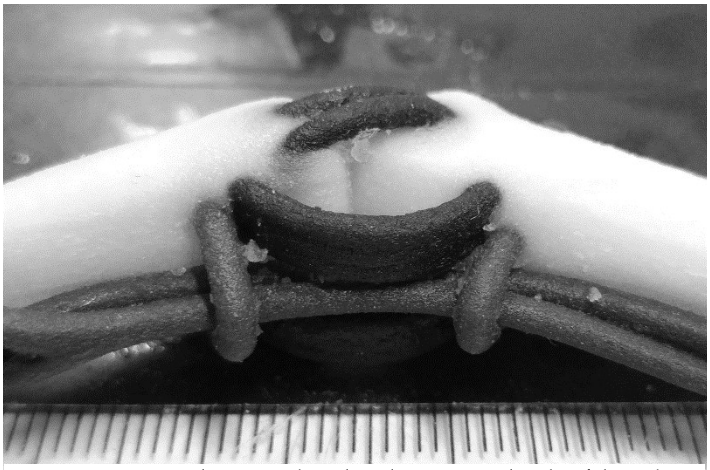

Figure 5.19New and improved tendon sheets on each side of the palmar ligament.

Iteration 3

The print of iteration 3 turned out ok with regards to the length of the helper tendon. With enough space between the tendon and the bone the helper tendon had room to move and curled up nice when the tendon laid close to the bone. There were still problem with material strength. In order to acquire a flexible enough helper tendon it had to be resized to 1mm which has proven to be a problem before. The helper tendon, Figure 5.20, only lasted a little while before rupturing.

The biggest downside to this iteration was that printing the finger fully flexed meant that after bending the joint, the joint would bend itself back to fully extended form. This made it hard to test the extensor tendon functionality.

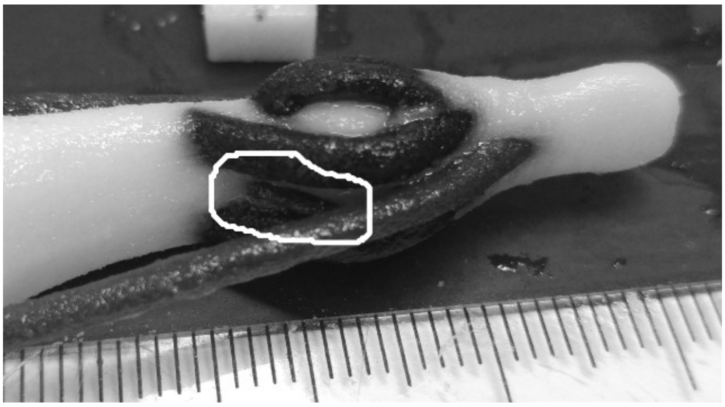

Figure 5.20 Straight joint with FDP tendon (bottom) and its helper tendon, Vinculum Breve (circled).

5. 6. Shortcuts

Because of the need to create almost all of the components in an enlarged state to get the material strength needed to get a functional result some parts of the hand creation process was omitted. Another reason for not creating certain parts was also because of the time frame of the thesis. By focusing on the joint of the middle finger and get a full understanding and functional creation before progressing, the process of creating the remaining omitted parts could be accelerated.

5. 6. 1. Muscles

The choice was made to not try and create the functionality of muscle components in the hand. In order to create any sort of muscle functionality in the finger, as close to biology as possible, a pneumatic system with the Tango material could be used as mentioned in Chapter 3. 8. This was seen as too great of an endeavour to try and create within the timespan of the thesis, and the expected size needed to create enough movement would be too large to fit within the confines of the hand. Controlling the tendons manually was seen as a huge success in itself.

5. 6. 2. Joint capsule

The part of joint capsule was omitted. With the components as thick as they are in the final result, the movement in the joints are already impaired. The thickness needed in a joint capsule to hinder tearing in the material would mean little to none movement left in the joint. Also creation of a closed environment (the joint capsule) would not enable removing of support within the joint. Since the main function of the joint capsule is to keep the synovial fluids, not possible to create on the Objet, inside the joint this was seen as a small sacrifice to make.

The omitting of the joint capsule enabled the creation of a finger that show bone movement based on force transfer through tendons. It also enables a better view of the joint and how the joint functions.

5. 6. 3. Thumb

The thumb differs from the rest of the fingers in the hand by the fact that it has two extensor tendons instead of one. And one flexor tendon, instead of two. This can be seen when moving the distal portion of the thumb. A person can move the distal portion of the thumb without affecting the neighboring proximal phalanx.

The creation of the thumb for the complete model of the hand was done by removing the metacarpal bone and the flexor tendons of the middle finger. Then the extensor tendon was adjusted, and copied so that two separate tendons are fastened to the distal and middle phalanx Figure 5.21. No separate printing of the thumb was done and it was only used in the final print of the entire hand.

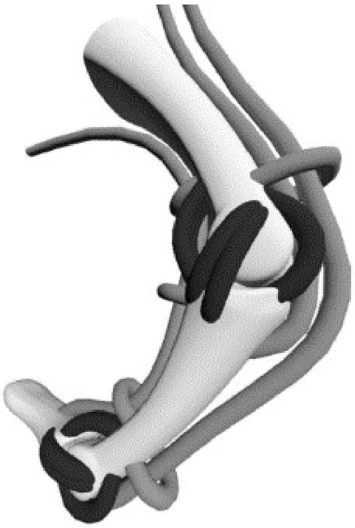

Figure 5.21 Model of thumb. Modified version derived from the middle finger.

5. 6. 4. Tendons

The tendons dorsal expansion hood and ligaments of the extensor tendon fastened to the interosseous and lumbrical muscle, Figure 2.3, was omitted since they were not necessary to show functionality of the extensor tendon. The functionality of the tendon fastened to the interosseous and lumbrical muscle is mainly to move the finger in a sideways motion and to some degree controlled flexion.

The helper tendons was also removed because of the space limitations in Chapter 5. 5. 2. iteration 1. Even though iteration 3 was a partial success it was decided that the design without helper tendons from iteration 2 would be better to move forward with because. Reprints of iteration 2 worked better over time and could be handled and tested more without rupturing parts as easily.

5. 7. Summary

The end result is an artificial hand with some of the functionality seen in a human hand. The ligaments restrict the bone, giving the joints natural movement. The material used for ligament are more elastic than normal ligaments resulting in the ability to manipulate the joints beyond what is normal in the hand. This is an effect caused by the need to use the Tango material, in order to not damage the ligaments during movement. Manipulating the tendon moves the bone. Because of the need to remove helper tendons, and the fact that no tendon length optimization has been done, there is limited movement.

Material used in the final result can be seen in Table 5.1. Figure 5.22 and Figure 5.23 are pictures of a single finger with and without support. Figure 5.24 and Figure 5.25 are the final resulting print of an entire hand with and without support.

Component:	Material:
Bone	VeroWhitePlus
Tendon Sheaths	FLX-9795/9895-DM
Tendons	FLX-9785/9885-DM
Ligament	TangoBlackPlus/TangoPlus

Table 5.1 Materials used on final result.

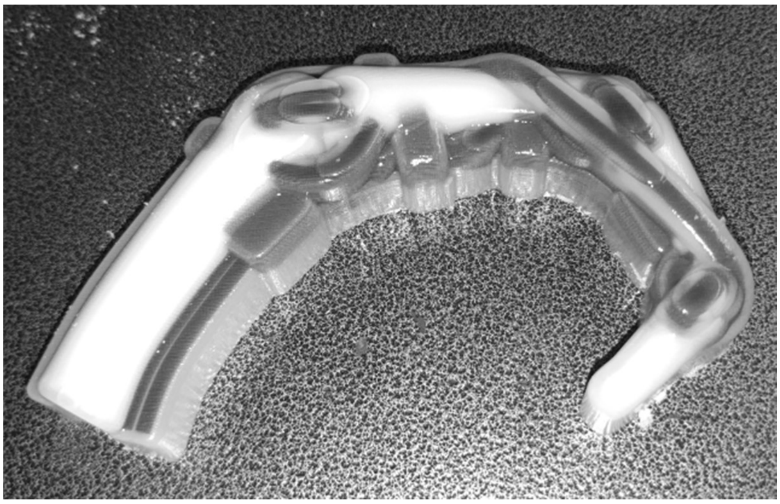

Figure 5.22 Single finger, with support. Finger with ligaments, tendons and bone.

Figure 5.23 Single finger, without support. Finger with ligaments, tendons and bone.

