Feasibility study in using Intelligent-Materials to create Actuators with Muscle Capabilities that can enhance Prosthetics

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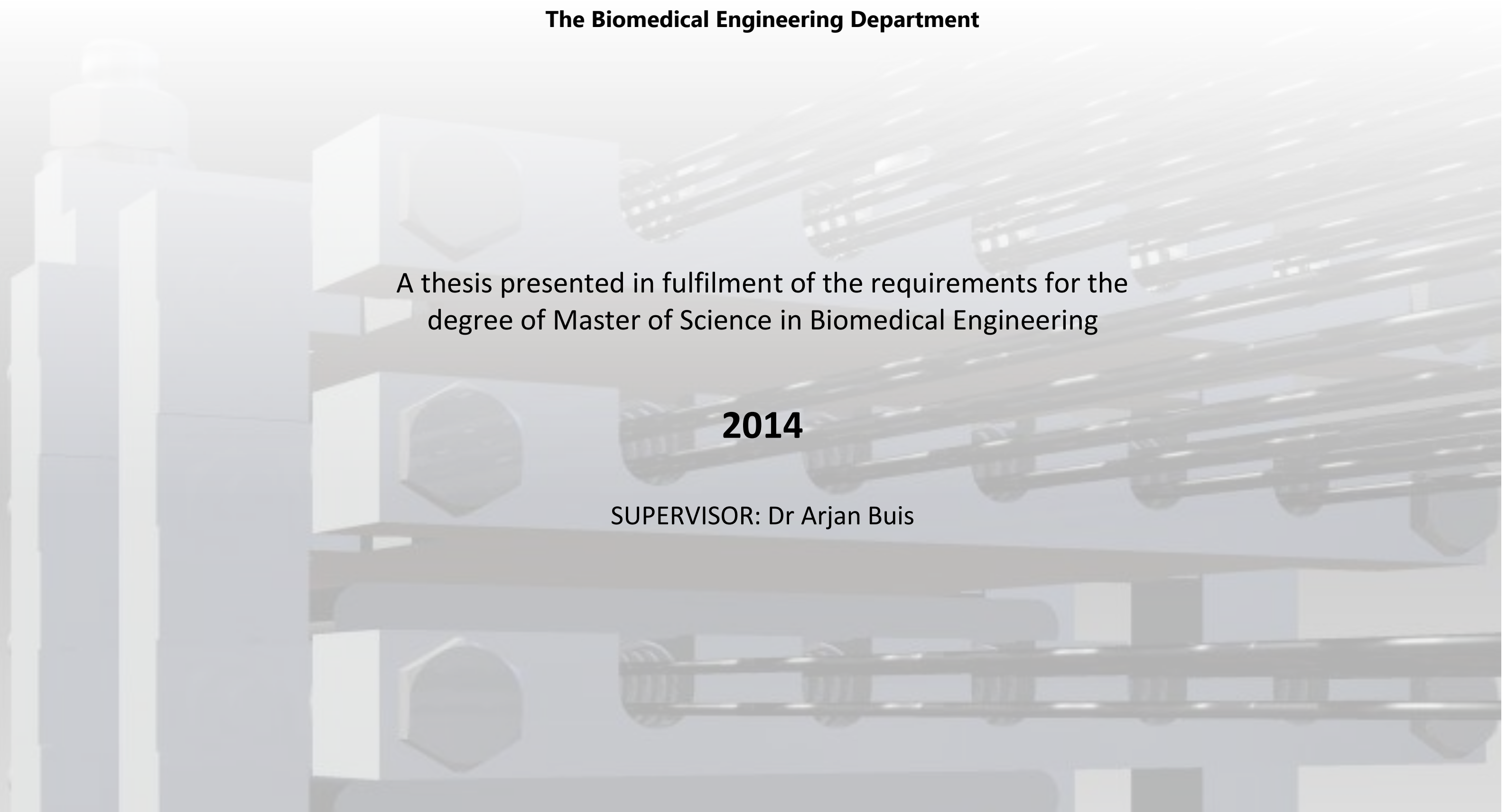

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ABSTRACT

Actuators with muscle similar capabilities can provide new solutions to the industry and is a potential key factor in revolutionising prosthetic interventions after limb loss. To this date there have been developed rather few actuators with similar capabilities and functionality as skeletal muscles, where none yet has obtained a broader use. Intelligent materials show great potential in creating new actuators. Previous attempts in creating muscle similar actuators have in general been an effort of material science, resulting in a range of various materials; shape memory alloys, electro active polymers, piezoelectric ceramics and carbon nanotubes. A *product design specification* that described the material's fulfillment of specified design requirements was used to select *one* of the materials for further development. Actuators that can obtain similar capabilities as human skeletal muscles.

However, the intelligent materials are in general lacking some main capabilities compared to skeletal muscles, whereas especially a sufficient strain proves to be the largest setback. Mechanisms that could amplify these intelligent materials' strain were therefore investigated. This lead to the development of a prototype of a multiplying mechanism, where the theoretical model of the design indicates that the final setup has potential to obtain the same capabilities as human skeletal muscles.

Further development is however required, before a full scale test to prove that the concept can be performed. Though, data was assured, which may help guide any future development.

ACKNOWLEDGEMENTS

I have with eager seen this project as an opportunity to test my newly acquired skills from my Master of Science in Biomedical Engineering and to outlive my passion for creating assistive technology, which can be of help for those who are less fortunate. My work resulted in an actuator design that may have quite similar capabilities as skeletal muscles.

The project has been exiting, intense and productive, but it would not have been possible, had it not been for guidance from my supervisor and colleagues. Therefore I would first like to thank my supervisor, Dr Arjan Buis, for his guidance and help to structure the process. I would also like to thank Dr Mario Giardini and Haripaashanth Elangovan for sharing their insight in the electronic area of intelligent materials and giving suggestions and recommendations. In this regard I would also like to thank Nigel Bolster for his open hearted help in providing 3D prints, which enabled the construction and investigation of the prototype. Furthermore, I would like to thank my colleagues Andre Attard and Laurent Van Eyck for their consistent and indispensable help in assisting me in the Idea process and giving me feedback, which provided key elements in the final design. Finally, I would like to thank Camilla Clasen for her assistance in editing the thesis.

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CHAPTER 1: INTRODUCTION

Actuators have proven to be irreplaceable components in a developed society, as they make sophisticated products possible through multiple varieties and combinations of movements. Thus allowing cars to drive, elevators to lift and in general perform movements that assist humans in everyday activities. This high usage level and attention has led to intense research and development of actuators throughout time. Currently, some of the most common used or “conventional” actuators are the electrical driven motors known as AC-, DC- and stepper motors. Similar are hydraulics actuators, which are also often used because of their high power capabilities. Robust and high performing actuators as these are in general used in the industrial sector, where a small size and weight may not be of much concern. In the medical Sector, on the other hand, there is an increasingly need to reduce size, mass and power consumption and cost. This is due to the devices that in some cases are *invasive* or *attached* to the body, which gives limited space for technology. Here conventional actuators are sadly proving to have far too low energy efficiency, large in volume, and heavy. Hence, alternative and novel designs, materials, and working paradigms for actuators are needed to create more lightweight, compact and powerful actuation systems for the medical sector.

A rather unpractised, but high potential technology for this matter, is the usage of intelligent materials to create actuators with similar capabilities as muscles. Capabilities that could create a new era of limb prosthetics and electrical driven exoskeletons for rehabilitation. Especially upper limb prosthetics are in focus, when considering such actuators (DEKA Research and Development, 2009). Currently powered limb prosthetics are mainly using conventional actuators, which makes setups that are heavy, rigid, noisy, weak or slow, too energy consuming, inorganic in shape and poor in tactile interaction. These parameters together lower current prosthetics’ anthropomorphic characteristics. Hence, conventional powered prosthetics may have an anti-social effect for some users, thereby troubling them to identify themselves with the prosthetic. New “non-conventional” actuators that on the other hand are powered by intelligent materials, may have more muscle similar capabilities (less noisy, flexible, soft and higher power) and thereby help overcome previous mentioned problems to improve user experience. However, there are several challenges to overcome when using intelligent materials for actuators; especially in close proximity with the human body. An issue as safety is in particular a challenge, as many of the materials either require high voltage or current to be actuated or may have materials that pose biohazards. Furthermore, some of the intelligent materials are rather untested in grand scale and in delivering similar capabilities to human skeletal muscle; high force output, flexible linear actuation, 20-40 % actuation and high operational frequency. Therefore, it is necessary to investigate the capabilities of several intelligent materials and select the most suitable for the task.

A main issue of many intelligent materials is often the low contraction or elongation percentage (strain), which in most cases are nowhere near that of skeletal muscles. This will significantly limit the mobility that the intelligent materials can perform on the prosthetic Therefore it is necessary to investigate methods that can increase the strain. Methods such as *strain multiplying mechanism* that for some intelligent materials may be able to increase the strain substantially. Though, intelligent materials differ in shapes, mass and modulus depending on the material's structure and processing. This can make it difficult to create mechanics of the setups; attachments, gearing, bearings and powering. A final challenge is to take the materials energy consumption into account.

It is however anticipated that a revelation in developing muscle similar actuators, can fulfil similar demands of compact and powerful actuators for other applications in robotics, biotechnology, information technology, space, manufacturing, entertainment and military.

1 Scope

Based on the previous section the project-aim can then be described as follow; 1) find the most suitable intelligent material for the task, 2) develop a mechanism that increases strain and transforms its output into a muscle similar actuation and 3) test this particular setup's capabilities. Hence, doing a proof of concept, which may help guide future research.

However, developing lower limb prosthetics can prove to be a rather complicated task, as leg prosthetics need to follow a specific walking pattern and endure particular high forces. Due to concerns of limited time it was then chosen to work on actuators for upper limb prosthetics. It was anticipated that it would help increase the focus and time for development of the actuator itself, as there seem to be less rigid working patterns and lighter requirements for upper limb prosthetics than lower limb prosthetics. Furthermore, *unpowered lower limb prosthetics* to date are already able to fulfil its users' needs fairly well, while the mobility and manipulation of *unpowered upper limb prosthetics* are rather limited (Westcoast Brace & Limb, 2011). Finally, as the upper limbs are not used as frequent as lower limbs, it is then anticipated that the overall energy consumption may be less. This can make the energy consumption a less significant requirement, as high power demands will happen less frequent.

Due to limited time it is then necessary to thoroughly consider what challenges are most important to investigate and solve. Hence, it is likely that some issues cannot be solved in the given project time. The project may instead help guide future research and highlight remaining challenges. For instance, this project is mainly focused on mechanical details and properties, while the attention to electronic powering- and control systems has been left to a minimum.

2 Problem statement

Based on the previous sections, an overall problem statement can then be made:

How can intelligent materials be used to enhance upper limb prosthetic's actuators performance and improve user-interaction?

Further sub statements are also made to describe the project's case:

- What type of intelligent material is most suitable for the task?
- How can disadvantages of using intelligent material for actuators with capabilities similar to skeletal muscles be balanced or overcome?

CHAPTER 2: LITERATURE REVIEW

3 Prosthetics

3.1 User needs

The main function of limb prosthetics is to help patients increase or regain lost mobility that is caused by absence of a limb. This can for upper extremities be due to either **congenital absence** (18 %) or **surgical removal** due to trauma (43 %) or cancer (14 %) (Ministry of Defence, 2008) (Figure 3-1). The traumas are in the western countries often caused by motor vehicle accidents, factory-, farm- or power tool accidents, or due to impact during military service (MedlinPlus, u.d.). The causes behind amputations and their frequency, are however varying between lower and upper limbs. In the United Kingdom 3-15 % of amputations are upper limb amputation, where the level of amputation can be *forequarter* (2%), *shoulder disarticulation* (5%), *trans-humeral* (28%), *elbow disarticulation* (0.3%), *trans-radial* (19%), *wrist disarticulation* (2%), *partial hand* (19%) and *digit* (22%) (Ministry of Defence, 2008) (Figure 3-2). Vascular diseases (including diabetes and peripheral arterial disease) are meanwhile more often the cause for amputation of lower extremities (counts for 70 % of lower limb amputations) (NHS, 2013) and are most typical for elder patients (Patient information Publications, 2012).

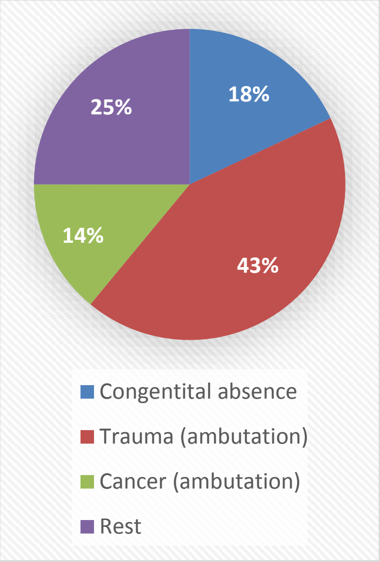


Figure 3-1: Cause of upper limb absence

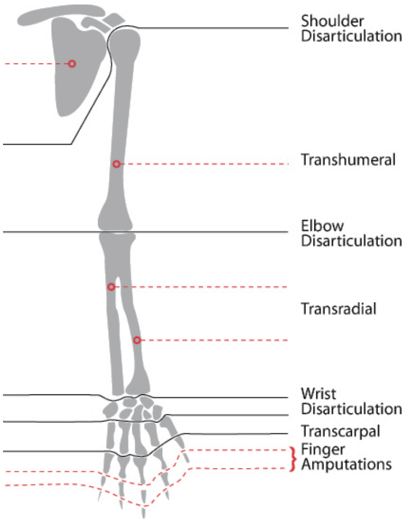


Figure 3-2: Levels of arm amputation (Westcoast Brace & Limb, 2011)

These multiple levels of amputation require different methods and prosthetic setups, which have led to a large number of different types of arm prosthetics being developed, that are differentiating on their level of amputation, environment of usage and mechanisms.

3.2 Function

Designs of upper limb prosthetics have continued to become more advanced, in order to continuously better fulfil the demand of limb replacement. Today, *powered* prosthetics are beginning to gain ground on the market, as they better enable the user to fulfil everyday activities. For lower limb prosthetic it enables better performance of walking, running and climbing stairs, while it has helped increase the mobility and fine manipulation for arm prosthetics. Subsequently, there is major focus on improving the user interaction of arm prosthetics, where external EMG- or invasive nerve sensors are used to register outputs. This has helped to further increase the user's control and is known as *myoelectric prostheses* (ottobock, 2013).

However, the empowerment of prosthetic is also adding complexity compared to their non-powered ancestors, which makes new issues emerge from the empowerment; noise emission from the actuators, short usage due to energy consumption and inorganic tactile sensation and shape. These issues lower the anthropomorphic experience of the prosthetic, which may makes the users observe the prosthetic as a device rather than an extension of their body. Hence, it is preferred that the prosthetic are capable of recreating the sensation of a healthy human limb. An upper limb prosthetic therefore also needs to be able to perform more varying kinds of limb motions according to the user's input, which in this case are manipulation, grasping and lifting. Some upper limb prosthetic meanwhile contributes with *cosmetic attributes* rather than of actual *mobility*, as it helps make some users feel more comfortable in social communities. There are few powered upper limb prosthetics that both have high cosmetic and mobile attributes.

Current powered prosthetics already enable a better life quality for their users. However, it is still possible to obtain better results by looking for new mechanics and actuators that can reduce imperfections such as noise emission, low force capabilities and poor anthropomorphic interaction.

4 Actuators

Actuators are a main element that requires a high amount of attention, when developing limb prosthetics. Any enhancements of prosthetic functions, such as more degrees-of-freedom (DOF), better control of movements, lower weight, anthropomorphic characteristics and better power-to-weight ratio (specific power), depend directly on the actuators and the mechanisms present in the prosthetic (Cura & et.al, 2003).

To date there have been developed numerous types of actuators, each with its own particular features. Though, in order to meet the constructive and functional requirements for prostheses, they generally need to be lightweight, compact, energy efficient, have a high power density, low noise emission, short reaction time and high operational frequency, create a low amount of heat, and be easy to control. The mechanical parts of limb prosthetics should have similarly well-defined sets of characteristics such as a high DOF, easy and low-cost production, easy activation, and the ability to simulate anthropomorphic movements. Well-matched actuators and mechanisms guarantee both optimal operation and greater internal space to house electronic control circuits and a power source (Cura & et.al, 2003).