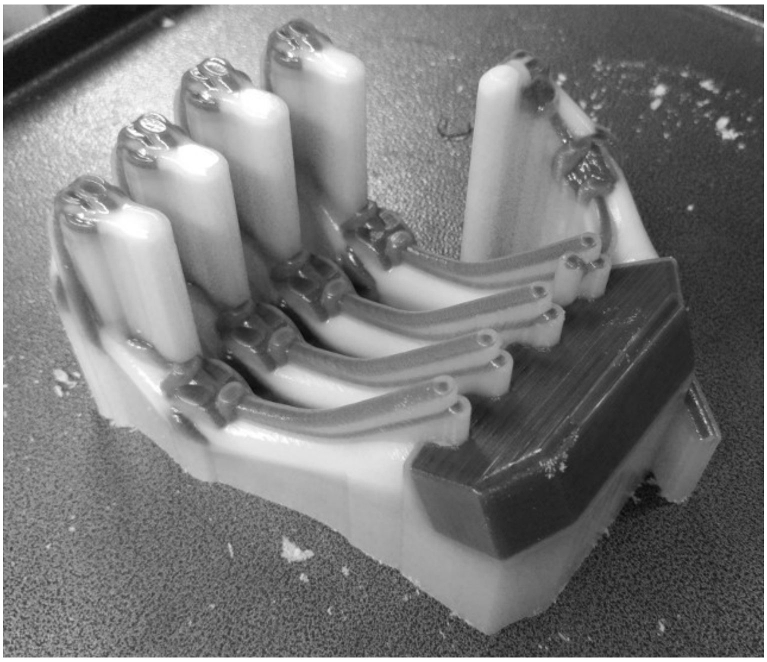

Figure 5.24 Full hand with support.

Figure 5.25Full hand after 2 hours of cleaning support.

Chapter 6.

Material testing

This chapter contains test on materials printed with the Objet. The material tests are done on the simplified test rig described in Chapter 4. 2. and are meant as proof of concept only, they are not done on an official test rig for tension testing of vulcanized rubber (D-412 [48]).

Different components of the human hand need different types of biomechanical properties. This chapter demonstrates to what degree the Objet can be used to produce components with the mechanical properties needed to serve as artificial copies of components from the human hand. It will also contain research on materials that are being used in the body today and comparisons to its biological counterparts.

With the failure of printing functional ligaments in Chapter 5. 4. 3. iteration 1, the decision was made to get better acquainted with the material. By acquiring a greater understanding of how the material behaves, the process of modelling and printing could improve.

The results in Chapter 6. 1. 3. Are confined to UTS because of limitations of the tensile strength test machine, Chapter 4. 2. 5.

6. 1. Objet material properties

Materials for use in the human body need to adhere to certain standards. If an implant breaks after a certain time or starts behaving differently over time it is not only a matter of fixing or replacing components, but can in worst case lead to serious injury/infection or death. It was already known that the materials would not behave as normal. Because of the material failure in Chapter 5. 4. 3. iteration 1, tests were performed to try and understand why the material could not uphold to the standard needed. Because of time limitations and as not to move to far outside the scope of the thesis the tests was confined to engineering stress.

6. 1. 1. First material hypothesis

The first sub hypothesis was that the material properties would degrade too such an extent, that over time the materials would behave in a completely different manner. Since most of the material from the Objet is stated to absorb water [49] this could affect material properties over a period of time [50]. All the materials in this test was printed in a single batch and stored in a container over the period of 4, 8 and 20 days.

Already after 4 days a decline in average material strength of 13%-23% can be seen, Table 6.1. Some drop in material strength as part of a curing process can be acceptable, but considering total amount of material weakening and the fact that Stratasys reports no curing is needed [51] indicates severe weakness in the material.

Between day 8 and day 20 the material strengthens. No test was made on material elasticity, but this indicates that the material may harden over time making it stronger but less elastic. This can of course not be verified without further testing, but that will have to be done in future work.

6. 1. 2. Second material hypothesis

The second sub hypothesis was that the material would be weaker in the cross section where two different materials join. Since different materials have different molecular binding, unless steps are taken, this could weaken the binding, significantly reducing material strength.

The materials were printed in two sets with different orientation. One set was printed so the length of the test piece was oriented with the printing direction (print-dir) and the other set was oriented perpendicular to printing direction (perp-dir).

Some material blends showed weakness in the joints like the one seen in Figure 6.1. In Table 6.2, the 2-print-dir test, 2 out of 5 of the material pieces tested tore in the intersection between materials. If this was because the individual material strength was greater than the strength in the cross section between materials or if different material blends has inferior binding properties cannot be said with certainty without more extensive testing.

In Chapter 5. 4. iteration 2 where ligament is fastened to bone, weakness in material transition is avoided by printing a part of the material within the other giving a larger contact surface between the two materials. This will weaken the biomechanics of the bone since we are altering its structure, but was seen as the only choice moving forward when earlier prints of ligaments, Chapter 5. 4. 3. iteration 1, proved unsuccessful.

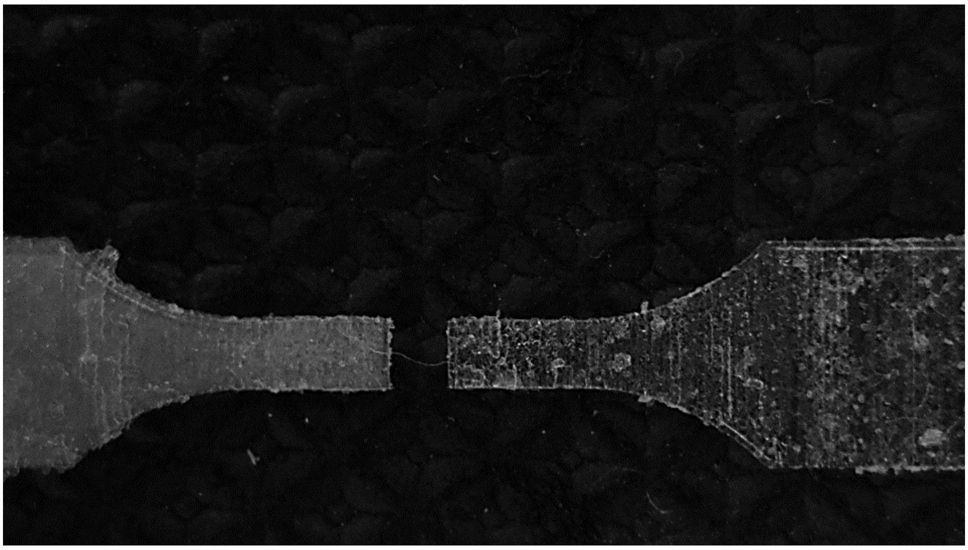

Figure 6.1 Material split in cross section

6. 1. 3. Results

The tensile strength of materials are calculated with the formula:
$\sigma = F_n/A$ [52] where,
$\sigma =$ normal stress $((Pa)\frac{N}{m^2}, psi)$
$F_n =$ normal component force $(N, lb_f, (alt. kips))$
$A =$ area (m^2, in^2)

First test

Test in order to compare the material strength over the course of days to see just how much change there would be in material strength, Table 6.1.

	Day 1		Day 4		Day 8		Day 20	
Material	Avg.	Median	Avg.	Median	Avg.	Median	Avg.	Median
FLX9740-DM	1.527 MPa	1.500 MPa	1.322 MPa	1.3251 MPa	1.272 MPa	1.290 MPa	1.427 MPa	1.416 MPa
FLX9760-DM	3.239 MPa	3.372 MPa	2.485 MPa	2.475 MPa	2.487 MPA	2.433 MPa	3.134 MPa	3.225 MPa
FLX9785-DM	5.498 MPa	5.511 MPa	4.827 MPa	4.866 MPa	4.465 MPa	4.592 MPa	4.751 MPa	4.838 MPa

Table 6.1 Material degradation over time.

Second test

Test in order to check for material weakness in the transition between two different materials, Table 6.2. The materials next to each other would be the two materials closest in material mixture percentage.

Test piece orientation:	Avg. MPa:	Median MPa:	Difference comp. to avg. in percent:
6-perp-dir	1.004	1.010	15.36
6-print-dir	1.106	1.115	12.57
4-perp-dir	1.743	1.795	24.14
4-print-dir	2.287	2.370	25.14
2-perp-dir	3.472	3.569	17.57
2-print-dir	4.426	4.368	25.35

Table 6.2 Test piece divided into 6 (Tango+, 9740, 9750, 9760, 9770, 9785), 4 (9750, 9760, 9770, 9785) and 2 (9770, 9785) different materials printed in printer movement direction and cut direction to test for cross material weakness.

6. 2. Bio material property comparison

In some cases more than one material can be used to substitute its organic counterpart. This is a short chapter with focus on materials used in implants and robotic limbs today. Comparing organic materials, to artificial replacements. Including the Objet materials used in Chapter 5, to see how well the Objet materials as well as others function as replacements.

In this chapter the material specifications from Stratasys [51] [46] will be used since their tests contain more data.

6. 2. 1. Bone

In the case of bone a lot of materials can and has been used as replacements because its main purpose is areas like the hand and feet is support and toughness.

Material	Tensile strength MPa	Compressive strength MPa	Elastic modulus GPa	Fracture toughness $MPA.m^{-1/2}$
Bioglass	42	500	35	2
VeroWhite+	50-65	N/A	2-3	N/A
Bone	50-151	100-230	6-30	2-12
Titanium	345	250-600	102.7	58-66
Stainless	465-950	1000	200	55-95
Ti-Alloys	596-1100	450-1850	55-144	40-92
Aluminia	270-500	3000-5000	380-410	5-6
Hydroxuapatites	40-300	500-1000	80-120	0.6-1

Table 6.3 Mechanical properties of biomaterials and the Objet VeroWhite+ with data gathered from the Wikipedia foundation.

6. 2. 2. Ligament and tendons

With ligaments and tendons it is harder to find replacements because of its unique biomechanics and material composition with the purpose of constricting movement.

Material	Tensile strength MPa	Elastic modulus GPa
TangoBlack+/ Tango+	0.8-1.5	N/A
Elastin (bovine ligament)	2	0.0011
FLX-9785/9885-DM	5-7	N/A
FLX-9795/9895-DM	8.5-10	N/A
Collagen (mammalian tendon)	120	1.2
Kevlar	3600	130
Carbon fibre	4000	300

Table 6.4 Mechanical properties of elastic proteins [53] and the Objet material equivalent.

6. 3. Summary

The materials produced by the Objet clearly needs more research to be able to choose the best materials for each purpose. It does not help that Stratasys themselves informs the user, in the materials data sheet [46] [49], that the material specifications are for information purposes only and should not be considered advice.

Both tests in Chapter 6. 1. show that not much is needed to create completely different material properties. This, in turn, makes it hard to choose what material to use for any specific purpose without extensive testing and a great number of prints with different materials for each step of a project process.

Still, there are other materials that can serve as replacements for the materials produced by the Objet, Chapter 6. 2.

Chapter 7.

Discussion and Conclusions

When starting to work on the thesis it was going to change the world, be something no one had done before and be invaluable research in further bionic research. Painstakingly so I have discovered just how complex something can be even though in theory it seems so simple.

7. 1. Discussion

When the process of creating an entire hand seemed impossible over the time span of this thesis. Being able to create a single joint, as close to biology as possible, was seen as a better use of time. Actually being able to create a finger and acquiring some degree of actual functionality was seen as a success. Even with the issues of the subjects discussed in the next subchapter, to be able to print an entire hand was an even greater accomplishment.

7. 1. 1. Complexity

When starting the project the scope of the thesis enveloped the entire forearm. It soon became apparent that this was too wide a focus, so the focus was narrowed to the hand. After a couple of months with researching the biology of the human hand, even the hand as a whole was seemed too complex to start creating for a single person over the course of this thesis. When it could be narrowed down to the creation of a single joint, Chapter 5, work started to get done. Soon, after work on ligament creation had started, the apparent weakness in material strength of the materials printed on the Objet became apparent. But by being adjustable with regard to size relations, an actual moving finger could be created. Replicating this to the remaining joints of a finger, and soon after the rest of the fingers in the hand, hurried the creation process along. Better time management could have enabled a better final result, but all in all the work done turned out great.

7. 1. 2. Assumptions

Assumptions of the usability of some research has been made. A lot of the technology talked about in Chapter 3 has not reached a point in where human testing has been performed but still it is assumed that this will happen at some point and that it could be used as implants or in prosthetics. Even though it has not been tested on humans it is till usable in creation of components in robotic limbs and can still be implemented to see if the possibility of a fully functional bionic limbs could be possible to create in the future.

7. 1. 3. Using the Objet

The usage of the Objet as the basis for creating a human hand as close to biology as possible has an apparent initial weakness, and that is that the Objet cannot print the type of biological materials with the needed biomechanics. Even though the thesis set out to explore the possibility of creating something as close to biology as possible when creating a human hand, a printer without the necessary functionality was chosen. It could have been better to work with a printer that could actually print organic material, or have the possibility to be customising it to do so. But no such printer exist as of today, except a prototype built at Massachusetts Institute of Technology (MIT) [54].

Another apparent weakness in choosing the Objet as a basis for printing is that to create something for use in the human body, more control over how material is deposited on the print surface would be beneficial. Materials change properties with its structure and this greatly affects materials strength and weakness. Choosing a printer with no possibility of printer pattern customisation limited the ability of affecting material strength other than changing the orientation of the object printed.

A third weakness was that the support material the printer used would be hard to impossible to remove without affecting the material in a negative way. With specialized tools for support removal, damage can be mitigated, but a printer without the need for support structure would have enabled better joint composition.

7. 1. 4. Medical science

A significant amount of time was spent during this thesis to understand the biomechanics and anatomy of the human hand. How different components in the hand works, how they are connected and how they interact with each other. If this thesis had been written as a cooperation project with a faculty with medical experience, development could have progressed faster and time could have been spent on other parts of the assignment, more suited to my field of informatics and engineering. Without having any medical or biology background at all a larger part than intended of the thesis revolves around anatomical research and proof of concept through theory rather than actually producing scientific results.

7. 1. 5. Theory of creation

In Chapter 3 every step in the process of creating an artificial hand is explored, and a lot of focus has been put in the possibility of implanting components in the body.

In Chapter 3. 1. and 3. 2. it is established that it is possible to extract exact models of organs and that there exist methods of implanting foreign materials in the human body with minimized risks of rejection. This may not be relevant for development of robotic limbs, but when developing a prosthesis, if the prosthesis could be implanted within the body, instead of as an external component, it is believed this would benefit the host. Since the prosthesis would look and act more like a natural limb a host would feel more comfortable utilising said prosthesis.

7. 1. 6. Material choice

Materials used in the human body will differ vastly from materials used within robotics. The field of engineering and robotics will always have an interest in creating robotic parts that are stronger, lighter or better performing than the human organ counterpart it is mimicking.

In medicine and biology on the other hand a lot of focus has to be put into how the materials interacts with the body in a number of different ways so as not to endanger a person using or having implanted said material. Producing a printer able to optimise for both occurrences may be difficult.

Different materials available for the Objet will change over time and so in the future, materials with the needed biomechanical properties to serve in the creation of organic matter or artificial organs/tissue may appear, but the way in which some of the tissue in the human hand operates may indicate that new ways of creating said tissue may be needed.

7. 2. Conclusion

The main assignment of this thesis was figuring out if the fields of medicine and engineering have reached a point where it is possible to develop new and advanced robotic limbs or prosthetics as similar as possible to something as intricate as the human hand.

With focus on the bone, ligament and tendon system each of these complex components in the hand has been replicated and tested to demonstrate that it is possible to do so on the Objet printer. Review of literature has shown that existing technology for creation of artificial and biological components in the hand exists. By utilizing different printing techniques and materials it is possible to replicate some of the biomechanics and functionality of the human hand.

A lot of challenge still lies in developing materials with the needed biomechanical properties of living tissue. The materials available for the Objet printer made it possible to create something with similar functionality as that of an actual hand, but it lacks the needed functionality to create a hand with all of the biomechanical properties and components you would expect in a human hand. Many different processes are needed to generate each of the components as close to its biological counterpart with the technology available today. Compressing the entire production process into a single printer would be ideal with regards to availability and cost, but is as of today not available.

The thesis goes a long way in proving it is possible to create a hand with its fingers relatively close to biology. Every day there are new and exciting improvements in fields like biomaterials and hardware. It is just a matter of time before the materials needed to fully replicate biology is available.

7. 3. Future work

What this thesis has not been able to do is actually create a copy with the exact biomechanical functionality of the original human hand. I have yet to see a robotic limb or prosthesis with joints with all its components designed to look and act anatomically correct. Possible further work, and something that would be really exciting to see, would be a fully functional hand.

By collaboration with medical professionals and material engineers, further work towards a hand with all of the necessary parts for movement and as similar to biology as possible could be a huge step in both the medical industry as well as further development of humanoid like robotics.

The creation of a testbed similar to the ACT hand developed by John Hopkins University (JHU), Chapter 2. 5. 3, with focus on anatomically correct ligaments could actually be even better. If a working testbed could be created, collaboration with the team developing the tendon driven system from JHU could provide some interesting research.

Bibliography

[1] B. Clarke, “Normal Bone Anatomy and Physiology,” *Clinical Journal of the American Society of Nephrology,* vol. 3, no. 3, pp. 131-139, 2008.

[2] J. K. Sherwood, S. L. Riley, R. Palazzolo, S. C. Brown, D. C. Monkhouse, M. Coates, L. G. Griffith, L. K. Landeen and A. Ratcliffe, “A three-dimensional osteochondral composite scaffold for articular cartilage repair,” *Biometarials,* vol. 23, no. 24, pp. 4739-4751, 2002.

[3] F. Malekipour, C. Whitton, D. Oetomo and P. V. Sin Lee, “Shock absorbing ability of articular cartilage and subchondral bone under impact compression,” *Journal of the Mechanical Behavior of Biomedical Materials,* vol. 26, pp. 127-135, 2013.

[4] J. Cluett M.D., “Synovium,” About Health, 25 November 2014. [Online]. Available: http://orthopedics.about.com/cs/arthritis/g/synovium.htm. [Accessed 07 November 2015].

[5] R. C. Bray, P. Ackermann and P. T. Salo, “Normal Ligament Structure, Physiology and Function,” *Sports Medicine and Arthroscopy Review,* vol. 4, no. 2, pp. 199-201, 2005.

[6] P. Kannus, “Structure of the tendon connective tissue,” *Scandinavian Journal of Medicine & Science in Sports,* vol. 10, no. 6, pp. 312-320, 2000.

[7] “Physiological cross-sectional area,” Wikimedia Foundation, Inc., 16 May 2014. [Online]. Available: https://en.wikipedia.org/wiki/Physiological_cross-sectional_area. [Accessed 24 September 2015].