There have been developed numerous varieties of actuators, many that already are commercially available, while others still are being researched. Generating movement based on either electromagnetism or intelligent materials are what defines an actuator as either *conventional* or *non-conventional* (Cura & et.al, 2003).

4.1 Conventional actuators

Conventional actuators have, as previous mentioned, had a high level of research and development and have been applied throughout the industrial and private sector. Conventional actuators range over electric motors using magnetism (Faraday's Law) and hydraulic and pneumatic pumps (Mavroidis, 2002). For prosthetics, the most commonly used actuators are a *miniature* format of DC motors (Figure 4-1), which can be further divided into two groups; *coreless DC micromotors* and *brushless DC micromotors* (Cura & et.al, 2003). Though, hydraulics pistons are also commonly used in the field of prosthetics, due to their immense force output.

Figure 4-1: Miniature DC motor (Cedrat Technologies, 2012)

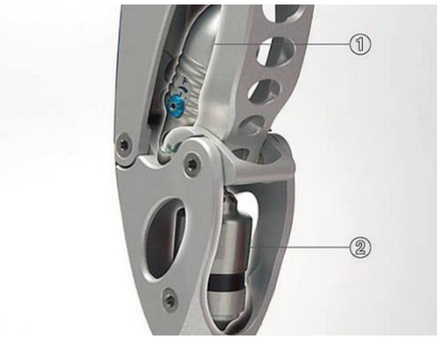


Figure 4-2: Prosthetics knee EBSpro using hydraulics (Ottobock, 2014)

However, it is a great challenge to fulfil all previous mentioned requirements for a prosthetic actuator with conventional actuators. Current commercial prosthetics seem to have been compromising some of these requirements, in order to obtain a commercial product. While DC motors and their gearbox are relatively heavy, rigid, inflexible, noisy and have a lowered anthropomorphic characteristic, then hydraulic actuators also have complications with a high weight compared to their mechanical output (Figure 5-20), due to the required pump. Pneumatic actuators have a similar problem; however, with less force output and -weight than the hydraulic actuators (Mavroidis, 2002).

Furthermore, using conventional actuators for prosthetics somewhat inverses the bearing structure, when comparing it to a human limb; the actuators reside in the centre of application, while the rigid bearing elements are positioned outside. This reminds more of an exoskeleton than an endoskeleton, which also reduces the tactile interface and thereby the anthropomorphic factor.

4.2 Non-Conventional actuators

Non-conventional actuators are generally associated with the atomic structure of the material and the changes it performs according to specific input. This creates various properties of some metal alloys, piezoelectric materials, and polymeric gel-type chemical compounds. Each material has its own advantages and disadvantages (Cura & et.al, 2003). Non-conventional actuators as piezoelectric ceramics have already proven useful in the medical field by enabling applications such as scanning through ultrasound.

4.3 Skeletal muscles

Skeletal muscle is one of the three human muscle types: the cardiac muscle composing the heart; the *smooth muscle* lining the hollow internal organs; and the *skeletal muscle,* which is attached to the skeleton via tendons. There are more than 430 skeletal muscles paired symmetrically at the right and left side of median plane (Nordin & Frankel, 2001, pp. 149-174), which account for 40 to 45 % of the human body's total weight, making it the most abundant tissue.

Their function is to provide strength and protection to the skeleton, distribute loads and absorb shocks, enable *dynamic movements* and provide *static work* to maintain body posture. To achieve this are skeletal muscle attached between two different bones as a minimum.

4.3.1 Composition structure

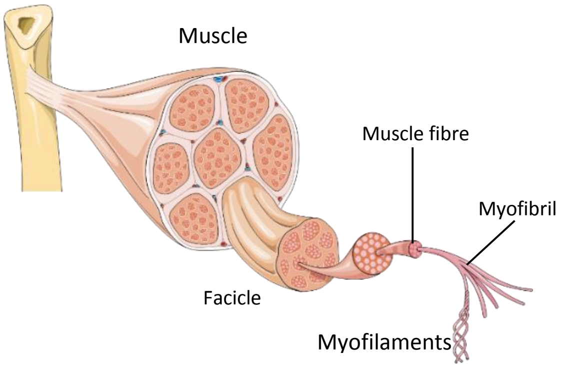


Figure 4-3: Structure of muscle (EuroStemCell, 2013)

The overall structure of skeletal muscle is fibre long cylindrical cells with hundreds of nucleis. The fibres thickness varies from 10 to 100 µm and the length from 0.01 to 0.30 m (Nordin & Frankel, 2001, pp. 149-174). Muscles are structured in bundles of fibres with multiple levels of subunits (Figure 4-3):

1) First are the overall structure, the **muscle** that is surrounded by Epimysium
2) From here are sections of **Fascicles** surrounded by perimysium dividing
3) Here are multiple **muscle fibres** (cells) contained,
4) Each which has multiple **myofibrils.**
5) That are made of series of sections called **sacromeres** (Figure 4-4)
6) At nanoscale the sacromeres are made of groups of interacting proteins called **myofilaments** (Figure 4-4)

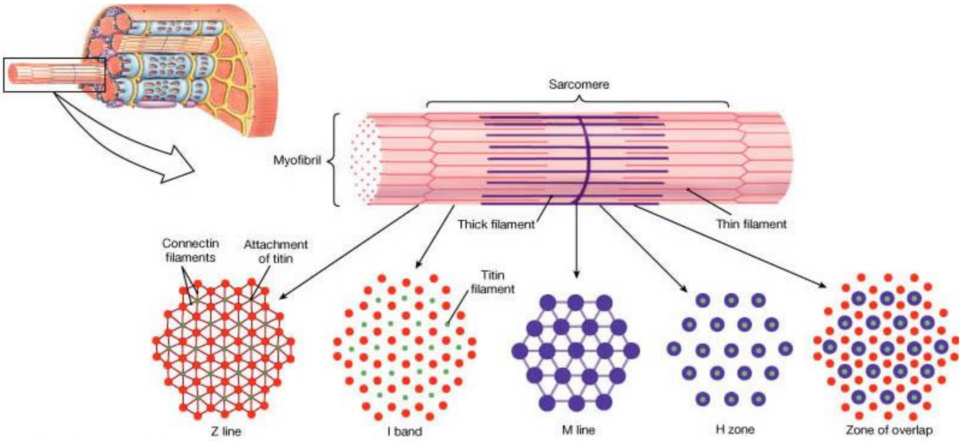


Figure 4-4: Structure of sarcomeres and myofilaments (Martini, 2009, p. 300)

In this project a focus has been the crawling mechanics of skeletal muscles at nanoscale and the arrangement molecules within each sacromere. These crawling mechanisms between the actin- and myosin filaments are the ones performing the contraction of skeletal muscles (Figure 4-5). During contraction the myosin will connect with the actin strand. The myosin will then create a drag, as the myosin hinge bends by the power from ATP. As the myosin drags the actin towards the M-line, the H-band will then decrease in length, making the overall sacromere shorter; creating a contraction.

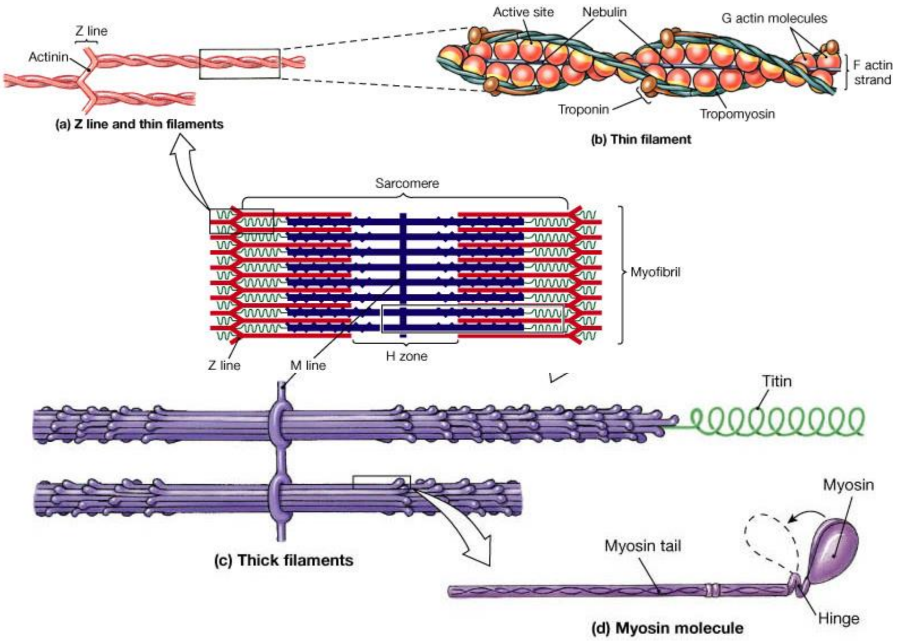


Figure 4-5: Molecular structure of a myofibril (Martini, 2009, p. 302)

4.3.2 Physical performance

Skeletal muscles are fascinating units capable of providing billions of work cycles, self-repairs, creating contractions from 20 to more than 40 %, increase strength and change stiffness in response to need, generate stresses of approximately 0.35 MPa, contract at 50% per second (Table 4-1), and can even be transformed into energy. They convert the energy from the safe and energetic ATP into mechanical energy with an efficiency from 25 to 40 % (Table 4-1).

Table 4-1: Marmalian skeletal muscle capabilities (Madden, et al., 2004)

PROPERTY	TYPICAL	MAXIMUM
Strain (%)	20	> 40
Stress (MPa)	0.1	0.35
Work Density (kJ m^{-3})	8	40
Density (kg m^{-3})	1037	
Strain Rate (% s^{-1})		> 50
Specific Power (W kg^{-1})	50	284
Efficiency (%)		40
Cycle Life		> 10^9
Modulus (MPa)	10 - 60	

4.4 “Artificial muscle” term

When looking into developing actuators with muscle similar capabilities, it is then of importance to be able to understand the jargon. As the goal is to obtain an actuator with *muscle similar capabilities*, it would then be tempting to use the term “artificial muscles” to describe the device. However, artificial muscle describes specific methodology to create a muscle similar actuation. Instead of trying to follow nature by creating large strains through a combined effect of a series of smaller actuations, the artificial muscles are then using an overall *material deformation*. Hence, instead of using mechanical crawling, artificial muscles are then one single deforming band/unit.

For artificial muscle, the strain is typically inverse related to the force output (Hunter & Lafontaine, 1992) (Baughman, 2005) (Baughman, et al., 2014). Hence high tensile forces may be possible to obtain, but strain is then usually only a fraction of what skeletal muscles can perform and vice versa. For some artificial muscle setups using materials such as *nylon* (Baughman, et al., 2014) or silicone tubing for *pneumatic actuators* (Daerden & Lefeber, 2002), the force is then still sufficient even at high strains. However, they then face other issues such as the power supply.

It becomes more obvious how skeletal muscle both obtain high strain and tensile stress, when considering its macroscopic mechanism that creates multiple serial and parallel powerful actuations between myosin and actin (Martini, 2009) (Nordin & Frankel, 2001, pp. 149-174). Hence, instead of losing force when trying to make the entire strain in one go, it is then possible to maintain a high force through a series of small strains. Associations can be drawn to a *multiplying mechanism of strain* such as an *inchworm*.

4.5 Strain multiplying mechanism

A strain multiplying mechanism can be used to increase the actuators movement, in case that an intelligent materials strain is not sufficient; below 20 to 40 % (section 4.3).

Using a multiplying mechanism will however alter other parameters in exchange for movement. Hence, an increase in strain will decrease another parameter proportional. This is similar to gearing boxes, which transforms rotational velocity into torque instead.

4.5.1 Hydraulics

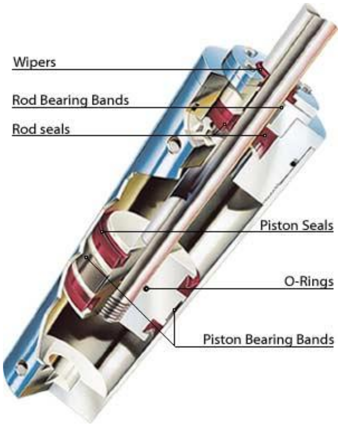


Figure 4-6: Pascal ram (Allied Metrics Seals & Fasteners, Inc, 2008)

There are numerous opportunities in using hydraulics for a multiplying mechanism. Hydraulic pistons work by pressurising and transferring incompressible liquids, such as oil or water. Incompressible liquids are optimal for pressure transference as there is no change in volume, which would otherwise absorb the pressure. Typical hydraulic setups have a pump, which is used to build up pressure and create a flow. The pressurised flow can then be controlled by valves and guided into an actuator such as a piston (Figure 4-6). A piston will create movement related to the flow and pressure. This is based on *Pascal's Law*, which states that an increase in pressure at any point in a confined fluid will create an equal increase at every other point in the container (equation 1).

$$P_1 = P_2 \tag{1}$$

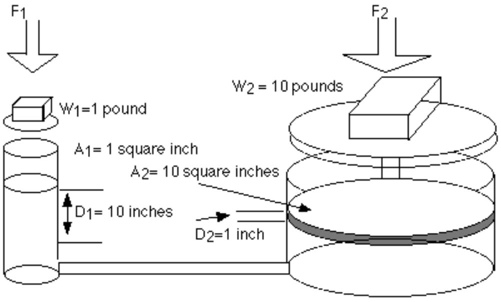


Figure 4-7: Pascal Princible (NASA, 1996)

This is shown in Figure 4-7 where it by following Pascal's law is possible to multiply a force or movement.

As pressure equals to *force per unit area* according to Pascal's law, it can then be stated as follows:

$$P_1 = P_2 \;\rightarrow\; \frac{F_1}{A_1} = \frac{F_2}{A_2} \tag{2}$$

Where F_1 is the force and A_1 is the cross sectional area of the first piston, while F_2 and A_2 similarly account for the second piston.

By knowing that the volume change [V_1] in one piston needs to be equal to the volume change in the second piston [V_2], it is the possible to set up another function:

$$V_1 = V_2 \rightarrow \tag{3}$$

$$A_1\,D_1 = A_2\,D_2 \tag{4}$$

Where D_1 and D_2 are the displacement of each piston. This can finally create an expression for how the piston displacements and areas are related:

$$\frac{A_1}{A_2} = \frac{D_1}{D_2} \tag{5}$$

Hence, the cross sectional areas can be altered in order to increase displacement changes. This is necessary if a pump's piston only has limited movement as the intelligent material and it is required that the actuator performs a far greater movement (20 to 40 % strain). For example, if the pump only can make a displacement of 4 % and the actuator needs to undergo 30 %, the actuator piston's cross sectional area then needs to be 7.5 times smaller than the pump's.

4.5.2 Inchworm

Another type of multiplying mechanism is the *inchworm*, which performs a series of small contractions that adds up to create one larger stroke (Figure 4-8). This mechanism is used in fluid pumps (Mavroidis, 2002), linear actuators (Suleman & Burns, 2001) (Liang, et al., 2012) and small mobile vehicles (Images SI, Inc., 2007). The inchworm works by a locking mechanism and a strain mechanism (Figure 4-8). The setup has two initial steps that it undergoes when beginning actuation: **Relaxation** where both mechanisms are passive and **Initialization** where the rear end is locked. From here there are a set of *cycles* performed in order to create movement. Each cycle contains six steps (Figure 4-8):

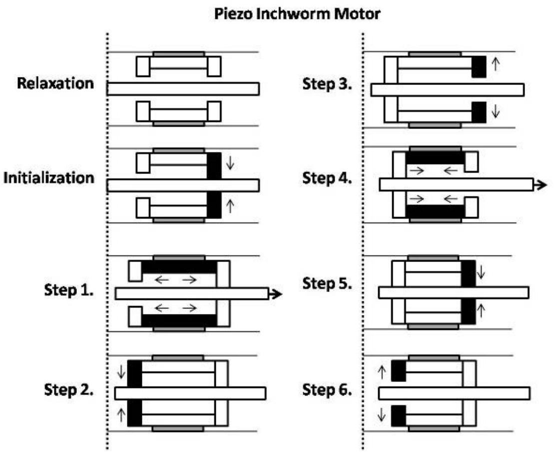


Figure 4-8: Piezoelectrical inchwom motor (Wikipedia, 2014)

1) An elongation is initiated
2) The inchworm's front is locked
3) The rear is unlocked
4) The material returns to its initial length
5) The rear end is again locked
6) The front end is unlocked

Such mechanism is a type of gearing, which increases the strain for the cost of space or time usually. This specific inchworm mechanism is suitable for piezoelectrical ceramics as they do not have a high strain, but have a potentially high operational frequency.