[8] S. V. Murphy and A. Atala, “3D bioprinting of tissues and organs,” *NATURE BIOTECHNOLOGY,* no. 32, p. 773–785, 2014.

[9] C. Mézel, A. Souquet, L. Hallo and F. Guillemot, “Bioprinting by laser-induced forward tramnsfer for tissue engineering applications: jet formatting modeling,” *Biofabrication,* vol. 2, no. 1, 2010.

[10] M. Starr, “'Bionic' rebuild gives three amputees mind-controlled robotic arms,” The Lancet, 25 February 2015. [Online]. Available: http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(14)61776-1/abstract. [Accessed September 2015].

[11] “U. S. Food and Drug Administration,” 9 May 2014. [Online]. Available: http://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm396688.htm. [Accessed 21 Oktober 2015].

[12] J. Stone, “DARPA's 'Luke Skywalker' Prosthetic Arm Could Soon Have Sense Of Touch, But It Will Cost $100k,” International buisness times, 9 July 2015. [Online]. Available: http://www.ibtimes.com/darpas-luke-skywalker-prosthetic-arm-could-soon-have-sense-touch-it-will-cost-100k-2001214. [Accessed 15 November 2015].

[13] J. A. Berg, J. F. Dammann, F. V. Tenore, G. A. Tabot, J. L. Boback, L. R. Manfredi, M. L. Peterson, K. D. Katyal, M. S. Johannes, A. Makhlin, R. Wilcox, R. K. Franklin, R. J. Vogelstein, N. G. Hatsopoulos and S. J. Bensmaia, “Behavioral Demonstration of a Somatosensory Neuroprosthesis,” *Neural Systems and Rehabilitation Engineering,* vol. 21, no. 3, pp. 500-507, 2013.

[14] A. D. Deshpande, Z. (. Xu, M. J. Vande Weghe, B. H. Brown, J. Ko, L. Y. Chang, D. D. Wilkinson, S. M. Bidic and Y. Matsuoka, “Mechanisms of the Anatomically Correct Testbed Hand,” *Mechatronics, IEEE/ASME Transactions on,* vol. 18, no. 1, pp. 238-250, 2013.

[15] “RAPHaEL: Robotic Air Powered Hand with Elastic Ligaments,” Romela Robotics and Machanisms Laboratory, [Online]. Available: http://www.romela.org/raphael-robotic-air-powered-hand-with-elastic-ligaments/. [Accessed 21 Oktober 2015].

[16] “Tendon Transfer Surgery to Restore Hand Function,” Spinal Cord Injury Association of Illinois, [Online]. Available: http://www.sci-illinois.org/surgery_hand_function. [Accessed 16 November 2015].

[17] Admin, “5 Incredible Things You Didn’t Know About Your Hands,” University Orthopaedic Associates, 13 October 2015. [Online]. Available: https://www.uoanj.com/5-incredible-things-you-didnt-know-about-your-hands/. [Accessed 16 November 2015].

[18] T. Hardgrove, “Dem Bones: Skeletal Structure and Movement Function,” Bettermovement.org, 18 March 2012. [Online]. Available: http://www.bettermovement.org/2012/skeletal-structure-movement-function/. [Accessed 26 September 2015].

[19] GE Healthcare, “GE Healthcare,” General Electric Company, 21 April 2015. [Online]. Available: http://www3.gehealthcare.com/en/Products/Categories/Computed_Tomography/Revolution_CT#tabs/tabBC0235705219445B83B96D3E59D194B6. [Accessed 15 September 2015].

[20] P. J. Busse and D. Zieve, “Transplant rejection,” MedlinePlus, 26 June 2013. [Online]. Available: https://www.nlm.nih.gov/medlineplus/ency/article/000815.htm. [Accessed 6 Oktober 2015].

[21] J. M. Anderson, A. Rodriguez and D. T. Chang, “Foreign body reaction to biomaterials,” *Seminars in immunology,* vol. 20, no. 2, pp. 86-100, 2008.

[22] V. S. d. Viteri and E. Fuentes, “Titanium and Titanium alloys as Biomaterials,” in *Tribology - Fundamentals and Advancements*, InTech, 2013, pp. 155-181.

[23] L. Zhang, Z. Cao, T. Bai, L. Carr, J.-R. Ella-Menya, C. Irvin, B. D. Ratner and S. Jiang, “Zwitterionic hydrogels implanted in mice resist the foreign-body reaction,” *Nature Biotechnology,* no. 31, pp. 553-556, 2012.

[24] R. Williams, Surface modification of biomaterials: Methods Analysis and Application, Elsevier, 2010.

[25] F. J. O'Brien, “Biomaterials & scaffolds for tissue enginering,” *Materials Today,* vol. 14, no. 3, pp. 88-95, 2011.

[26] S. Bose, S. Vahabzadeh and A. Bandyopahyay, “Bone tissue engineering using 3D printing,” *Materials Today,* vol. 16, no. 12, pp. 496-504, 2013.

[27] U. Finardi and S. Sprio, “Human bone regeneration from wood: a novel hierarchically organised nnanomaterial,” *Int J. of Healthcare Tehcnology and Management,* vol. 13, no. 4, pp. 171-183, 2012.

[28] M. N. Cooke, J. P. Fisher, D. Dead, C. Rimnac and A. G. Mikos, “Use of stereolithography to manufacture critical-sized 3D biodegradable scaffolds for bone ingrowth,” *Journal of Biomedical Materials Research,* vol. 64B, no. 2, pp. 65-69, 2003.

[29] H. Seitz, W. Reider, S. Irsen, B. Leukers and T. Carsten, “Three-Dimensional Printing of Porous Ceramic Scaffolds for Bone Tissue Engineering,” *Journal of Biomedical Materials Research Part B: Applied Biomaterials,* vol. 74B, no. 2, pp. 782-788, 2005.

[30] A. Hertz and I. J. Bruce, “Inorganic materials for bone repair or replacement applications,” *Nanomedicine,* vol. 2, no. 6, pp. 899-918, 2007.

[31] J. Chen, J. Tan and A. X. Zhang, “In Vivo Length Changes of the Proximal Interphalangeal Joint Proper and Accessory Collateral Ligaments During Flexion,” *The Journal of Hand Surgery,* vol. 40, no. 6, pp. 1130-1137, 2025.

[32] A. Diamond, R. Knight, D. Devereux and O. Holland, “Anthropomimetic Robots: Concept, Construction and modelling,” *International Journal of Advanced Robotioc Systems,* vol. 9, no. 209, 2012.

[33] P. D. Parchi, C. Gianluca, L. Dolfi, A. Baluganti, P. Nicola, F. Chiellini and M. Lisanti, “Anterior cruciate ligament reconstruction with LARS™ artificial ligament results at a mean follow-up of eight years,” *International Orthopaedics,* vol. 20, no. 8, pp. 1567-1574, 2013.

[34] J. A. Mcgeough, “Joint Replacement,” in *The Engineering of Human Joint Replacement*, Chister, UK, John Wiley & Sons Ltd, 2013, pp. 181-183.

[35] M. Oka, K. Ushio, P. Kumar, K. Ikeuchi, S. H. Hyon, T. Nakamura and H. Fujita, “Development of artificial articular cartilage,” *Journal of Engineering in Medicine,* vol. 214, no. 1, pp. 59-68, 2000.

[36] F. Daerden and D. Lefeber, “Pneumatic Artificial Muscles: actuators for robotics and automation,” Department of Mechanical Engineering , Vrije Universiteit Brussel, 2002.

[37] M. Ortiz-Catalan, B. Håkansson and R. Brånemark, “An osseointegrated human-machine gateway for long-term sensory feedback and motor control of artificial limbs,” *Science Translational Medicine,* vol. 6, no. 257, 8 October 2014.

[38] Y.-L. Park, B.-R. Chen and R. J. Wood, “Design and Fabrication of Soft Artificial Skin Using Embedded Microchannels and Liquid,” *IEEE Sensor Journal,* vol. 12, no. 8, pp. 2711-2718, 2012.

[39] J. Kim, M. Lee, H. J. Shim, R. Ghaffari, H. R. Cho, D. Son, Y. H. Jung, M. Soh, C. Choi, S. Jung, K. Chu, D. Jeon, S.-T. Lee, J. H. Kim, S. H. Choi, T. Hyeon and D.-H. Kim, “Stretchable silicon nanoribbon electronics for skin prosthesis,” *Nature Communication,* vol. 5, 2014.

[40] “Maya Overview,” Autodesk, [Online]. Available: http://www.autodesk.com/products/maya/overview. [Accessed 14 November 2015].

[41] “Blender Front Page,” Blender, [Online]. Available: https://www.blender.org/. [Accessed 14 November 2015].

[42] “Rhinoceros Front Page,” McNeel, [Online]. Available: https://www.rhino3d.com/. [Accessed 14 November 2015].

[43] “Silo Front Page,” Never Center, [Online]. Available: http://www.nevercenter.com/silo/. [Accessed 14 November 2015].

[44] A. Schlegel, *ControlP5 Library (Version 2.2.5),* 2015.

[45] “Polyjet: a 3D Printing Technology,” Materialise, [Online]. Available: http://manufacturing.materialise.com/polyjet. [Accessed 16 November 2015].

[46] Stratasys, “Digital Materials Data Sheet,” [Online]. Available: http://usglobalimages.stratasys.com/Main/Files/Material_Spec_Sheets/MSS_PJ_DigitalMaterialsDataSheet.pdf?v=635796522191362278. [Accessed 20 Oktober 2015].

[47] BodyParts3D, “Anatomography,” The Database Center for Life Science, Japan, 2015.

[48] “Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension,” ASTM International, 2013. [Online]. Available: http://www.astm.org/Standards/D412.htm. [Accessed 15 10 2015].

[49] Stratasys, “Polyjet Materials Data Sheet,” [Online]. Available: http://usglobalimages.stratasys.com/Main/Files/Material_Spec_Sheets/MSS_PJ_PJMaterialsDataSheet.pdf?v=635785205440671440. [Accessed 20 Oktober 2015].

[50] C. K. Y. Yiu, N. M. King, D. H. Pashley, B. I. Suh, R. M. Carvalho, M. R. O. Carrilho and F. R. Tay, “Effect of resin hydrophilicity and watr storage on resin strength,” *Biomaterials,* vol. 25, no. 26, pp. 5789-5796, 2004.

[51] Stratasys, “How PolyJet 3D Printing Works,” [Online]. Available: http://www.stratasys.com/3d-printers/technologies/polyjet-technology. [Accessed 5 November 2015].

[52] “Stress, Strain and Young's Modulus,” The Engineering ToolBox, [Online]. Available: http://www.engineeringtoolbox.com/stress-strain-d_950.html. [Accessed 26 Oktober 2015].

[53] J. Gosline, M. Lillie, E. Carrington, P. Guerette, C. Ortlepp and K. Savage, “Elastic proteins: biological roles and mechanical properties,” *The Royal Society,* vol. 357, no. 1418, 2002.

[54] P. Sitthi-Amorn, J. E. Ramos, Y. Wang, J. Kwan, J. Lan, W. Wang and W. Matsuik, “MultiFab: A Machine Vision Assisted Platform for Multi-material 3D Printing,” The Computational Fabrication Group at MIT, 2015. [Online]. Available: http://cfg.mit.edu/content/multifab-machine-vision-assisted-platform-multi-material-3d-printing. [Accessed 2 November 2015].

[55] M. Schaefer, “Craniofacial implants have come a long way,” 3 March 2015. [Online]. Available: http://www.onlinetmd.com/tmd0315-Craniofacial-implants-technology.aspx#.VehU1Paqqko.

[56] National Heart, Lung, and Blood Institute, “NIH,” U.S. Department of Health & Human Services, 6 July 2012. [Online]. Available: https://www.nhlbi.nih.gov/health/health-topics/topics/tah. [Accessed 15 September 2015].

[57] M. Plus, Artist, *Tendon vs. ligament.* [Art]. Medline Plus, 2014.

[58] Romainbehar, Artist, *Catmull-Clark subdivision surface.* [Art]. 2006.

[59] M. R. Villarreal, Artist, *Main division on the (right) human hand..* [Art]. 2007.

[60] P. Lavoie, J. Fletcher and N. Duval, “Patient satisfaction needs as related to knee stability and objective findings after ACL reconstruction using the LARS artificial ligament,” *The Knee,* vol. 7, no. 3, pp. 157-163, 2000.

[61] N. Gialias and Y. Matsuoka, “Anatomically Correct Testbed (ACT) Hand,” *Robotics and automation,* vol. 4, pp. 3380-3385, 2004.

[62] *Metacarpophalangeal ligaments.* [Art]. Medscape, 2013.

[63] *Metacarpophalangeal ligaments and interphalangeal ligaments..* [Art]. Medscape, 2013.

[64] Y. Hirai, K. Yoshida, K. Yamanaka, A. Inoue, K.-i. Yamaki and M. Yoshizuka, “An anatomic study of the extensor tendons of the human hand,” *The Journal of Hand Surgery,* vol. 26, no. 6, pp. 1009-1015, 2001.

[65] B. M. M. Petre, *Proximal Interphalangeal Joint,* Orthopaedic and Sports Medicine Center, Annapolis, MD: Medscape Drugs & Diseases, (http://emedicine.medscape.com/), 2015.

[66] V. A. a. DEKA, Artist, *DEKA arm holds a lightbulb.* [Art]. Veterans Affairs and DEKA, 2010.

[67] FDA, Artist, *DARPA APL arm.* [Art]. Flickr, 2011.

[68] K. Cothem, Artist, *RAPHaEL: Robotic Air Powered Hand with Elastic Ligaments.* [Art]. RoMeLa: Robotics & Mechanisms Laboratory, 2009.

Appendix A Computer code

ARDUINO: Load Sensor Output:

```
float rigweigth = 111;
boolean run = true;

void setup() {
  // initialize the serial communication:
  Serial.begin(9600);
  run = true;
}

void loop() {
  // send the value of analog input 0:
  if (run) {
    float a = analogRead(A0)-rigweigth;

    Serial.println(a);
    delay(20);

  }
}
```