5 Intelligent Materials

Intelligent materials show great potential in creating new actuators that have a similar behaviour as human muscles (European Scientific Network for Artificial Muscles, 2014).

Previous attempts in creating actuators with muscle similar capabilities have in general been an effort of material science, resulting in usage of intelligent materials for a range of various kinds of *artificial muscle* setups. These intelligent materials include shape memory alloys (SMA), electroactive polymers (EAP), electrorheological fluids (ER), piezoelectric ceramics, carbon nanotubes (CNT) and others; magnetostrictive materials, electrorheological fluids, polymers. (Mavroidis, 2002). Each class requires its own type of input to perform actuation. Furthermore, each class also contains various subclasses, where there can be further differences in the input type, depending on material composition. The difference in atomic compositions can also change the output criteria further. This creates a great range of possible usages and combinations, but the need for expertise also becomes far greater. Though, for this project only five of the most suitable subclasses will be considered.

A *product design specification* will be used to select one of these materials for usage in the actuator*,* which describes the material's fulfilment of a set of *design criteria* (Cura & et.al, 2003) and performance in similar setups (Mavroidis, 2002) (Nespoli, et al., 2010).

5.1 Shape memory alloy, NiTi

Shape memory alloys (SMAs) are a well-known class of intelligent materials. It was discovered in 1932, but was first practical used after 1962. William Beuhler, working at the US Naval labs, discovered the shape memory effect in an alloy of 55 % nickel and 45 % titanium; which is described as *NiTi.* The discovery led to the brand name *Nitinol* (Images SI, Inc, 2014)*.* Another known brand is *Flexinol* by *Dynalloy, Inc,* which has mainly been investigated in this project (Dynalloy, Inc, 2014).

5.1.1 Actuation

The main feature of SMA is the ability to change physical shape during heating/cooling cycles; typical from 70 to 90 ^{O}C. This is due to the atomic alignment of the material that has two different crystallographic phases. A *martensite* crystal structure is stable at low temperatures of the material, while it is an *austenite* crystal structure that is stable at high temperatures (Figure 5-1).

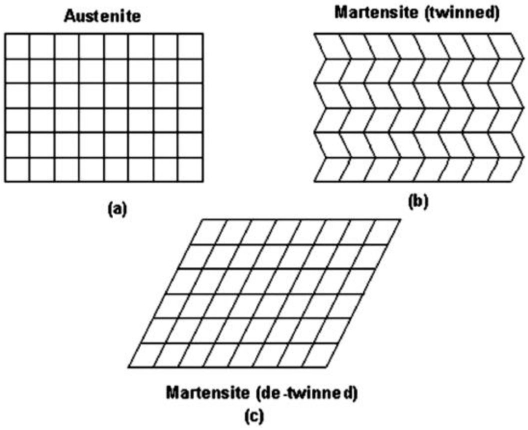


Figure 5-1: Crystalline arrangement of austenite and martensite (Mavroidis, 2002)

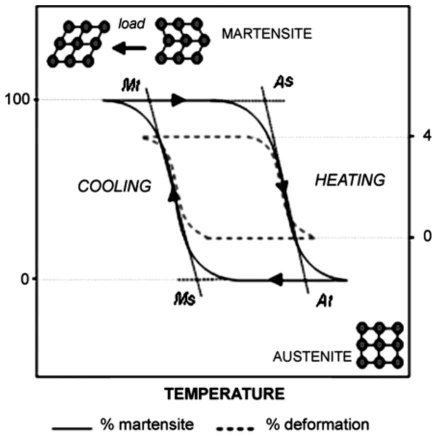


Figure 5-2: Transcendence phases and hysteresis of SMA (Mavroidis, 2002)

The temperature where the transition between these two crystal alignments occurs depends mainly on the material's composition of alloys. An offset can be found, when investigating the temperatures where the transitions start and finish for martensite (start = Ms; finish = Mf) and austenite (start = As; finish = Af) (Figure 5-2). Hence, the materials transformation has a thermal hysteresis that typically is 20-40 ^{O}C. The Nitinol's overall transformation depends on how it has been trained and the temperature where autenite occurs. A contraction of 4 % is usually the desired value, as any higher contractions will cause the material to lose its memory faster (Mavroidis, 2002).

5.1.2 Output

Nitinol has an outstanding contraction force. NiTi materials outmatch all other materials when comparing the mechanical output (Figure 5-20). A NiTi wire is capable of reaching stresses above 200 MPa (Mavroidis, 2002). Which is 570 times more than skeletal muscles stress output (Table 4-1). However, the mechanical stress also depends on the strain obtained, which unfortunately are far less than muscles. The service expectancy of a NiTi material is inverse proportional to the strain and stress. Hence, it is recommended that NiTi materials such as Flexinol at maximum operate at contractions of 4 % and stresses of 42 MPa (Dynalloy, Inc, 2014). Beside a low strain, some of the largest weaknesses of SMA materials are its low energy efficiency (less than 5 %), a low operational frequency (due to their cooling time) and difficulties in control.

5.1.3 Applications

Nitinol is currently used in the medical sector. One of its best known contributes is stents (Figure 5-3). Nitinol stents perform an expansion when released inside a blood vessel, in order to increase the vessel´s diameter and flow. However, there are only few companies worldwide using SMA for actuators. Nonetheless, there have been performed a high quantity of studies regarding it. One company that produces SMA actuators is called *Miga Motor Company* (Figure 5-4) (Nespoli, et al., 2010).

Figure 5-3: Nitinol stent (medint pro, u.d.)

Figure 5-4: Micro actuator created by (Miga Motor Company, 2014)

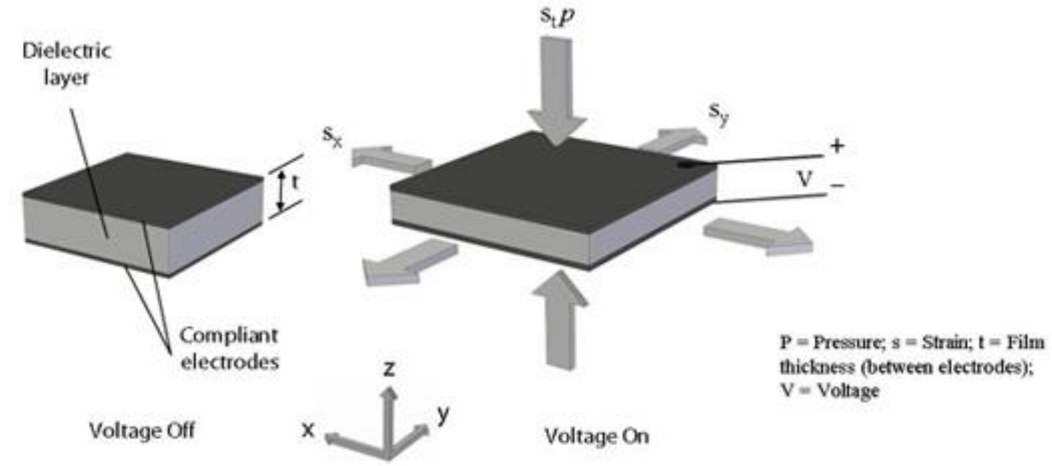
5.2 Electroactive Polymer

In recent time, numerous of different types of electroactive polymers (EAP) have been developed, creating a broad family of; dielectric electroative polymer, ferroelectric polymers, electrostrictive graft polymers, ionic electroactive polymer and ionic polymer-metal composite. Each may have multiple different structure types, composition and types of input to create actuation. Hence, it is a challenge to make any general description of EAP’s capabilities. Furthermore, EAP actuators are a delicate technology, where each type requires a high level of work to master. This complicates making a broad span of the technologies.

Thus, the main attention of EAP based intelligent materials has been focused at dielectric electroactive polymers (DEAP). The author has previously worked with DEAP during an internship at Danfoss PolyPower A/S and through his bachelor project (Billeschou, 2013).

5.2.1 General DEAP actuation

DEAP in general functions around an elastomeric film, which has been coated on both sides with silver electrodes. By connecting the electrodes to a circuit and applying a voltage [V], it is then possible to create an electrostatic pressure [P]. During actuation the electrostatic pressure can become strong enough to create mechanical compression on the elastomer, which cannot be reduced in volume; causing a decrease in thickness and expansion in planar directions (Figure 5-5). The electrostatic pressure enables DEAPs to obtain high strains. When the charge is removed, the elastomer film then returns to its original non-compressed thickness [t] and planar size.



P = Pressure; s = Strain; t = Film thickness (between electrodes); V = Voltage

Figure 5-5: Using voltage to put DEAP under electrostatic pressure (Danfoss PolyPower A/S, 2012)

DEAPs way of working can be compared to capacitor; however, with a change of the capacitance when a voltage is applied. This is due to the polymer being compressed and obtaining a larger planar area (Figure 5-5).

However, using DEAP for actuators poses a main hazard, as a high voltage level is required. This complicates the required safety measures for close interaction with the human body (Bar-Cohen & et.at, 2005).

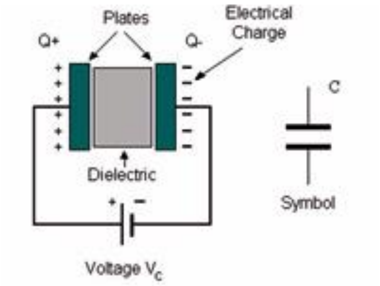


Figure 5-6: Symbol representing DEAP (Danfoss PolyPower A/S, 2012)

Figure 5-7: A DEAP sensor kit (Danfoss PolyPower A/S, 2013)

5.2.2 Application

DEAP can be used as sensors, actuators and generators. Though, while DEAP sensors (Figure 5-7) are currently entering the market from some of the few DEAP manufacturing companies, their manufacturing systems are then not prepared for a large scale production of actuators. Research and development however are continuing to make a mass production and greater standards for DEAP actuators closer to reality.

For this project two different DEAP actuator setups have been investigated; *rolled* and *stacked*. There are, as mentioned, a vast amount of other possible EAP actuators, but only few are at a similar state of development as DEAP (Kim, et al., 2013).

5.2.3 Dielectric Electroactive Polymer ROLLED

The DEAP product of *Danfoss PolyPower A/S*, *PolyPower*, has shown to have great elasticity, is able to actuate at high frequencies - in the degree of sound waves, thereby able to play music (the Technical University of Denmark, 2012), create a great strain and has one directional movements rather than planer expansion as Figure 5-5 shows (Danfoss PolyPower A/S, 2012). The high elasticity possesses great qualities for new sensors, actuators (Figure 5-8), dampers and generators (Bar-Cohen & et.at, 2005). PolyPower's capabilities are also suitable to be used in artificial muscles, which are currently being researched (European Scientific Network for Artificial Muscles, 2014).

Figure 5-8: Rolled DEAP actuators made from PolyPower (Sarban1, et al., 2009)

The material's structure is based on double layered film (Figure 5-10). Each layer consists of an elastomer and an electrode. A film with a pair of electrodes is created by laying the two layers together; typical in back-to-back format, making the elastomer connect (Figure 5-10).

Figure 5-9: Polypower film
A film with a single elastomer and electrode layer roller around a pylon; ready to be combined (Danfoss PolyPower A/S, 2011)

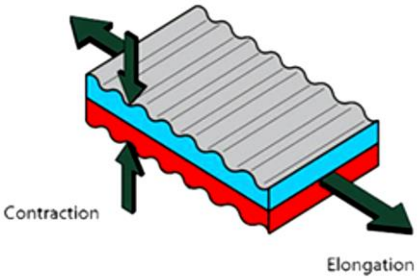


Figure 5-10: Back-to-back format for a DEAP
The elastomer is marked by the red and cyan colour. Each elastomer has its own electrode (Danfoss PolyPower A/S, 2012)

The current version of PolyPower film is as little as 40 µm thick, while the silver electrode is only 110 nm thick (Danfoss PolyPower A/S, 2012). A DEAP sensor uses the two electrodes as a capacitor, where any strain of the elastomer will also decrease the thickness (Figure 5-10). This will make a detectable change in the capacitance. It is recommended that the sensor is stretched 80 % as maximum (Danfoss PolyPower A/S, 2013). A rolled DEAP *actuator* is created by using a greater span of film (Figure 5-9), which then is rolled up upon itself (Figure 5-12), in order to increase the layers and the cross sectional area. The film needs to be in a Back-to-Front format, as the electrodes otherwise would connect and create a short circuit.

When powered up to 3600 volts (Danfoss PolyPower A/S, 2012), the electrostatic field created between the electrodes will then squeeze the elastomer and thereby elongate it in one direction (Figure 5-11). This can potentially create up to 5 % of elongation with 0.05 MPa of stress (Danfoss PolyPower A/S, 2011). The ripples created in elastomer (Figure 5-11) ensure that the silver electrode does not fracture during stretching. This is because the surface area of the elastomer stays the same, while it is being stretched.

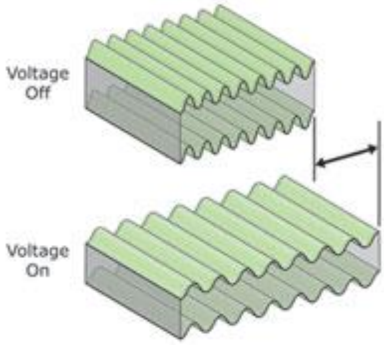


Figure 5-11: Electrostatic force stretching PolyPower film (Danfoss PolyPower A/S, 2013)

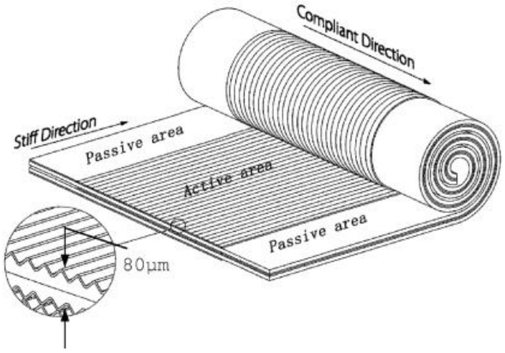


Figure 5-12: PolyPower film rolled up to an actuator (Jones & Sarban, 2012)

5.2.4 Dielectric Electroactive Polymer STACKED

Another DEAP design is to stack a large number of thin DEAP films (approximately 50 µm thick) on top of each other (EMPA, 2014) , rather than roll a film (Figure 5-13). When powered the electrodes will then in this design shorten the length of the overall structure (Kim, et al., 2013, pp. 153-177), rather than stretching as the rolled design.

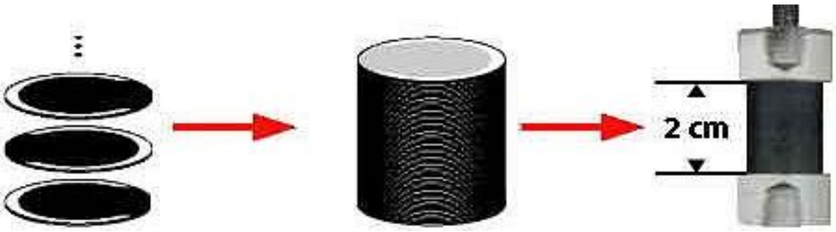


Figure 5-13: Stacked DEAP actuator created by EMPA **(EMPA, 2014)**

The contraction percentage is rather constant. Though, the length is adjusted by adding more layers. The force can be adjusted by changing the cross sectional area of the layers.

Most promising is the theoretical possibilities of this DEAP setup. The maximal theoretical actuation shows a potential of up to 40 % contraction with 0.16 MPa of tensile force (Kovacs, et al., 2009). This is nearly identical to that of an actual skeletal muscle (Table 4-1). Though, the main challenges are currently the manufacturing process and interaction at the end of the actuator. This setup is particularly weak against any shear or torsional forces, which questions its suitability for a bio-inspired prosthetic (EMPA, 2014). It is likely that this DEAP setup is better at replacing liquid in hydraulic pistons, as it then can be protected from shear- and torsional forces by the rigid cylinder.

5.3 Piezoelectric ceramics

Piezoelectric ceramics are a highly potent type of intelligent material. The materials can both be used as sensor, generator and actuator. When put under mechanical pressure the *piezoelectric effect* occurs (Noliac A/S, 2011), where the ceramics' crystalline structure produces a voltage proportional to the pressure:

$$P = d\,\sigma \tag{6}$$

Where P is the polarization, σ is the applied stress and d is the piezoelectric coefficient. On the other hand, when an electric field is applied to the ceramics, the *converse piezoelectric effect* occurs (Noliac A/S, 2011), as the crystalline structure then produces dimensional changes; actuation.

$$\varepsilon = d\,E \tag{7}$$

Here ε is the strain induced, d the piezoelectric coefficient and E is the applied electric field. This can be summarised into Figure 5-14.

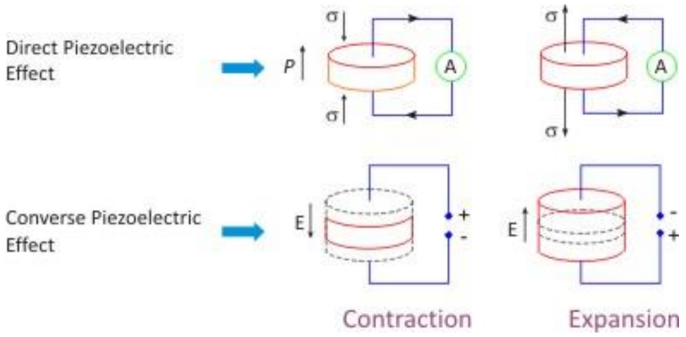


Figure 5-14: The piezoelectric- and converse piezoelectric effect (NPTEL, u.d.)

5.3.1 Output

Piezoelectric ceramics' mechanical output may vary according to which applications are desired. The strain in general is a rather limited 0.1 %, which just creates a few micrometers of actuation. Though, the ceramics are both capable of creating a high stress and work at an incredible operational frequency.

It is worth mentioning that piezoelectric ceramics stress output is inversely proportional to its strain. Hence, the highest strain will create little force, while low strain creates high stresses (Figure 5-15). This also accounts for other intelligent materials.

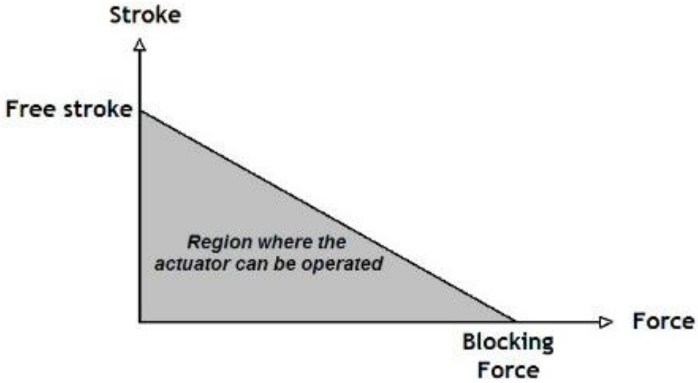


Figure 5-15: Stroke versus force curve for piezoelectric ceramics
The curve describes the piezoelectric ceramics' stroke and force output is inversely proportional to each other (Noliac A/S, 2011).

5.3.2 Current Applications

Piezoelectric ceramics can be used as sensors, actuators and generators. In each case piezoelectric ceramics are creating very compact and small size units. This is also a reason for why piezoelectric ceramics often are used for applications in the medical sector.

The extreme high operational frequency, that is possible with piezoelectric ceramic actuators, is one of its unique and unmatched capabilities. It makes the ceramics capable of creating ultrasonic waves, which can be used to create ultrasound for scanning tools. Furthermore, piezoelectric ceramics are being used in various sizes of pumps, nano-positioners and high force actuators (Physik Instrumente, 2014).

5.4 Carbon nanotube muscle fibre

Carbon nanotube (CNT) is a very promising material for artificial muscles. CNT's capabilities to work as actuators were discovered by *Ray Baugman* (University of Texas at Dallas, 2012) from *The Univesity of Texas at Dallas* back in 1999 (Baughman, et al., 1999). His team and fellow researchers have since continued to develop different kinds of artificial muscles based on carbon nanotubes (Baughman, et al., 2002) (Baughman, et al., 2004). This has led to many varieties of CNT actuators. For this project the main focus has been on the setup where multiple carbon nanotubes are highly twisted together (Figure 5-16). The strong capabilities of CNT yarns are the ability of working in temperature above 1,000 C^{O}, perform a high quantity of cycles, strong, flexible and are extremely lightweight (Baughman, et al., 2002). Though, twisted CNT actuators can only perform a contraction of maximum 2 %, is very expensive to produce and has not been used outside research yet.

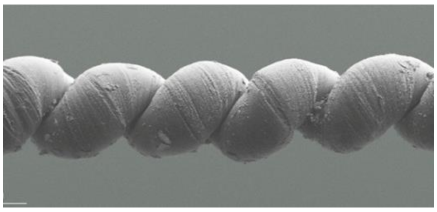


Figure 5-16: Twist CNT coil with paraffin wax (University of Texas at Dallas, 2012)

5.5 Nylon

Recent studies has shown that it is possible to use polymers as nylon fibres to create an actuating element; artificial muscles. It is stated that the actuator setup provides a fast, scalable, non-hysteretic, long-life, and tensile/torsional artificial muscle (Baughman, et al., 2014). Though, more interesting is the fact that standard nylon sewing threads and -fishing lines can be used to create these contractible fibres. Four different materials were tested in the studies; polyethylene fishing wire, *nylon 6.6/Ag*, *nylon 6* and *nylon 6.6*, where nylon 6.6 proved to have the most suitable characteristics (Baughman, et al., 2014).

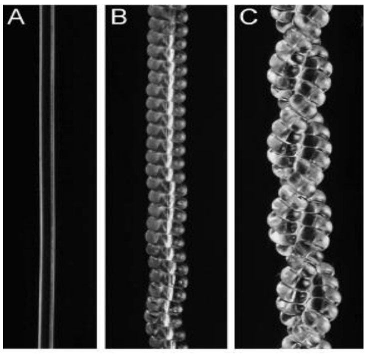


Figure 5-17: Twisted structure of nylon yarns
(A) a non-twisted Ø300 mm fibre; (B) the fibre of (A) after coiling by twist insertion; (C) a helix formed from two coils of (B) (Baughman, et al., 2014)

The fibres were transformed into actuating elements through coiling (Figure 5-17) at specific tensional loads (Table 5-1); specifying how tightly the fibres would coil and their following actuation strain and stress.

Table 5-1: Coiling of polymer fibres to create actuators (Baughman, et al., 2014)

Material	Diameter (µm)	Load during coiling (MPa)	Twist to coil (turns/m)
Nylon 6 monofilament fishing line	270	17	1430
Nylon 6.6 monofilament sewing thread	127	16	3020
Nylon 6.6 silver plated multifilament sewing thread	180	14	2430
Polyethylene braided fishing line	130	37	2270

Structure

A higher load during coiling will create a greater tensile actuating, while lesser load will ensure a greater contraction (Figure 5-18). Extreme twisting with little load produces coiled muscles that can contract up to 49%, while heavy load during coiling can ensure a tensile strength that are 100 times more than skeletal muscles of the same length and weight. This creates an extreme power density of 5300 W/kg (Haines, et al., 2014). It is however necessary to ensure that the fibres do not untwist. This can be done by thermal annealing to set the structure, or by forming torque-balanced structures (Figure 5-17C).

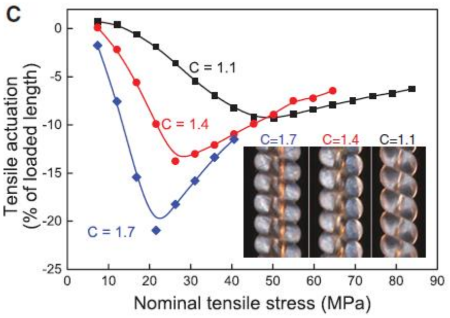


Figure 5-18: Tensile stroke versus load
Shows outputs of three Ø127 mm nylon 6.6 monofilament fibre coilded under 10, 16, and 35 MPa, resulting in spring indices of 1.7, 1.4, and 1.1 (Baughman, et al., 2014)

Output

Thermal changes from 20 to 200 C^{O} are used to make the polymer element actuate (Figure 5-19). However, the material´s low operational frequency and energy efficiency are of concern. Hence, high and rapid temperature shifts are necessary in order to increase the frequency. In the study it was possible to obtain a frequency of 5 Hz, by using heated and cooled oil (Baughman, et al., 2014). The energy efficiency of the material is as little as 1.08 %. It is at current state also rather unknown how well the elements will act in long term; using water or oil to cool can weaken the polymer and long term exposure to air can make the polymer brittle.

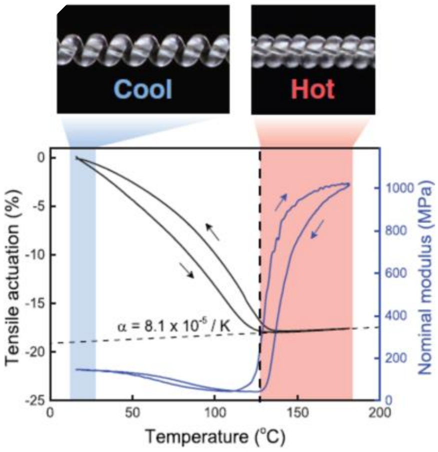


Figure 5-19: Tensile stroke and nominal modulus versus temperature
A Ø300 mm nylon 6.6 monofilament under 7.5 MPa static and 0.5MPa dynamic load. At 130°C the coils intercept, which dramatically increases the nominal elastic modulus and causes the thermal expansion coefficient to become positive. (Baughman, et al., 2014)

5.6 Summary

Specific power

The *specific power* ratio of the various classes of intelligent materials differs. However, when comparing with more established conventional actuators such as DC motors or hydraulics actuators, it then becomes clear where the intelligent materials have advantages (Figure 5-20). For instance, while hydraulic actuators may have a high power output, they also have a high weight for the given force. SMA has meanwhile similar power, but also a significantly lower weight.

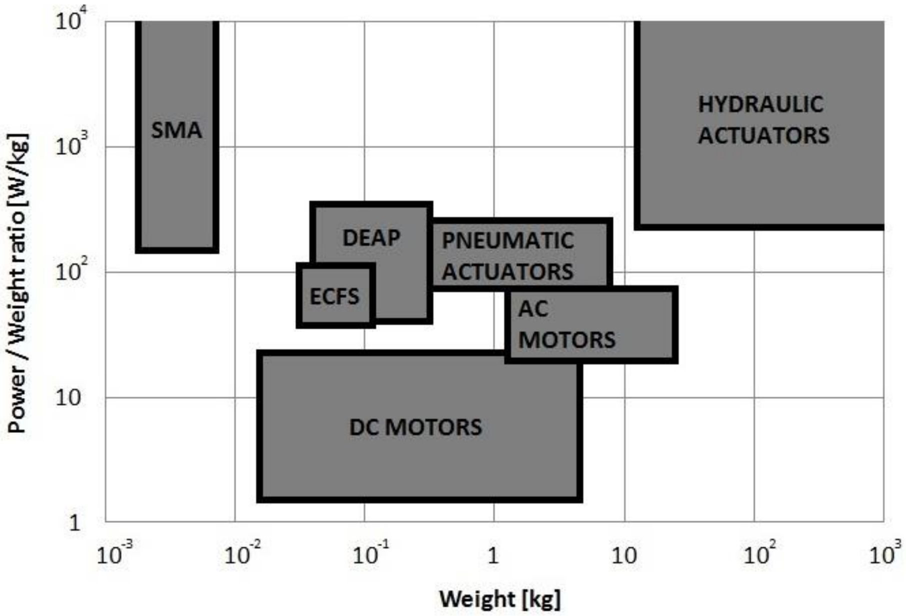


Figure 5-20: Force density of intelligent materials and conventional actuators
Values found in (Mavroidis, 2002) (Nespoli, et al., 2010)

This model considers both conventional and non-conventional actuators. Though, other parameters are not taken into consideration, such as strain, speed and energy efficiency.

Energy density

Figure 5-21 illustrate the various types of intelligent materials' *actuation strain* compared to their actuation stress, which also indicates the material's energy density. This creates, together with Figure 5-20, a more detailed picture of the intelligent materials' actuation. Hence, some materials such as piezoelectric ceramics may have a rather low actuation strain; however, as still are able to create a high actuation stress, their energy density then becomes fairly high. Meanwhile, shape memory alloys both possess a high actuation stress- and strain, creating an energy density of up to 10 MJ/m^3 (Figure 5-21).

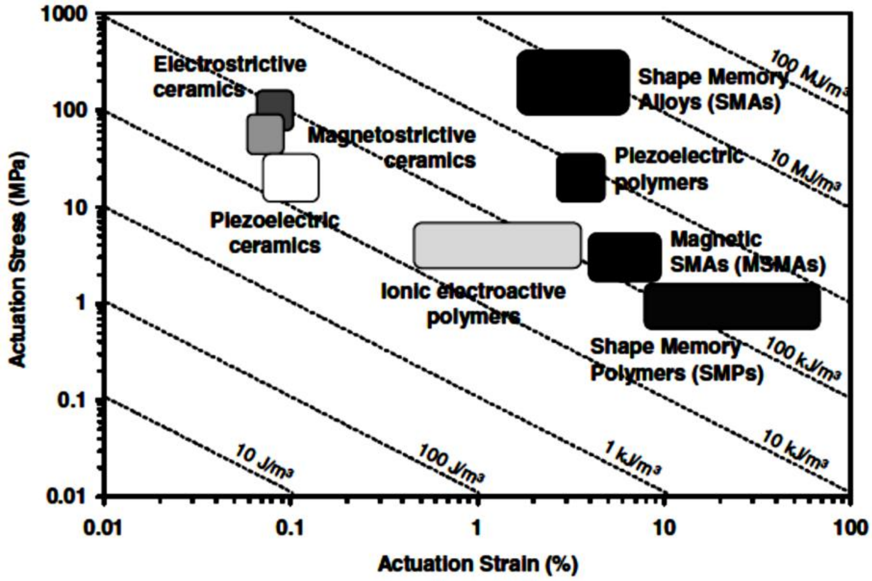


Figure 5-21: Actuation energy density diagram
Indicating typical ranges of actuation stress, actuation strain, and the actuation energy densities of different active materials that exhibit direct coupling (Lagoudas, 2008)

Operational frequency

SMA may show to have the greatest energy density; however, its operational frequency is low compared to other intelligent materials such as piezoelectrical ceramics. Piezoelectrical ceramics´ high operational frequency is well known and is, as mentioned, commonly used to create ultrasound for various applications such as scanning.

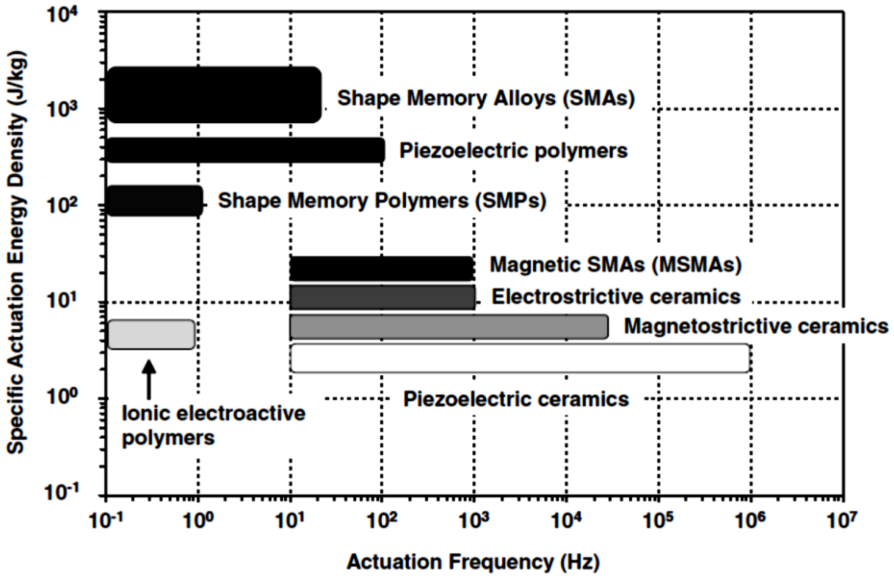


Figure 5-22: Operational frequency diagram
Making comparisons of the actuation frequency ranges of different active materials that exhibit direct coupling (Lagoudas, 2008)

Overall output

The capabilities of the previous mentioned intelligent materials can be summarized into Table 5-2. The capabilities of skeletal muscles are added to this table, as it can help make comparisons to the human arm.

It has to be taken into consideration that these values are the different intelligent materials maximum output. It is recommended that they are used at less harsh values.