PROCESSING: GUI Interface

```
import processing.serial.*;
import controlP5.*;
import java.util.Arrays;
import java.io.FileWriter;


GUI gui;

Serial myPort;
Serial listenPort;

int id = 1;
int lf = 10;    // Linefeed
int offset = 1024;
int RPM = 1;
int chartSize = 2000;
ArrayList<Float> matData = new ArrayList<Float>(chartSize);

float max = 0;
float val = 0;
float start = 0;

int timeStart = 0;
int timeStop = 0;
int stabcnt = 0;

boolean stable = false;
boolean runTest = false;
boolean terminate = false;
```

```
String myString = null;

void setup(){

  String dynamixelport = "COM3";
  String sensorport = "COM4";

  int baudid = 1;
  int dynaBaudrate = 2000000 / (baudid + 1);
  int sensorBaudrate = 9600;

  println("DYNA-COM:" + dynamixelport);
  println("SENSOR-COM:" + sensorport);
  println("ID:" + id);

  //ControlP5
  gui = new GUI(this);

  //Window Size
  size(1600,1200);

  //Dynamixel motor port
  myPort = new Serial(this, dynamixelport, dynaBaudrate);

  //Sensor port
  listenPort = new Serial(this,sensorport,sensorBaudrate);
}

void writeToFile(ArrayList<Float> array) {
  //try {
  PrintWriter output = createWriter("bck/mat_test_" +
year() + ""
  + month() + "" + day() + "_" + hour() + "" + minute() +
"" + second() + ".txt");
//= new FileWriter(fileName + ".txt");
  //} catch ()
  for(Float val: array) {
    output.println(Float.toString(val));
  }
  output.flush();
  output.close();
}

void writeToFile(ArrayList<Float> array, String name) {
  //try {
  PrintWriter output = createWriter(name + "_" + year() +
"" + month()
  + "" + day() + "_" + hour() + "" + minute() + "" +
second() + ".txt");
//= new FileWriter(fileName + ".txt");
  //} catch ()
  for(Float val: array) {
    output.println(Float.toString(val));
  }
  output.flush();
  output.close();
}

void draw() {
```

```
  String s = null;
  while(listenPort.available() > 0) {
    s = listenPort.readStringUntil(lf);
    if (stable && s != null) {
      val = Float.parseFloat(s);
      if(!terminate)
      println("MAX/VAL: " + max + "/" + val);
      if (runTest) {
        if (val > max) {
          max = val;
        } else if (val < max*0.5 && val > 0) {
          println("END");
          stopB();
        }
        if(val >= 0.0) {
          matData.add(val);
          gui.myChart.push("incoming", val);
        }
      }
    } else if (!stable && isNumeric(s)) {
      stabcnt++;
    } else if (stabcnt > 20){
      stable = true;
      //start = Float.parseFloat(s);
    }
  }
  //gui.myChart.push("incoming", (sin(frameCount*0.1)*5));
}

public static boolean isNumeric(String str)  {
  try  {
    Float d = Float.parseFloat(str);
    //print(d);
  } catch(NumberFormatException nfe)  {
    return false;
  } catch(NullPointerException npe) {
    return false;
  }

  return true;
}

public void savefile() {
  String name =
gui.cp5.get(Textfield.class,"savename").getText();
  println(name);
  writeToFile(matData,name);
}

public void startB() {
  runTest = true;
  terminate = false;
  timeStart = millis();
  setRPM(RPM);
}

public void stopB() {
  runTest = false;
  timeStop = millis();
```

```
  println("TIME: " + ((timeStop-timeStart)/1000));
  float newt = max*0.00980665;
  println("FORCE: " + newt + " Newton");
  float crossa = (0.5*2)/1000000;
  println("AREA: " + crossa + " mm^2");
  float pa = newt/crossa;
  println("MPa: " + pa/1000000);
  terminate = true;
  setRPM(0);
  writeToFile(matData);
}

public void RESET() {
  max = 0;
  terminate = true;
  runTest = false;
  matData = new ArrayList<Float>(chartSize);
  gui.myChart.setData("incoming", new float[chartSize]);
}

public void CCW() {
  offset = 0;
}

public void CW() {
  offset = 1024;
}

void controlEvent(CallbackEvent callEvent) {
  if(callEvent.getController().getName().equals("RUN")) {
    switch(callEvent.getAction()) {
      case(ControlP5.ACTION_PRESSED):setRPM(RPM);;break;
      case(ControlP5.ACTION_RELEASED):setRPM(0);;break;
    }
  }
}

public void load(int val) {
  String s = gui.cp5.get(Textfield.class,"rpm").getText();
  println("LOAD: " + s);
  RPM = Integer.parseInt(s);
}

void setRPM(int n) {
  float factor = 0.114;
  float rpm = (float)n/factor;
  int speed = (int)rpm+offset;
  if (rpm <= 1023) {
    setReg2(id, 32, speed);
  } else {
    println("RPM must be lower than 116");
  }
}

//
***********************************************************
**************************************
```

```
//
*********************************************************
*************************************
// ******* Dynamixel bareBone methods
*********************************************************
***

// ====================== Writes 0<val<255 to register
"regNo" in servo "id" ======================

void setReg1(int id, int regNo, int val)
{
    byte b[] = {
        (byte)0xFF, (byte)0xFF, (byte)0, (byte)0, (byte)3,
(byte)0, (byte)0, (byte)0
    };

    b[2] = (byte)id;
    b[5] = (byte)regNo;
    b[6] = (byte)val;

    b = addChecksumAndLength(b);
    myPort.write(b);
}

// ====================== Writes 0<val<1023 to register
"regNoLSB/regNoLSB+1" in servo "id" =======

void setReg2(int id, int regNoLSB, int val)
{
    byte b[] = {
        (byte)0xFF, (byte)0xFF, (byte)0, (byte)0, (byte)3,
(byte)0, (byte)0, (byte)0, (byte)0
    };

    b[2] = (byte)id;
    b[5] = (byte)regNoLSB;
    b[6] = (byte)( val & 255 );
    b[7] = (byte)( (val >> 8) & 255 );

    b = addChecksumAndLength(b);
    myPort.write(b);
}

// ====================== read from register, status
packet printout is handled by serialEvent() ==

void regRead(int id, int firstRegAdress, int
noOfBytesToRead)
{
    println(" "); // console newline before serialEvent()
printout

    byte b[] = {
        (byte)0xFF, (byte)0xFF, (byte)0, (byte)0, (byte)2,
(byte)0X2B, (byte)0X01, (byte)0
    };

    b[2] = (byte)id;
```

```
    b[5] = (byte)firstRegAdress;
    b[6] = (byte)noOfBytesToRead;

    b = addChecksumAndLength(b);
    myPort.write(b);
}

// ======================= Sends a 1 byte command to servo
id ======================================

void sendCmd(int id, int cmd)
{
    byte b[] = {
        (byte)0xFF, (byte)0xFF, (byte)0, (byte)0, (byte)0,
(byte)0
    };

    b[2] = (byte)id;
    b[4] = (byte)cmd;

    b = addChecksumAndLength(b);
    myPort.write(b);
}

// ======================= adds checksum and length bytes
to the ASCII byte packet =================

byte[] addChecksumAndLength(byte[] b)
{
    // adding length
    b[3] = (byte)(b.length - 4);

    // finding sum
    int teller = 0;
    for (int i=2; i<(b.length-1); i++)
    {
        int tmp = (int)b[i];
        if (tmp < 0)
            tmp = tmp + 256;
        teller = teller + tmp;
    }

    // inverting bits
    teller = ~teller;
    // int2byte
    teller = teller & 255;

    // adding checkSum
    b[b.length-1] = (byte)teller;

    return b;
}

// ======================= just plain Java - pauses current
thread ================================

void pause(int ms)
{
    try
```

```
    {
        Thread.currentThread().sleep(ms);
    }
    catch(Exception ie)
    {
        // whatever you like to complain about
    }
}

/*class myCanvas extends Canvas {

}*/

class GUI {
  ControlP5 cp5;
  Canvas cc;
  controlP5.Textfield t;
  Chart myChart;
  //float data[] = new float[chartSize];
  GUI(PApplet thePApplet) {
    cp5 = new ControlP5(thePApplet);
    //cc = new myCanvas();
    startup();
  }

  void startup() {
    PFont pfont = createFont("Arial",20,true); // use
true/false for smooth/no-smooth
    ControlFont font = new ControlFont(pfont,40);



    Group g1 = cp5.addGroup("Parameters")
    .setBackgroundHeight(100)
    .setPosition(100,100)
    .setSize(137, 50)
    ;

    cp5.addTextfield("rpm")
    .setPosition(0,0)
    .setSize(75, 50)
    .setGroup(g1)
    .setFont(font)
    .setAutoClear(false)
    //.keepFocus(true)

    .getCaptionLabel()
    .setFont(font)
    .setSize(30)
    ;

    cp5.addButton("load")
    .setPosition(77,0)
    .setSize(60, 50)
    .setGroup(g1)

    .getCaptionLabel()
    .setFont(font)
    .setSize(20)
```

```
;

cp5.addButton("startB")
.setPosition(0,100)
.setSize(67, 50)
.setGroup(g1)
.setLabel("START")

.getCaptionLabel()
.setFont(font)
.setSize(20)
;

cp5.addButton("stopB")
.setPosition(72,100)
.setSize(67, 50)
.setGroup(g1)
.setLabel("STOP")

.getCaptionLabel()
.setFont(font)
.setSize(20)
;

cp5.addButton("CCW")
.setPosition(0,154)
.setSize(67, 50)
.setGroup(g1)

.getCaptionLabel()
.setFont(font)
.setSize(20)
.setText("PUSH")
;

cp5.addButton("CW")
.setPosition(72,154)
.setSize(67, 50)
.setGroup(g1)

.getCaptionLabel()
.setFont(font)
.setSize(20)
.setText("PULL")
;

cp5.addButton("RUN")
.setPosition(0,208)
.setSize(139,100)
.setGroup(g1)

.getCaptionLabel()
.setFont(font)
.setSize(20)
;

cp5.addButton("RESET")
.setPosition(0,312)
.setSize(139,100)
```

```
    .setGroup(g1)

    .getCaptionLabel()
    .setFont(font)
    .setSize(20)
    ;

    myChart = cp5.addChart("dataflow")
               .setPosition(300, 90)
               .setSize(1200, 800)
               .setRange(0, 912)
               .setView(Chart.LINE) // use Chart.LINE,
Chart.PIE, Chart.AREA, Chart.BAR_CENTERED
               .setStrokeWeight(1.5)
               ;

    myChart.getCaptionLabel()
                .setFont(font)
                .setSize(20)
                .setColor(40)
                .setText("WEIGTH LOAD");
    myChart.addDataSet("incoming");
    myChart.setData("incoming", new float[chartSize]);

    cp5.addTextfield("savename")
    .setPosition(300,895)
    .setSize(400, 50)
    //.setGroup(g1)
    .setFont(font)
    .setAutoClear(false)
    //.keepFocus(true)

    .getCaptionLabel()
    .setFont(font)
    .setSize(25)
    ;

    cp5.addButton("savefile")
    .setPosition(705,895)
    .setSize(60,50)
    .setLabel("SAVE")
    //.setGroup(g1)

    .getCaptionLabel()
    .setFont(font)
    .setSize(20)
    ;
  }

}
```