It was not possible to find all material capabilities, as there either was missing research due to the intelligent material being new (Nylon 6.6 actuators), varying production (stacked DEAP) or due to the production companies did not provide all details (NiTi-springs). Unfound capabilities are marked with a question mark [?].

Table 5-2: Properties of selected intelligent materials
For the intelligent materials and human skeletal muscles have the capabilities density, actuation stress, stiffness, actuation strain, power density, energy density, life cycles and efficiency been specified. The table describes the materials maximum values. Hence, not that the typical values often are lower.

Class	Subclass	Density g/cm^3	Stress MPa	Stifness GPa	Strain %	Strain rate %/s	Power kW/kg	Energy kJ/m^3	Life cylcles	Eff. %
Skeletal muscle	Human	1.037	0.35	0.06	20	>50	0.284	<40	>10^9	<40
SMA	Fiber	6.45	200 (42)	78	>5	300	>50	> 1000	>10^5	<5
	Spring1.2	?	0,007	?	40.6	300	>50	~1.2	?	<5
	Spring2.17	?	0,012	?	40	300	>50	~1.2	?	<5
DEAP	Rolled	1.11	0.05	0.0011	4	34,000	~0.5	10	>10^6	<80
	Stacked	?	0.16	?	40	34,000	~0.5	10	>10^6	<80
Piezo-electric	Ceramics	7.500	35	40	0.09	?	4.5	>10	>10^8	<60
CNT	Yarn	>0.15	35	1.250	<2	19	0.27	40	>10^6	0.1
Nylon 6.6	Spr. In 1.1	1.15	50	3	9.3	?	27.1	~2.48	?	<1.08
	Spr. In 1.7	1.15	22	3	21	?	27.1	~2.48	?	<1.08
	Spr. In 5.5	1.15	1	3	49	?	?	?	?	<1.08

References:
Skeletal muscle: (Madden, et al., 2004) (Hunter & Lafontaine, 1992) (Baughman, et al., 2014)
SMA: (Madden, et al., 2004) (Hunter & Lafontaine, 1992) (Kim, et al., 2009) (Euroflex, 2014)
DEAP: (Madden, et al., 2004) (Kovacs, et al., 2009) (Danfoss PolyPower A/S, 2012)
Piezoelectric: (Campolo, et al., 2003)
CNT: (Madden, et al., 2004) (A. Krishnan, 1998) (Baughman, et al., 2002) (Baughman, et al., 2004)
Nylon 6.6: (Baughman, et al., 2014)

Table 5-3: Summary of intelligent material performance
Parts supported by (Madden, et al., 2004)

Actuator	Advantages	Disadvantages	Comments
Mammalian skeletal muscle	Large strains (20 to 40 %) Moderate stress (0.35 MPa) Variable stiffness High energy fuel (20-40 MJ/kg) Efficient (~40 %) Good work density (<40 kJ/kg) High cycle life (regeneration)	Not yet an engineering material Narrow temperature range of operation No catch state (expends energy to maintain force w/o moving, unlike mollusk muscle)	Incredible elegant mechanism that is a challenge to emulate. Muscle in a 3D nanofabricated system with integrated sensors, energy delivery, water/heat removal, local energy supply and repair mechanism.
Shape memory alloy	Very high stress (200 MPa,; 42 MPa recommended) Unmatched specific power (> 100 kW/kg) Moderate to large strain (1-8 %) Low voltage Great work density (> 1MJ/m^3)	Difficult to control (usually run between fully contracted and fully extended, but not between) Large current and low efficiency (< 5 %) Cycle life is very short at large strain amplitudes	Readily and available. Generally thought of as slow, but can achieve millisecond response times using short high current pulses and water cooling.
Dielectric elastomers	Large strain (8-34 %) Moderate stress (0.05-0.4 MPa) Large work density (10K – 3.4 MJ/m^3) Moderate to high bandwidth (10 Hz to > 1kHz) Relative low cost Low current Good electromechanical coupling & efficiency (15 % typical, 90 % max)	High voltage (2.5 - 4 kV) and fields (~150 MV/m) Can require DC-DC converters Compliant (E ~ 1 MPa) Pre stretching required	Potential to lower fields using high dielectric materials Small devices are favoured for high frequency operation e.g. MEMS (due to the more efficient heat transfer which prevents thermal degradation, and the higher resonant frequency)
Piezoelectric ceramics	High stress (35 MPa) Extreme operational frequency	Rigid and inflexible structure High voltage Low strain (0.3 %)	It can be hard to work with the small sizes. Readily available for multi purposes.
Carbon nanotube	High stress (> 10 MPa) Low voltage (~5 V) Very large operating temperature range Lightweight (0.15 g/cm^3) Flexible	Small strain (2 %) Currently has low coupling Material are presently expensive	A lightweight fast reacting material, capable of working in high temperatures. It is likely that the production cost will lower
Nylon 6.6	High power density (5.3 kW/kg) High strains (>40 %) Flexibility Fair operational frequency (5 Hz) Low-cost	Poor efficiency (1 %) Short life expectancy Requires high temperature for actuation	An element that are easy to produce, strong, high strain and low cost. Suits application where power consumption are of no concern

CHAPTER 3: METHODS

6 Idea generation

6.1 Brainstorm

A brainstorm session is suitable for when a challenge has been identified, and knowledge needs to be translated into sustainable ideas. Brainstorm can help create a vast number of research based ideas fast

Method

A brainstorming session starts with a topic or problem, which the idea generation then is based upon. The brainstorm works in cycles. First is a session of idea generation performed. It is not allowed to criticise during this session. When the idea generation session is over, the next step is to pick out the best ideas. Another cycle may then start and focus on further development of the chosen ideas. Multiple cycles are performed on top of each other until a satisfyingly detailed idea is obtained.

6.2 Total Design

6.2.1 Product Design Specification

Pugh's *Design Core* for *product design specification* (Pugh, 1991, pp. 44-66) has been used to list and describe crucial design requirements for the application (Figure 6-1). The chart creates a *core*, which can help create an overview of the requirements that are necessary to fulfil for a given product.

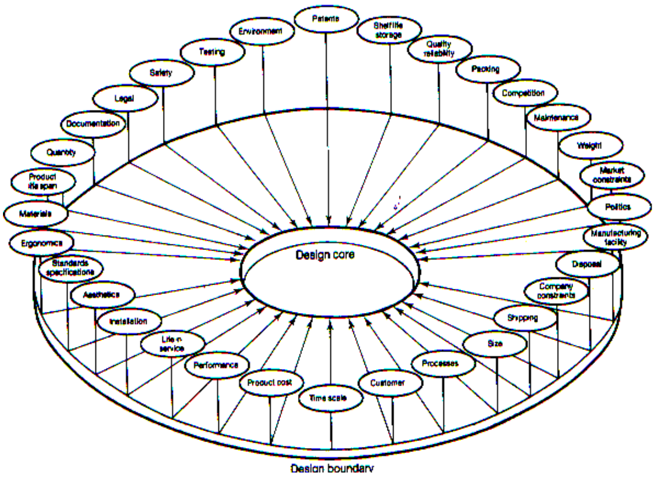
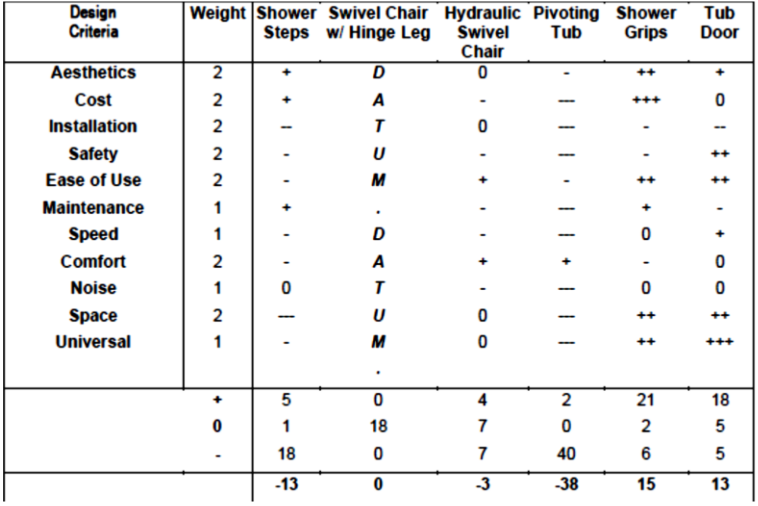


Figure 6-1: Model of parameters making a design core (Pugh, 1991)

6.2.2 Pugh Chart

A Pugh Chart is a strong tool that can help indicate how well the developed ideas actually are following the requirements, that are needed to be fulfilled (Pugh, 1991, pp. 67-100). The Pugh Chart is optimal in early stages of development and can help systemize the selection process. The Pugh Chart is structured with all the design requirements in the far left column (Table 6-1). A weighting factor is the given to each requirement according to how important it is to be fulfilled; for example 1 for low-, 4 for medium- and 9 for high importance of being fulfilled properly. In the first row are all the selected design ideas listed. Each the idea is then given a score of how well it follows the given parameters. The weighting factor is afterwards multiplied with the scores. All the multiplied scores are then summed in the last row, in order to show which idea or object for evaluation best follows the parameters. The design with the highest score is not necessarily the best; though, if the numbers seem incorrect, readjustments of the ratings and weights may then be necessary (Pugh, 1996).

Table 6-1: Example of a Pugh Chart
Ideas to help elderly people balance in showers and transfer in and out of a tub (Pugh, 1996)



Design Criteria	Weight	Shower Steps	Swivel Chair w/ Hinge Leg	Hydraulic Swivel Chair	Pivoting Tub	Shower Grips	Tub Door
Aesthetics	2	+	*D*	0	-	++	+
Cost	2	+	*A*	-	---	+++	0
Installation	2	--	*T*	0	---	-	--
Safety	2	-	*U*	-	---	-	++
Ease of Use	2	-	*M*	+	-	++	++
Maintenance	1	+	.	-	---	+	-
Speed	1	-	*D*	-	---	0	+
Comfort	2	-	*A*	+	+	-	0
Noise	1	0	*T*	-	---	0	0
Space	2	---	*U*	0	---	++	++
Universal	1	-	*M*	0	---	++	+++
			.				
	+	5	0	4	2	21	18
	0	1	18	7	0	2	5
	-	18	0	7	40	6	5
		-13	0	-3	-38	15	13

7 Modelling methods

7.1 Bio-inspiration

Organic shapes can be difficult to work with and applying any rigid type of actuators to. Hence, in order to figure out how to interact better with the organic shapes of the human body, it may then be appropriate to be inspired by biology. This can also be a way to speed up development and help support some designs, which may be well proven in nature. Furthermore, the design that has proven to be far most effective in manipulation and movement of objects is the human arm itself. It can therefore be an advantage to have knowledge of its design and be inspired by the mechanics. Furthermore, it is also the human arm's design and capabilities that is desired to substitute with a prosthetic.

However, it is important not to mix bio-inspiration with bio-mimicking, which are rather following nature blindly and do not consider how well it can be recreated by technology.

7.2 Cad-modelling

In order to model a selected concept, it is then necessary to master 3D CAD modelling software. Links from a mathematical program as *Wolfram Mathematica* and *Excel* to a 3D CAD software as *Autodesk Inventor* were used as a frame and guide for the designs.

7.3 Finite Element Analysis

7.3.1 Stress analysis

Simulation is used to investigate the CAD models reactions to opposed static- or dynamic loads; indicating deformations and fractures (Figure 7-1). This is practical, as it helps to indicate if a structure is capable of withstanding the forces it needs to undergo in practise. The structure is to be indicated sufficient, if the stress from the applied force is less than the yield strength. At the same time it gives opportunities for optimization, as it can tell if some of the structure is over dimensioned.

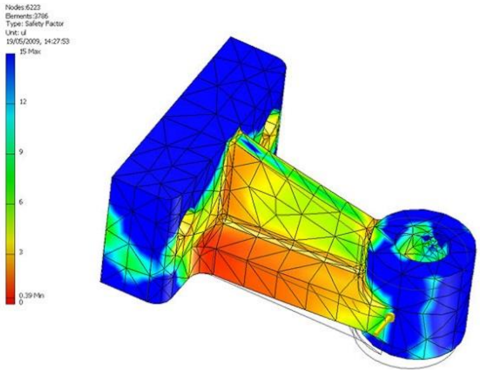


Figure 7-1: Stress analysis example
(CAD/CAM Fundamentals, 2014)

8 Rapid-prototyping

Rapid prototyping is suitable when a functional model is needed and time is limited. A polypropylene prototype was in this project obtained by using a 3D printer named *Strathsys - Object Eden 350* (The University of Strathclyde, 2014).

9 Testing

9.1 Initial product concept testing

A medical product as limb prosthetics first needs to get acknowledged through medical testing, before it can be used in a broader market. Initial, it will not be possible to perform medical testing at any subjects, if the prosthetic still pose worse hazards. Hence, it is needed to perform multiple sets of high level tests of the technology and product itself first; also known as *Utility tests*. The utility tests will prove the products reliability and detect any potential errors (Pugh, 1991, p. 58).

9.1.1 Utility testing

Utility tests typically run in cycles where; 1) the prototype is first developed (or corrected from previous test), 2) then produced, and 3) tested 4) which can indicate any potential errors. This will start another cycle (Figure 9-1). This is done until the safety factors/mechanisms have be proven satisfying.

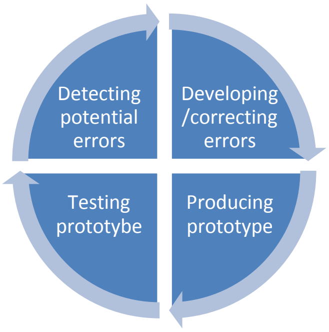


Figure 9-1: Stage one testing indicating the one cycle of testing

9.1.2 Medical testing

The second stage is then the *medical testing*, which will prove the product’s function in contact with a human user.

CHAPTER 4: DESIGN SPECIFICATION

10 Actuator component

Creating actuators with intelligent materials pose unique methodical challenges; however, the requirements for prosthetic actuators increase this challenge. It is not expected that a single material will fulfil all the requirements perfectly, as each intelligent material both has advantages and disadvantages. Instead are some compromises likely to occur. However, these compromises can possibly be adjusted later by other components, such as a strain multiplying mechanism.

10.1 Specifications

10.1.1 Specific power

While the mass is desired to be kept low, the specific power is then needed to be high. A high specific power will ensure a great power output with even a low weight prosthetic actuator. The specific power needs to be high enough to make the powered prosthetic able to obtain similar lifting capability as the human arm.

10.1.2 Size

It is desired that the mechanics of the prosthetics are as compact as possible, as it will give space for cosmetics and enable more mobility in the given space. Thus, the mechanics need to be stream lined and not have any mechanical parts of abnormal shape (Pugh, 1991, p. 54).

10.1.3 Mass

It is important to consider features to keep the mass as low as possible. A high mass makes it harder for users to control the prosthetic and can make it tiresome to use the prosthetic. The mass is strong related to the size of the application (Pugh, 1991, p. 55).

10.1.4 Flexibility

It is desired that the actuator allows some degree of flexibility, as it will allow a more human-like design. Flexibility is required in order to use an endoskeleton support structure,

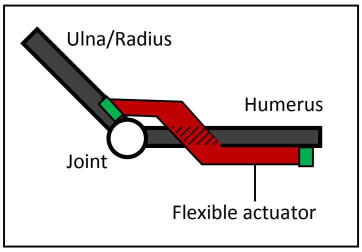


Figure 10-1: Flexible actuator setup Flexibility allows non-linear pathways between attachment points (green area), making actuators able to bend around rigid parts (stratified area).

as the actuators in some cases may need to overlap or create non-linear movements. Hence, the prosthetic's rigid structure will, like bones, reside in the centre, while the actuators will need to have a non-linear pathway around the rigid structure like skeletal muscles also have (Figure 10-1).A flexible actuator will also be applicable in exoskeletons for rehabilitation, as the same challenge is posed; the actuators needs to be able to adapt to the shape of the human body.

10.1.5 Noise emission

Regarding actuators and related mechanism, it is then important to keep the noise emission low or cancel it out completely, if possible. This is to improve the user interaction and obtain acceptance of the device, as mechanical noise has antisocial attributes for some users. Hence, the prosthetic's anthropomorphic attributes can be improved by limiting the noise emission. This may make the interaction feel more natural and as an actual body part.

10.1.6 Safety

Safety is one of the most crucial factors to ensure when working with prosthetics. The usage of the prosthetic is not allowed to pose hazards. Meaning, that if any toxic materials or potential dangerous hardware are used, it will then be necessary to create substantial encapsulation and safety barriers to cover these elements (Pugh, 1991, p. 58). For some hazards it may prove harder to obtain the required safety, which will limit the design.

10.1.7 Service expectancy and maintenance

It is important to consider the service expectancy when designing and performing the utility tests of the actuator. The service expectancy depends on multiple factors such as; size, number of parts, material interactions, friction, constant pressures and impact forces, environment and encapsulations (Pugh, 1991, pp. 50-57).

A good service expectancy can help minimize the cost for the buyer during the usage period. This is due to the little need of maintenance, which minimizes replacement of parts and work hours (Pugh, 1991, p. 50). Lowered need for attention to technical maintenance may also minimize the need for the user to learn about the product details, thereby simplifying the interaction. Hence, a long service expectance and little need of maintenance are factors that create a more satisfying product for the user. The anthropomorphic characteristics may be improved, as the user is not reminded that the prosthetic in fact is a piece of machinery.

10.1.8 Movement speed

Movement speed is an important factor for the user. Slower actuation than a healthy human arm is easily detected by the user and can be of possible annoyance. Hence, the movement speeds of an upper limb prosthetic need to be similar to the human arm in order to have a satisfying and convincing movement and manipulation. The elbow joint shall for example be flexed at velocities up to 200 degrees per second (Table 10-1).

Any lowered movement speed will weaken the anthropomorphic experience of the prosthetic, and may give the user reasons to reject the prosthetic.

Table 10-1: Angular velocity of the human body (Knudson, 2003)

Speed	deg/s
Knee extension: Sit to stand	150
Trunk extension: Vertical jump	170
Elbow flexion: Arm curl	200
Knee extension: Vertical jump	800
Ankle extension: Vertical jump	860
Wrist flexion: Baseball pitching	1000
Radio/Ulna pronation Tennis serve	1400

10.1.9 Operational frequency

While the movement speed needs to be similar to a human arm, it is then also important that the operational frequency is just as high. Hence, it is of no use, if a prosthetic limb only can create a single impulsive movement, for then requiring recharging time before another movement can be initiated. It is important that the prosthetic can make a series of continues movements, where the movement speed does not lower over time. This implies that the joints shall be able to go from being fully extended- to fully flexed position and back again in a short time span. The operational frequency is also indicating the respond time; the delay from any user input to an actual movement. Considering *body-powered prosthetics* (Figure 10-2) that are manually controlled by moving a proximal healthy joint (e.g. elbow flexion transferred to hand grasping), it is then noticeable that the movement

Figure 10-2: Body powered prosthetic (Westcoast Brace & Limb, 2011)

are transferred instantly. Hence, a simple mechanical setup can have a fully satisfying movement speed. This means that any external powered movements need to have a just as low reaction time in order to compete with conventional prosthetics. Any late response may inflict with new user inputs and cause lag.

10.1.10 Precision of actuation

More important are the *actuation precision,* as the movement speed and operational frequency are just the requirements for obtaining a series of desired positions. Hence, the prosthetic needs to follow the user's command inputs with a high precision, whatever it implies a high speed or operational frequency. It can be of annoyance, if the prosthetic's movement is different from the input. Though, there are different methods to create the user interaction, which depends on the hardware, control and sensors. Some system may only be able to make blurry readings of the user's input, while others will be able to read accurately what the desired movement is. High control may be obtained by reading nerve impulses directly through advanced sensors. A vaguer but less invasive control system might use switches as a simple manual control. It is desired that the actuators can be applied to both of these control systems. Thus, the actuation precision needs to be able to follow even the most advanced control interfaces.

10.1.11 Actuation strain

One of the main outputs of intelligent materials when actuated is their strain. Some materials elongate when actuated (some *EAP* and *piezoelectrical ceramics*), while other contract (NiTi, *nylon* and *carbon nanotube*). The strain [ε] is in percentages describing the material's change in length [Δs] compared to its original length [s].

$$\varepsilon = \frac{\Delta s}{s}$$

Actuation strain is used to describe the potential change in length according to controlled impulse. For example can a NiTi-wire contract 4 % when heated.

10.1.12 Hysteresis

The hysteresis describes an actuator's output according to its input. In case of a hysteresis the reaction will then not be linear or direct. Hence, in some cases, it might need to reach certain values in order to activate, while it acquires completely other values to deactivate. The actuation of SMA is an example of this (Figure 5-2).

10.1.13 Energy efficiency

Compared to other mechatronic devices as industrial robotic arms, it is then of higher importance to consider the energy efficiency of powered prosthetics, as they are not coupled to any constant power source. Hence, besides sensors, actuators and microcontrollers, it is then also necessary to implement an energy storage; such as a battery. This adds further mass and complexity to the structure.

Energy efficiency is commonly expressed in percentages and describes; how much of the used energy is actually transferred into mechanical force. The lower the energy efficiency is, the more energy is wasted and the more energy is then needed to be stored for a specific mechanical output. For example, if a motor is 50 % efficient, then there are for a specific actuator output (for example. 1 watt) required to be stored double the amount of energy (thereby 2 watts). This is found by dividing the efficiency with 100 %. Hence, if the actuator is 25 % energy efficient, then it is necessary to store four times the required energy; for 5 % efficient, twenty times are needed and for 1 % it is hundred times. This explains the exponential inverse relationship between energy efficiency and the energy storing factor and emphasizes the significance of great energy efficiency.

Technological advances of batteries can be considered, meaning that more compact and better batteries will be available over time. Though, the energy storage of batteries will still be proportional to their volume and mass. It is therefore still necessary to consider the power consumption of the actuators, as low energy efficiency will require more battery payload. Thus, more battery payload will require the actuators to work harder to position the arm, thereby consuming even more energy. As there are limits to what the prosthetic may weigh, it then means that there also is a limit for the battery mass and thereby storage. Hence, high energy consumption can significantly reduce the running time of the prosthetic. However, it is in general not a wide time span that all the actuators of upper limbs prosthetics are used per day. This may help expand the time between charging- or changing batteries.

10.1.14 Technical maturity

It is important to consider the technical maturity of an intelligent material before choosing. It requires far more development time and a larger work force to obtain a finalized product, when using a less mature intelligent material. Less mature materials requires more time to investigate and develop, if it still are in its research state (Pugh, 1991, p. 54). CNT actuators are an example of this. Furthermore, it can prove a challenge to find an established and steady production of such material. Both EAP and carbon nanotube are considered to be rather immature, as they do not yet have any commercial actuators.

10.1.15 Production similarities

Production similarities indicate how well a given product-line follows the same dimensions and capabilities. The production similarities of a specific product are based on the technical maturity of the parts and the design. If the intelligent material is not technical mature, it is then likely that there will be dissimilarities in the product line. This can overcomplicate any further manufacturing processes, as some parts may no longer fit together or as recalibration may be needed. This will further increase any manufacturing costs.

10.1.16 Learning curve

Developing an actuator with muscle similar capabilities will most likely require a team. It is therefore also necessary to consider the learning curve for the intelligent materials, as all members need to obtain greater insight before they can fulfil their task optimal.

10.1.17 Complexity factor

When developing the actuator it is of high importance to keep the design as simple as possible. An overcomplicated design is harder to produce and is more likely to have errors. A simple design has rather few parts, which also is easier to manufacture. Hence, when developing a design, it is then also necessary to consider the manufacturing process; which machines, tools and methods are going to be used? For example, if some parts are considered to be made in plastic it may then be suitable to use injection molding. In case of using injection molding it is then also necessary to consider the mold itself, how it is connected/separated and how all surfaces will be reached during this. Though, for rapid prototyping this level of manufacturing is very unlikely. Instead are machines such as lathes and 3D printers more likely to be used in a short term project like this.

10.1.18 Production costs

When developing the actuator it is important to consider ways to keep the production price relatively low. This is based on the materials, their technical maturity, production similarities, complexity factor and maintenance (Pugh, 1991, p. 51). A low production price will give a broader spectrum to set the sales price in. In some cases it may be possible to set the price high in order to gain more income for the production company. Though, too high prices can also limit the distribution, due to possible limited budget from buyers. In other cases it may be beneficial to set the selling price low in order to boost the distribution. Though, this will make the company’s income lower. However, this is a strategic choice that is done by sales groups. Hence, they are able to work more flexible, if the production price is low.

10.2 Specifications of material

With knowledge of each of the intelligent materials actuation capabilities it can then be investigated, which material best fulfil the stated requirements for a prosthetic actuator. A Pugh Chart was used for this matter (Table 10-2). Here, each actuator requirement was given a weighting factor of either 1, 4 or 9, defining the importance of it being fulfilled. The materials were valued how well they fulfilled each actuator; where 3 (+++) is the highest score, indicating a complete fulfilment, while -3 (- - -) is the lowest score, indicating a high level of complications. The fulfilment value is then multiplied with the weighting factor and summed to give a total score.

Table 10-2: Pugh Chart defining the most suitable intelligent material
The scoring off the materials is based on their ability to follow the product requirements (section 10.1)

	Design criteria	**Weighting**	NiTi	Dielectric Electroactive Polymer	Piezoelectric ceramics	Carbon nanotube	Nylon
Dimensions	Size	**4**	++	++	++	+++	+
	Mass	**9**	++	++	+++	+++	+++
	Flexibility	**4**	++	+	- -	+++	+++
Actuation	Safety	**9**	0	- - -	-	-	-
	Precision of actuation	**4**	+	++	+++	++	-
	Operational frequency	**4**	+	++	+++	++	-
	Movement speed	**1**	+	++	+++	++	0
	Force density	**4**	+++	+	++	+++	+++
	Strain	**9**	+	+	- -	+	++
	Hysteresis	**1**	- -	++	++	+	+
	Energy consumption	**4**	- - -	++	+++	++	- - -
	Noise emission	**4**	+++	++	-	++	+++
Production	Technical maturity	**4**	+++	+	++	- - -	++
	Learning curve	**1**	++	+	-	- - -	+++
	Production simplicity	**1**	++	-	-	- -	+++
	Production similarities	**9**	++	-	++	0	+
	Production cost	**4**	++	+	-	- - -	+++
	Service expectancy	**4**	+	++	0	++	++
		+	122	96	110	115	129
		0	9	0	4	9	1
		-	14	37	45	38	29
			108	59	65	77	100

11 Practical Usage

It can from Table 10-2 be seen that shape memory alloys (NiTi) was the material that scored the highest. Hence, NiTi has become the preferred intelligent material to use for actuators in upper limb prosthetics. Though, the material by itself cannot fulfil all the requirements satisfyingly. It is therefore chosen to implement a mechanical setup that can help enhance its capabilities and fulfil any compromised requirements; strain, operational frequency and precision. The energy efficiency of NiTi is also unsatisfyingly low; however, it is a parameter that cannot be increased. This may pose problems.

The mechanics shall, as previously mentioned (section 4.5), work as a multiplier of the actuation strain. Hence, multiplier needs to increase the NiTi-wires' 4 % actuation strain with a factor of 5 to 10, in order to obtain a required strain between 20 to 40 % (Table 4-1).

12 Suitable strain enhancement mechanism

12.1 Piezoelectric ceramics

While piezoelectrical ceramics did not score high in the Pugh Chart (Table 10-2), it can then still be of benefit to investigate some possible designs. This is due to the materials high power density, operational frequency and most of all; energy efficiency.

One disadvantage of piezoelectrical ceramics is a low strain of ~0.3 %. However, it might be possible to sum together a series of strains into a larger movement. As the material is able to work at high frequency, it should then be able to obtain 30 % through 100 cycles.

12.1.1 Linear Inchworm [PIEZO]

A *Linear Inchworm* was the first developed idea for a piezoelectric design. This design aims to use small modulated actuator units. Each module consisting of a set of piezoelectric elements that are paired together to make multiple inchworm mechanisms (Figure 12-1), which works by:

1) Actuating the first piezoelectric element, which has ratchet attached to its surface. This creates a connection with a geared shaft that is the moving part, which alter the prosthetic's joint angle.

2) Actuating of the second piezoelectric element push the first element forward, and thereby drags the shaft/wire along.
3) Deactivating both elements, which leads them back to their starting position (Figure 12-1). This makes it possible to initiate another cycle.

The shaft that is being actuated by the inchworm mechanism is the framework of the module (Figure 12-2). Hence, the module structure will contract in on itself when actuated.

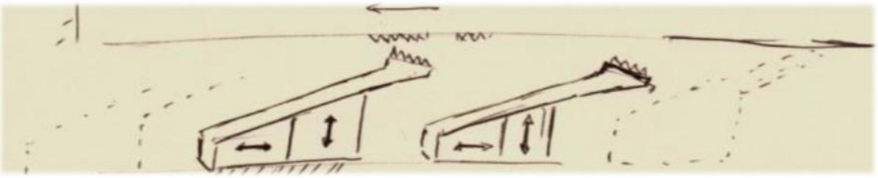


Figure 12-1: Modulated ratchet inchworm mechanism
Two piezoelectric elements are paired together and are actuating in different directions. The rear element creates a vertical movement, which connects a ratchet with a geared shaft. The front element then actuates to drag the shaft forward.

Each actuator module consists of six to eight pairs of (2 x 2 x 2) mm piezoelectric elements (Noliac, 2011), which are arranged in one line (Figure 12-2 A). The pairs are divided into two groups that faces towards each other (Figure 12-2 B). This will drag the module's framework/shaft (Figure 12-2 B, orange) towards the centre from both sides.

The pairs of piezoelectric elements are connected via a wire, which allows flexibility along the modules length. While it is unlikely that a single actuator module alone would be able to create sufficient movement and tensional stress, it is then possible to put multiple actuator modules in <u>series</u> to gain a *larger overall strain* and <u>parallel</u> to gain a larger overall *contraction force*. It is required that the module is capable of contracting up to 20 to 40 % of its length in under a second. This will create a system similar to the myofilaments of skeletal muscles (4.3.1).

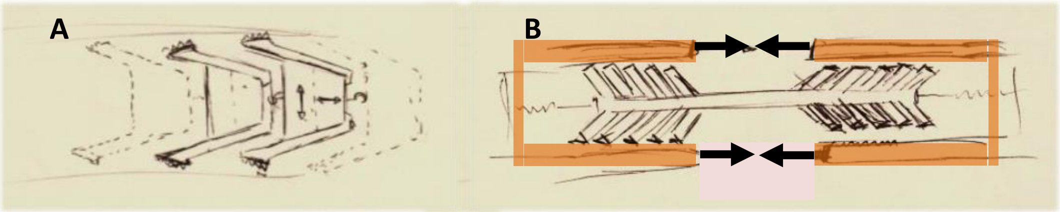


Figure 12-2: Single actuator module of piezoelectric inchworm
(A) Pairs of piezoelectric are positioned in series to increase tensional force [orange]. (B) The module has its elements divided into two groups, which points towards each other, in order to double the contraction speed.

The piezoelectric ceramics are only capable of performing steps of 2.6 µm. Hence, a greater series of contractions is needed to create a sufficient strain. For instance, if one module is 30 mm in length, the actuation will then need to be 12 mm per second to obtain a quick 20 to 40 % strain. This will in total require 4,615 steps, which makes it possible to calculate the operational frequency. Though, note that actuator module contract in on itself from two opposite directions (Figure 12-1 B, arrows). This results in a doubled contraction speed, which sets therequired operational frequency to:

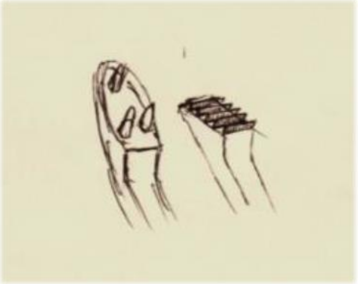


Figure 12-3: Possible ratchet designs for a Piezoelectric inchworm

$$\frac{4615}{2} = 2307.5\,Hz \qquad (8)$$

Hence, the maximum operational frequency the piezoelectric ceramics need to work at is 2,307.5 Hz. This may be low when considering the potential frequency that piezoelectric ceramics can work at. It is although questionable if the piezoelectric ceramics will be able to create a step of 2.6 µm and proper attachments at such frequency.