Appendix B Test rig

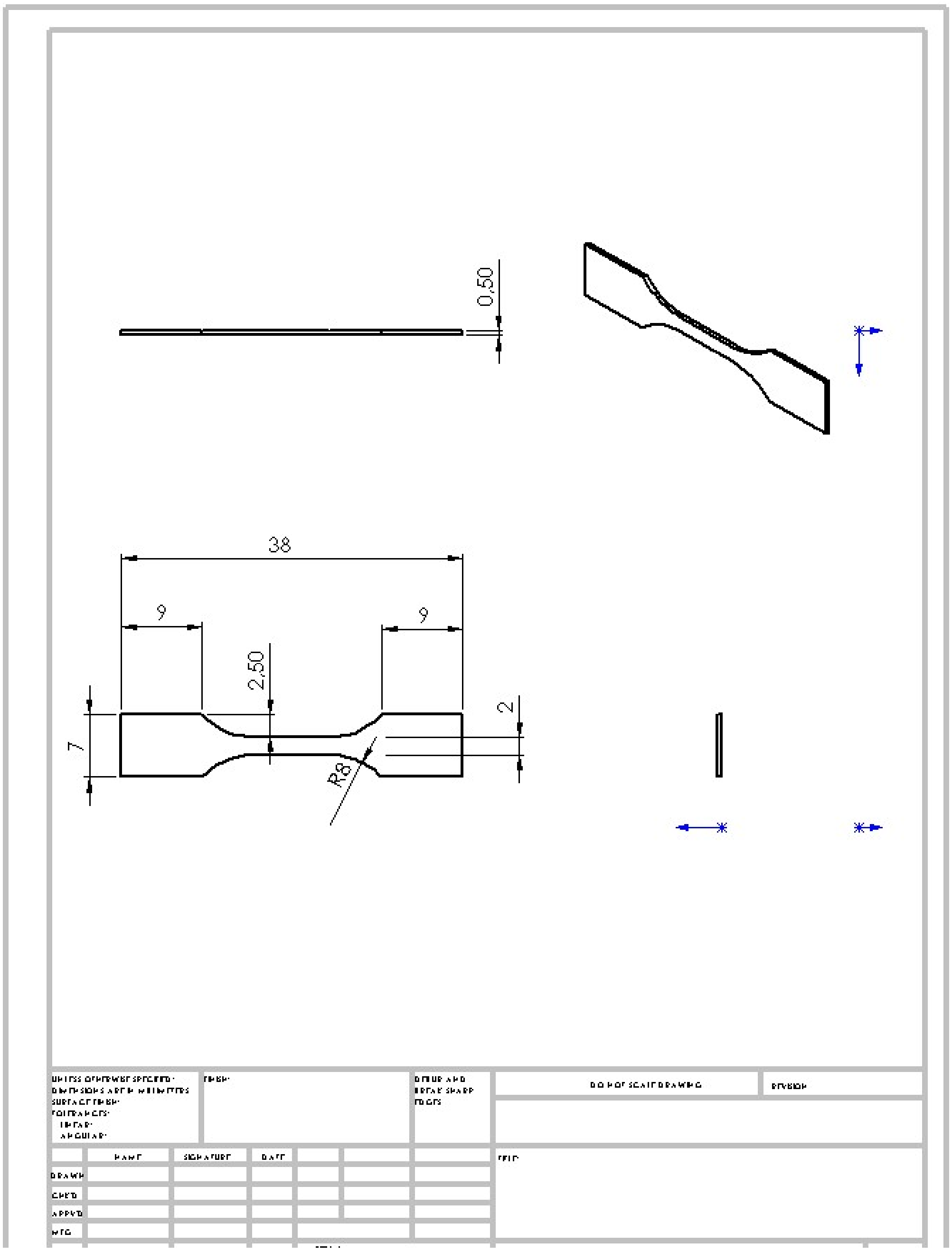

Figure 7.1 Technical drawing of the test piece used for material testing.

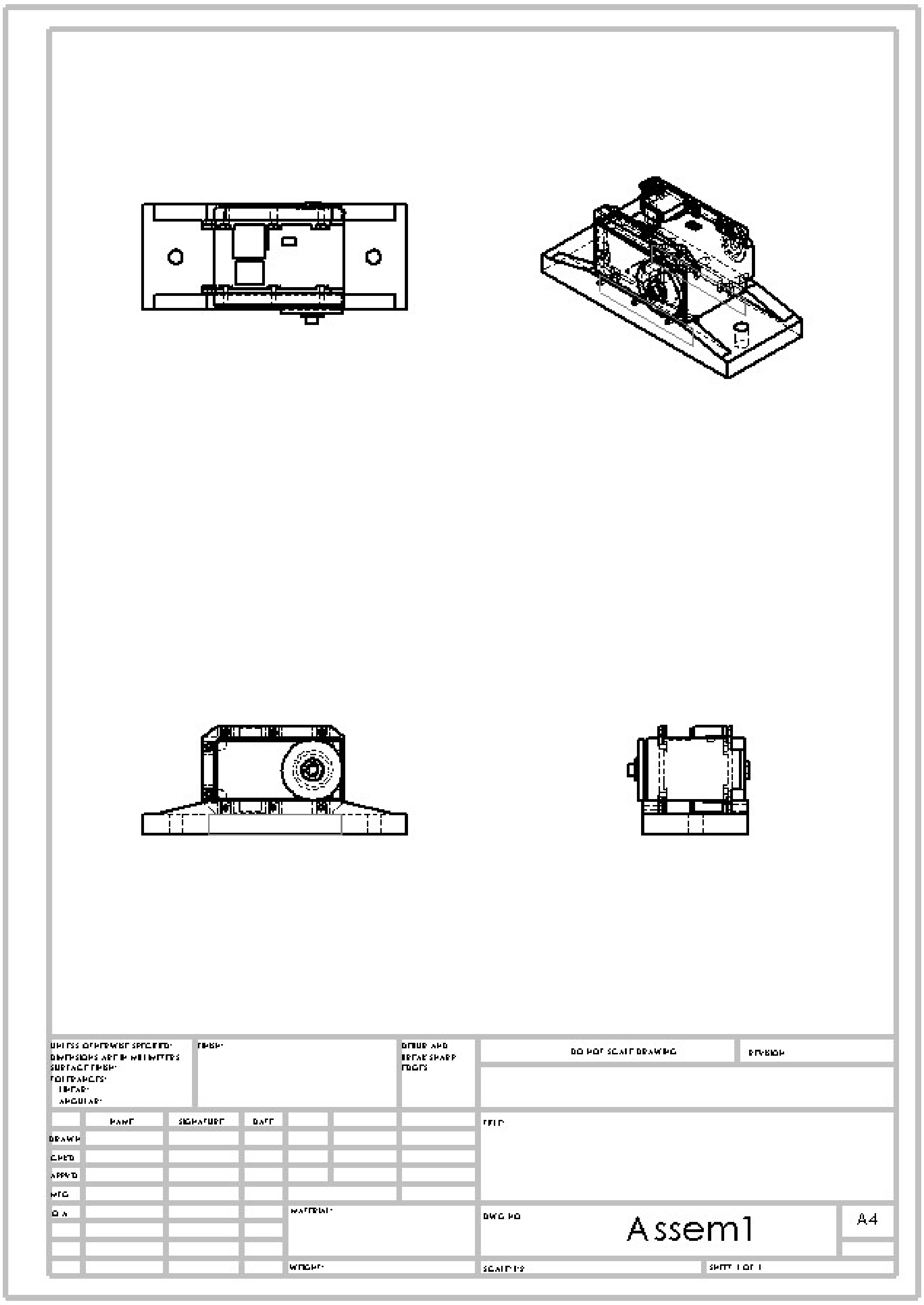

Figure 7.2 Technical drawing of the servo and its fastening system.

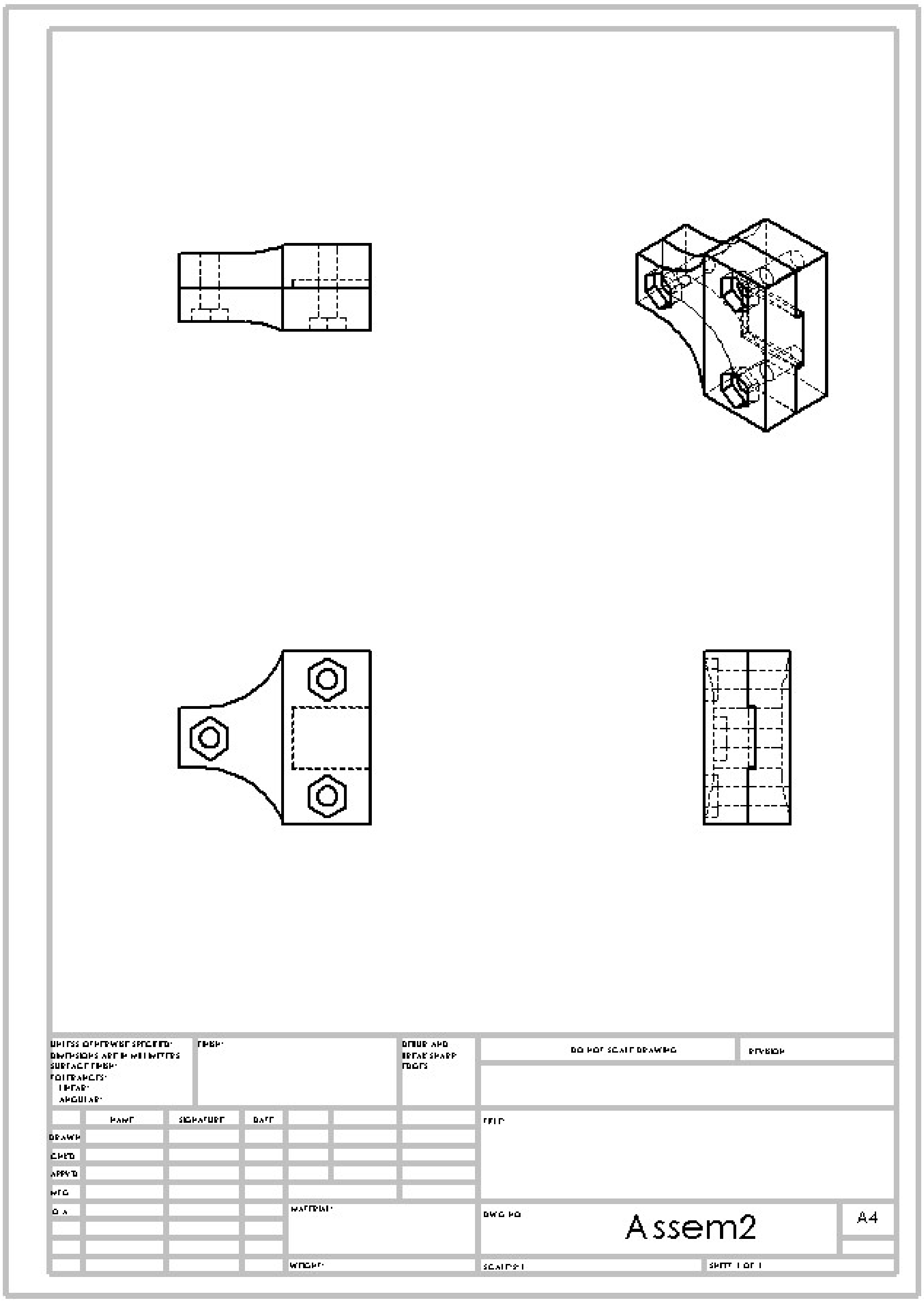

Figure 7.3 Technical drawing of the material test piece clamp.

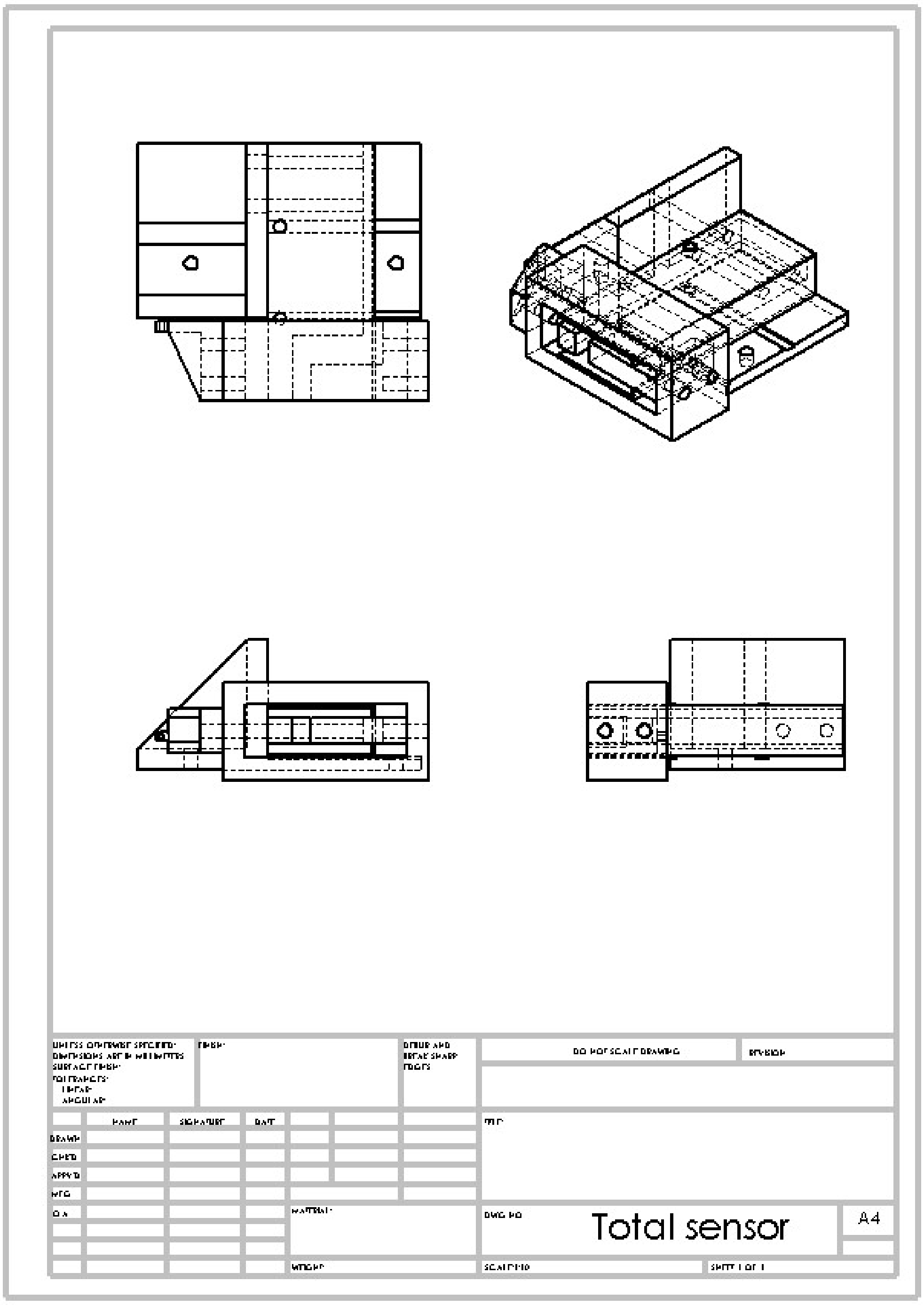

Figure 7.4 Technical drawing of load sensor and its fastening system.

Appendix C 3DSMax Models

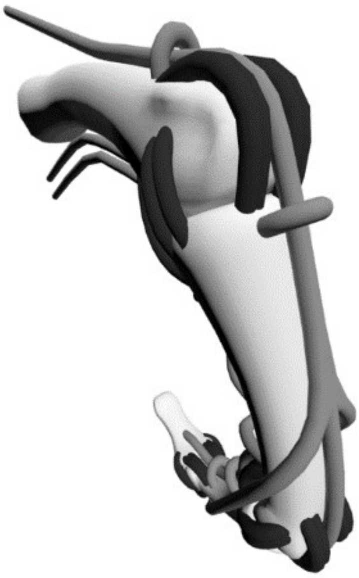

Figure 7.5 Whole finger, perspective view.

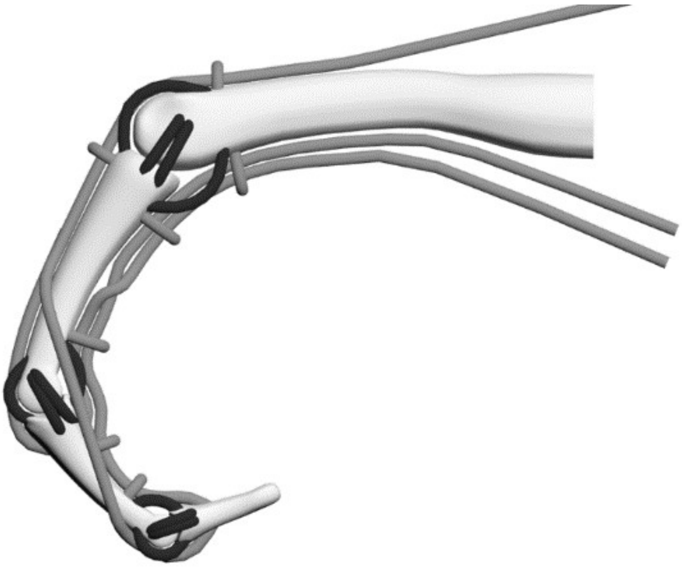

Figure 7.6 Whole finger, left view.

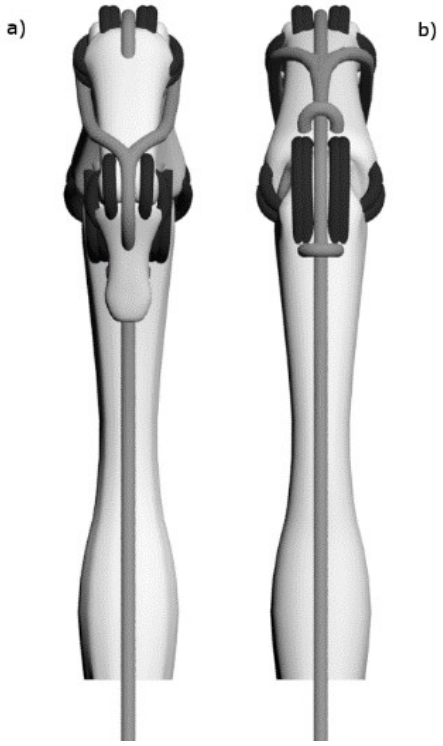

Figure 7.8 Whole finger, bottom a) and top b) view.

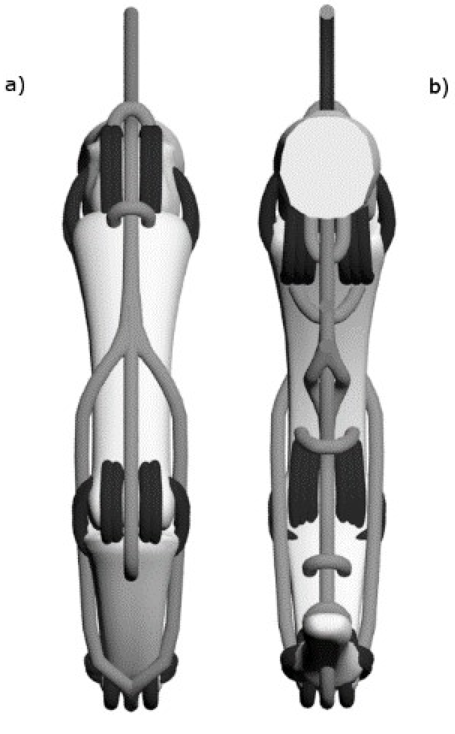

Figure 7.7 Whole finger, front a) and back b) view.