This ideas greatest challenge is the ratchet (Figure 12-3), as it is difficult to make a proper attachment at the microscopic scale. Hence, while the strain is only of 2.6 µm, the gears connecting with the ratchets then needs to be a tenth of this in length. This is to create multiple attachment points along the actuation length, which is needed to minimize slip. Furthermore, the micro scale ratchets need to withstand pressures as high as 168 N (Noliac, 2011), which makes a long service life seem unlikely. Other mechanisms for ratchets (magnets) were considered, but no type of system seemed to be able to withstand the forces or prevent slips.

12.1.2 Hydraulic pump

As the piezoelectric *Linear Inchworm's* main problem was to obtain a sufficient attachment, it was then considered to use hydraulics. Instead of using mechanical inchworms, the piezoelectric element can then be used to supply pressure and volume changes to a container. Two sets of check valves can be used to direct flow and create a large scale piezoelectric hydraulic pump. The pump mechanism can be compared to that of other piezoelectric micro-pumps (Figure 12-4).

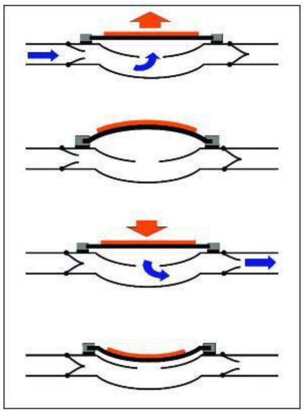


Figure 12-4: Mechanics of piezoelectric micro-pump (Physik Instrumente, 2011)

However, the main challenge will become to ensure the strength of the check-valves and inhibit backflow. A solution may be to create a peristaltic pump (Figure 12-5), which can make directional valves obsolete. Fluid inside a silicone tube will be pumped forwards in waves, by squeezing the tube with a series of piezoelectric elements. Though, the durability of this setup's tubing may be questioned. Furthermore, as the ceramics only have few µm of strain, there is a risk that an elastic tube will absorb the movement.

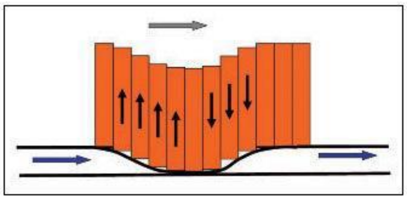


Figure 12-5: The principle of peristaltic pumping (Physik Instrumente, 2011)

12.2 Dieletric electroactive polymer

12.2.1 Linear Inchworm

Usage of DEAP was also shortly investigated. PolyPower was considered the most suitable DEAP. Though, it is then necessary to find a way to increase the strain from 4 % to a minimum of 20 %.

It was considered to create a Linear Inchworm with PolyPower. The design is similar to the idea for the Piezoelectric Linear Inchworm (12.1.1). The piezoelectric elements were just replaced with PolyPower DEAP elements instead. The challenge to create a sufficient ratchet system for this setup is not as critical, as the strain is higher and the stresses are lower. The DEAP material also provides an amount of flexibility to the design.

12.3 NiTi

A large quantity of ideas using SMA was developed, where both NiTi-wires and NiTi-springs were used.

12.3.1 Linear Inchworm

The first idea is to create a NiTi Linear Inchworm that uses ratchets and gears to create a pulling mechanism. This differs from previous inchworm designs, by having the multiplying mechanism more separated from the intelligent material, which in this case are NiTi-wires. Considering the actuator's overall structure, then will the NiTi-wires be attached to the prosthetic as one of the actuator's two attachment points and from there stretch out. The multiplier of the Linear Inchworm will meanwhile stretch out from the actuator's second attachment point.

The attachment of the Linear Inchworm multiplier (Figure 12-6E) starts out with the *Centre-rod* (Figure 12-6 D). The Centre-rod has gear teeth, which are circling around its circumference and continuing along its length (Figure 12-6 D). These gear teeth are meant to interact with ratchets. From the other attachment point (Figure 12-6 A) are eight pairs of NiTi wires (Figure 12-6 B) stretching towards to the Centre-rod. The NiTi wires are assembled in the *Connecter* (Figure 12-6C), which arranges the wires around the Centre-rod and connects them with a ratchet for each pair.

When the NiTi wires are actuated, the Connecter will then use the ratchets to lock them onto the Centre-rod. This will make the wires pull Centre-rod towards their attachment point (Figure 12-6A). By using multiple NiTi-wires around the rod, it is then possible to contract them in series, so their individual strain (4 %) are summed together to a greater contraction (20 to 40 %). Parallel contraction is another possible option, which will amplify the overall tensional force.

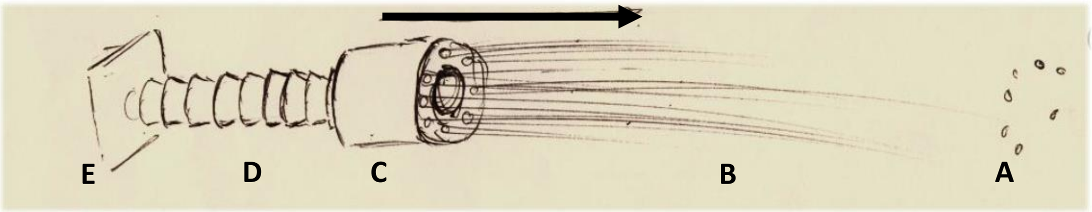


Figure 12-6: Linear NiTi Inchworm
The mechanisms are comprised of five major elements: The first is attachment point (A) that has NiTi wires (B) stretching towards the Connecter (C), which assembles and connects the wires to the Centre-rod (D). The Centre-rod then connects with the second attachment point (E).

12.3.2 Segmented Linear Inchworm

This idea is similar to the Linear NiTi Inchworm. However, instead of having single NiTi wires stretching the entire length to a single mechanical module (Figure 12-6C), it is then considered to segmentize the wires into shorter modulated units. This will create a higher amount of mini mechanisms along the entire length of the Centre-rod (Figure 12-6D). This can help increase the precision and control over the actuation. However, by segmenting the wires, there is then lost some of the contraction speed, but there is also gained a higher contraction force, as more wires can work in parallel.

12.3.3 Rotational Inchworm

NiTi wires can also be considered useful to rotate an axial joint. This can be done in a similar way as the linear inchworm. Here, the NiTi wires (Figure 12-7 A) are instead using ratchets to lock onto- and rotate an axis (Figure 12-7 B and C) rather than shifting a shaft.

The axis can then rotate a prosthetic's joint directly or pull another cable that controls a joint (Figure 12-7 D). Similar to the linear inchworm, these NiTi wires can be used in series and parallel; where serial contraction increases the *angular rotation* and the parallel increases the *torque*. It is also possible to create a gearing factor between the axis rotated by the NiTi wires (Figure 12-7 B) and the drum pulling the cable that alters the joint angle (Figure 12-7 D). Hence, it may be desired that each NiTi contraction of 4 % is geared to make a 10 % pull of the cable.

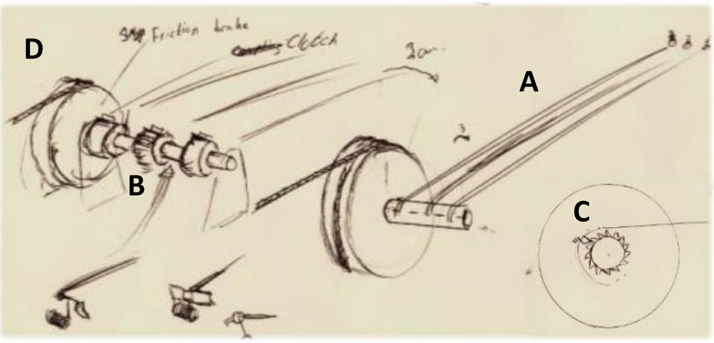


Figure 12-7: Rotational NiTi Inchworm

12.3.4 Parallel contraction

An idea to increase the strain was to cut NiTi-wire into sections an place them parallel to each other. This can be done by connecting each section of NiTi-wire (Figure 12-8A) between two rigid *Legs* (Figure 12-8B). One end of the wire will be connected to the lower end of one Leg, while the other end is attached to the top of a Leg next to the first (Figure 12-8, white dots). This pattern continues so approximately 8 NiTi-wiresare obtained, which create a series of conneted wires and Legs (Figure 12-8C). When actuated, the NiTi-wires then work as if they were one continuous wire, meaning that each wire's contraction percentage are added together ($4\ \% * 8 = 32\ \%$). Hence, when on wire contracts, it will then also move all following sections with it (Figure 12-8 from C to D). Though, the wires are placed in parallel, so the setup's overall length does not increase for each wire put in series.

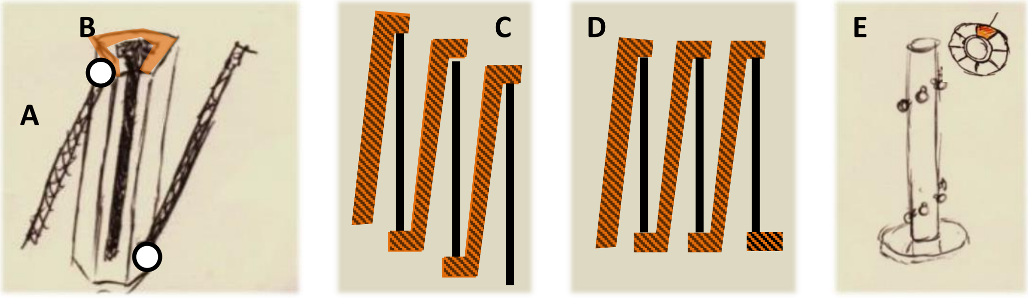


Figure 12-8: Parallel contraction of NiTi wire

This design is similar to one of the micro actuators from the Miga Motor Company (Figure 5-4); however, rather than having a flat base, the wires and their Leg are then assembled around a flexible and round *Centre-shaft* (Figure 12-8E). This creates a flexible actuator that can contract 32 %.

However, it is estimated that this setup's flexibility will be rather limited. It may prove difficult to make the Legs and the Centre-shaft flexible, due to friction and locking of movements. Furthermore, the setup has a large volume compared to the number of wires, which will decrease the energy density.

12.3.5 Pulley system

In the beginning it was considered to use a pulley system to coil up the wire in a rigid system, which would increase the contraction length and maintain most of the tensional output. Though, a common pulley system occupies a large volume of space, as the diameter of the pulleys are spacing out the NiTi-wires. A pulley system does not allow any flexible motion along the fibers either.

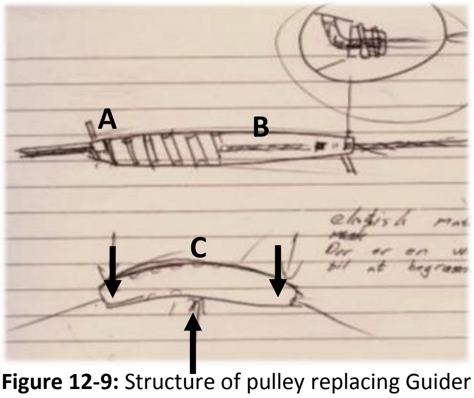


Figure 12-9: Structure of pulley replacing Guider

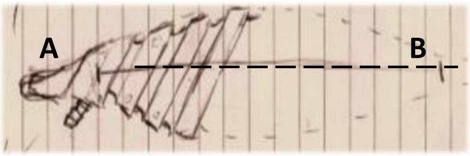


Figure 12-10: Pathway of NiTi-wire guiding system
A helical grove in the Guider, creates a parthway
where the NiTi-wire can reside and glide

It was the thought to create a guiding system (Guider) that maintains the NiTi-wire in a helix shape that is similar to a spring (Figure 12-9A). This way more NiTi-wire will be coiled up in the given length, which then will increase the overall contraction. By using low friction materials for the Guider, it is then possible to lower the friction of the wire significantly and thereby prevent any major loss of the tensile strength produced by the NiTi-wire. Low friction materials as polymers with various composition are commonly used as bushings for the industrial sector. A German company named *Igus* is specialised in manufacturing such bushings (Figure 12-11). They provide services to manufacture (Igus, 2014) or 3D print (Igus, 2014) costummade designs in low friction polymers. This makes it possible to create nearly any

Figure 12-11: Standard
Igus plastic bushing
Used to decrease friction
of rotational axis
(Igus, 2014)

design. Hence, the surface that guides the NiTi-wire can be 3D printet in low friction polymer. It is meanwhile planned that the Guider's supporting structure is made of elastic polymers, which will enable flexibility along the structure (Figure 12-9C).

The NiTi wire will in this setup need to be attached between two points of the prosthetic that makes it cross a joint (to create mobility). Inbetween these two attachement points will the NiTi-wire at some point along its length wind into the Guider. Thus, the Guider's helix path needs to start with a gradual rotation, in order to avoid sharp corners that could lock the wire (Figure 12-10A). As the NiTi-wire can pose a high stress on the Guider, it is then necessary to introduce an element that limit elongation of the structure. This could easily happen as the guider is made of an elastic material. By introducing a *non-elongating wire* through the centre axis of the Guider (Figure 12-9B and Figure 12-10 B), it is then possible to limit elongation, but at the same time allow flexibility.

However, this system can only hold one- or a small bundle of NiTi-wires, which will lower the operational frequency, as the bundle of NiTi-wires heats *close* together. This will increase NiTi-wires' cooling time. Furthermore, a high volume might be taken up by the guiding system, which will lower the energy density. Finally, even small frictions can lower the generated tensile force, which then might put the Guider under a high stress.

12.3.1 2D spring

The simplest design for increasing a NiTi-wire's strain to 20 - 40 %, is to create a *2D spring*. Here it would be necessary to make the NiTi-wire memorise the 2D spring shape for its austenite shape. Hence, it will be possible to stretch the wire when cooled, as it will not provide any significant resistant. However, when heated, the wire will work to obtain its 2D spring shape. The 2D spring shape allows the wire to coil up a more significant distance rather than just the straight contraction of 4 %. As the 2D spring is flat, it will then be easy to add it onto a mechanical structure. Furthermore, the setup has a high flexibility.

However, using a memorised spring shape radically reduces the actuation stress. This is seen in similar Nitinol springs on the market, which has a large volume, good strain, but a poor stress output (Euroflex, 2014).

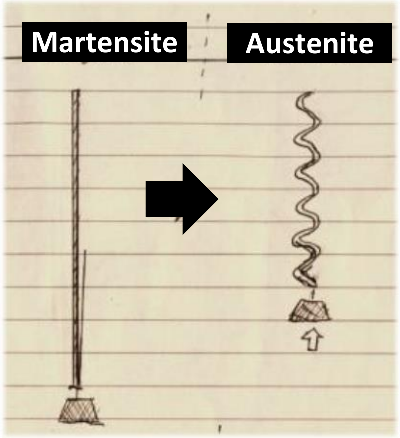


Figure 12-12: 2D spring setup
The springs martensite state is shown on the left and austenite on the right

12.4 Nitinol Hybrid

12.4.1 Rotational Inchworm with Servo motor

It is possible to further enhance the design of the Rotational Inchworm (section 12.3.3) by applying a servo motor to the rotational axis. In this case, the servo motor functions as a positioner of the joint giving energy efficient, smooth, fast and precise movement. The NiTi-wire's task is then to boost the system with extra torque in situations it is required. This creates a hybrid actuator. As the NiTi-wire has a higher specific power (Figure 5-20), it is then possible to obtain a lower volume and thereby a higher energy density compared to a conventional servo motor (Figure 13-12).

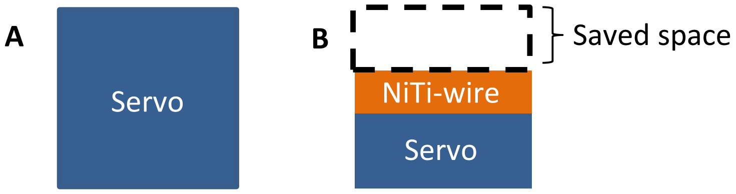


Figure 12-13: Comparison of single servo motor to a Ni-Ti hybrid
Illustration indicating a possible space reduction of hybrid systems. (A) Indicates a volume of a servo motor that can create the required torque, operational frequency and precision. (B) Shows a system fulfilling the same requirements, but uses NiTi-wires to obtain the torque and a servo motor to obtain the remaining requirements. This can lower overall volume, as NiTi-wires have a higher force density (Figure 5-20)

12.4.2 Hydraulic fluid pump

Another possible *hybrid system* can be made by using NiTi elements in a hydraulic setup to create a fluid pump. Inspiration obtained by investigating other studies and patents that use NiTi elements for hydraulics; flexible peristaltic pumps (Sagar & Sreekumar, 2013), large scale usage of Nitinol wires (Mavroidis, 2002), self-priming miniature tube pumps (Shkolnikov, et al., 2010), spring loaded peristaltic pumps (Whitehead & Groom, 1990) and attachment methods of NiTi-wires (Lewis, et al., 2012).

The final idea is both compatible with NiTi-wires and NiTi-springs, and has different assembling configurations of SMA elements (Figure 12-14). It is considered to replace a conventional hydraulic pump with NiTi elements instead (Figure 12-14, indicated by pink colour). The pump works by having the SMAs drag a *piston* inside a *cylinder barrel* during its autenite state. In the autenite state a negative pressure rises in the cylinder body during contraction. This chamber contains hydraulic fluid (Figure 12-14, indicated by orange colour) and has a connection to a reservoir through an inlet check-valve (Figure 12-14, indicated by inlet arrow). Hence, the negative pressure caused on volume expansion will draw fluid into the cylinder body. Furthermore, as the piston is being pulled by the NiTi element, it will then also interact with a constant spring (Figure 12-14, non-coloured spring). This means that in the case a *constant compression spring* is implemented (Figure 12-14 A and D), the spring will then be contracted during the autenite state. Conversely will a stretch occur if a *constant elongation spring* is implemented instead (Figure 12-14 B).

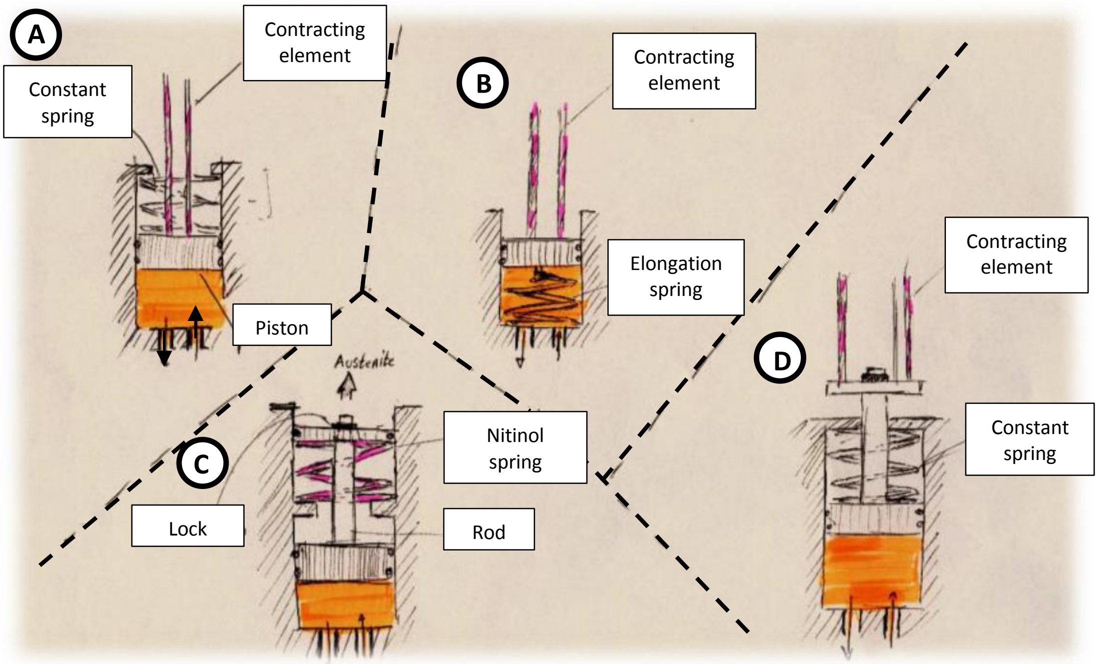


Figure 12-14: Multiple setups for hydraulic pumps using SMA
The orange colour of each figure resembles hydraulic fluid, while the pink colour resembles NiTi elements. The vertical striped part indicates the pistons, while diagonal stripes indicate the boarders of the cylinder barrels. The arrows at the bottom of each cylinder-end-cap indicate the inlet and outlet valves of the hydraulic fluid. Dark dots around the pistons resemble dynamic seals. Setup (A) uses NiTi-wire to draw in fluid and contract a compression spring. Setup (B) uses NiTi-wires to draw in fluid and stretch an elongation spring; the setup has a decreased height as the spring resides inside the fluid chamber. Setup (C) uses a NiTi-spring to draw in fluid in the autenite state and create pressure in its martensite state; a rod and end cap connected to the piston are used to hold the NiTi-spring. Setup (D) also has a rod and end cab connected to its piston; this gives more space for the NiTi-wires as they no longer has to pass through the centre of the spring as in setup (A).

The constant springs are implemented, as they when fully stretched/contracted attribute with a high constant opposite force to the NiTi elements during autensite state. They also have sufficient movement to allow the NiTi elements to undergo their full strain. When the NiTi element then proceeds to cool down, relax and return to its martensite state, the stress induced by the spring will then become dominant. Thus, the spring will now start to create an opposite movement in order to reach its original position; contraction springs will expand and elongation springs will contract. This will put pressure onto the hydraulic fluid, which will create a flow through the outlet check-valve (Figure 12-14, indicated by outlet arrow). Thus, the pressurized and flowing hydraulic fluid can be used to move the actuator controlling a prosthetic joint. However, the flow will be stopped if a subsequent *control valve* to outlet check-valve is *closed*. The constant spring will at the same time maintain the pressure onto the hydraulic fluid. This creates a pistons chamber with pre-pressurized hydraulic fluid that can be stored until needed, which may help counteract SMA's slow reaction time and operational frequency. It is possible to store more pre-pressurized fluid and create a greater flow, by connecting multiple pistons to the same control valve. Analogies can be drawn to how multiple pistons in a crank engine help create a smoother pump, where each pistons' transition between delivering (martensite) and loading (autenite) becomes vaguer in the overall system.

It is also possible to simplify the design by replacing the NiTi-wires and the constant spring with *NiTi-spings* (Figure 12-14 C). This is possible as the NiTi-spring can use two way memory, where a specific shape is memorised for both the martensite- and autenite state. This makes it possible to create a pull on the piston to draw in fluid during the austenite state (like the NiTi-wires), and subsequently pressurize the fluid during the spring's return in martensite state (like a constant compression spring). This can help to decrease the volume and weight of the setup.

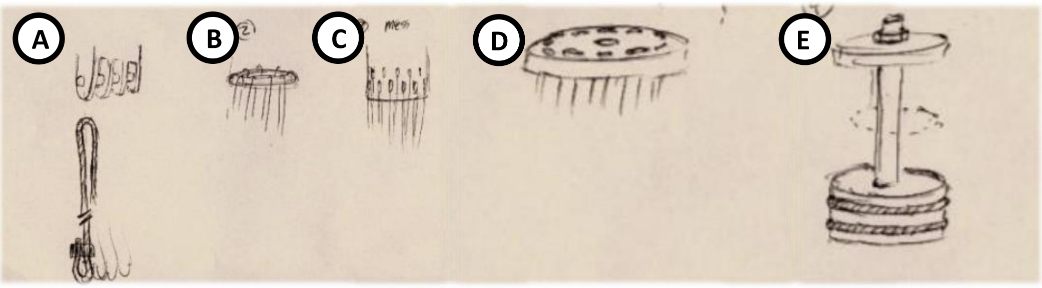


Figure 12-15: Ideas for attachment of NiTi-wires
For ideas (A, B, C and D) for attaching NiTi-wires to a piston (E)

Different attachment configurations for the NiTi-wires were also considered (Figure 12-15), as the wires' high elasticity complicates any fixation. Previous research setups seem to indicate that Figure 12-15 D is the best choice (Mavroidis, 2002). (Lewis, et al., 2012). The attachment setup at Figure 12-15 D does not use multiple sets of wires or fix them at each end. Instead, a single continuous wire is used, which is being looped through each attachment site. Small low friction plastic bushings (Figure 12-16) are used to guide the wires through the attachment panel. This helps decrease the attachments to two; one for each end of the entire wire. These configurations for attachment are also suitable with other ideas.

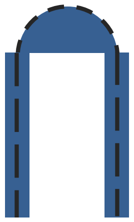


Figure 12-16: Plastic bushing wire guider
The dotted line indicate the pathway

12.5 Specification of multiplying mechanism

With multiple different ideas for a multiplying mechanism, it is then necessary to select a few for further development. A Pugh Chart is again used to guide the selection (Table 12-1). Further unmentioned considerations regarding each idea's fulfilment of the requirements are expressed in this chart.

The chart has a few changes in the requirements compared to the previous Pugh Chart for intelligent materials (Table 10-2). The requirements of an easy learning curve and production similarities have been removed, while a requirement for anthropomorphism has been added. The anthropomorphic requirement details how convincing human-like the overall actuation system is. This depends on some of the requirements specified under *Dimension* and *Actuation, which* are detailing noise emission, tactile interface and movement speed.

Table 12-1: Pugh chart determining the most suitable multiplying mechanism

Design criteria		**Weight**	Piezoelectric - Friction Inchworm	Piezoelectric - Hydraulic Inchworm	PolyPower - Inchworm	NiTi - Rotational Inchworm	NiTi - Linear Inchworm	NiTi - Segmented Linear Inchworm	NiTi - Parallel contraction	NiTi - Hydraulic fluid pump	NiTi - Pulley system	NiTi - 2D spring	NiTi Hybrid - Rotational Inchworm with Servo motor
Dimensions	Compactness of actuator components	**4**	+++	++	++	+	+++	++	+++	+	-	++	+
	Mass of actuator components	**9**	+++	++	++	++	++	++	++	+	+++	+++	-
	Flexibility/Degree of freedom along the axis	**4**	++	+	+++	+	++	+	0	+	-	+	+
Actuation	Precision of actuation	**4**	+++	++	+++	+	+	++	0	++	0	-	+++
	Operational frequency	**4**	+++	+++	+++	+	0	+	-	++	-	-	++
	Speed of actuation	**1**	++	++	++	+	0	-	++	+++	++	+	+
	Force density	**4**	+	+	0	++	++	+++	+	+++	+	--	+
	Strain	**9**	++	++	++	+++	++	++	+	++	+	++	+++
	Hysteresis	**1**	++	++	++	- -	- -	- -	- -	- -	- -	- -	0
	Energy consumption	**4**	+++	++	+++	- - -	- - -	- - -	- - -	- - -	- - -	- - -	-
	Noise emission	**9**	0	+	++	++	++	++	+++	+++	+++	+++	+
Production	Production Cost	**4**	- -	- -	0	++	++	+	++	0	++	+++	0
	Technical maturity of actuator components	**4**	+	+	- -	+++	+++	+++	+++	+++	+++	+++	+++
	Service expectancy	**9**	0	-	++	+	+	+	+	+	+	0	++
	Simplicity of design	**1**	- -	- -	0	++	++	+	++	0	++	+++	0
User	Safety	**9**	-	- -	- - -	0	0	0	0	+	0	0	++
	Anthropomorphism	**4**	++	++	++	+	++	++	++	+	0	+	+
		+	121	105	140	123	**125**	124	111	**127**	100	116	121
		0	18	0	9	9	**14**	9	17	**5**	17	9	5
		-	19	37	35	14	**14**	15	18	**14**	30	30	13
			102	68	105	109	**111**	109	93	**113**	70	86	108

CHAPTER 5: CONCEPT DESIGN

13 Multiplying concepts

The two best ideas according to the Pugh Chart (Table 12-1) are; the *Hydraulic Fluid Pump* using either NiTi-wires or NiTi-springs (section 12.4.2) and the *Linear Inchworm* using NiTi-wires (section 12.3.1). It was decided to develop Hydraulic Fluid Pump into a concept, as it both scored the highest, but also seemed to be the multiplier with the most predictable output. Hence, the idea's design is rather close to that of a standard hydraulic piston's (Figure 4-6), making it possible to draw experiences from these setups.

13.1 Actuator design guide for SMA

When developing an actuator that uses SMA; it is then necessary to consider implementing key elements. First of all, it is necessary to consider the mechanism that shall alter the temperature of the SMA, in order to actuate it.

13.1.1 Decide source of heat for actuating the SMA

In general, there are three different options to heat the SMA element (Dynalloy, Inc, 2014):

- **Air heating** can be used to change the SMA temperature via *convection*. Heating elements together with a fan is commonly used to create hot air and then direct it toward the SMA wire. This system can be rather lightweight, but is likely to create noise and needs pathways for the air.
- **Fluid heating** changes the SMAs' temperatures via *conduction*, which is far more effective than convection. This is usually done by having heat elements to heat fluid and a pump to create a flow. The flow then needs to be guided via tubes to the SMA. However, the system might prove to be far heavier and more rigid than an air heating system.
- **Joule heating** uses *electrical current* to heat up the SMA. Hence, electrical current is lead directly through the element. Depending on the input, joule heating can then create a fast reaction of the SMA; for instance 0.1 second. This system does not add any further weight and does not have any significant noise emission; however, it can pose hazards due to high currents.

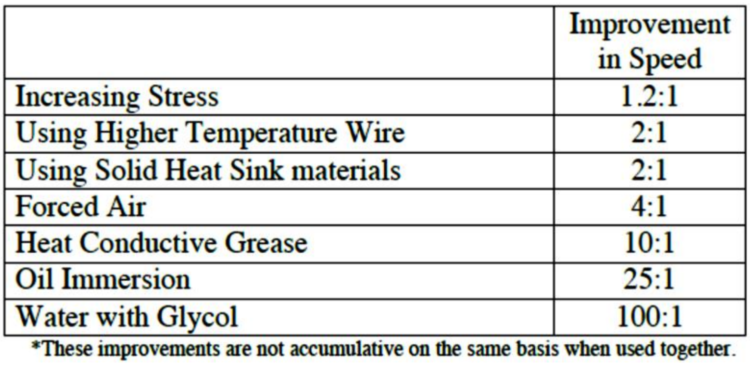
In this project, joule heating has been the preferred choice to reach the austenite state of SMA.

13.1.2 Deciding source of cooling

The cooling methods are similar to those of heating, just with a lower temperature output; air cooling and water cooling (with the exception of joule heating). The simplest cooling method is passive convection, meaning that no cooling system is applied. Instead, the SMA element is cooled by the surrounding air, which takes significantly longer time.

The different cooling methods and their improvement in cooling speed compared to passive cooling are summarised in Table 13-1. However, the usage of cooling has meanwhile not been investigated any further, due to limited project time.

Table 13-1: Relative effect of cooling methods (Dynalloy, Inc, 2014)



	Improvement in Speed
Increasing Stress	1.2:1
Using Higher Temperature Wire	2:1
Using Solid Heat Sink materials	2:1
Forced Air	4:1
Heat Conductive Grease	10:1
Oil Immersion	25:1
Water with Glycol	100:1

***These improvements are not accumulative on the same basis when used together.**

13.1.3 Regulating mechanism

Finally, it is necessary to consider control and regulation of the heating and cooling. Note that some heating and cooling system may be optimal for certain setups. For instance, in a scenario where the joule effect might be used to heat the SMA, while the fluid conduction is used to cool; it can then be considered that the maximum austenite state is reached through the joule effect, the SMA then also opens a valve, which opens the flow of cooling fluid.

13.2 Attachment and structure

The NiTi-wires need to be of substantial length, in order to create a significant strain. It was therefore decided to run the wires as far as possible, in order to increase the strain length and to keep the masses proximal (Figure 13-1). The attachment point of the wires to the lower arm segment therefore needs to be close to the joint-axis to make the strain create the most possible angular movement, while the attachment point to the upper arm segment needs to be as far from the joint as possible. This ensures both long wires and a good angular movement. It also reminds of a biceps brachii's structure and attachment. Finally, the multiplying mechanism is positioned in the proximal end of the upper arm (Figure 13-1, green), in order to lower the momentum on the arm.

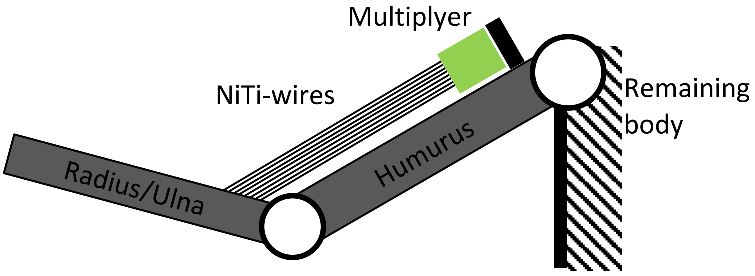


Figure 13-1: Setup of NiTi-wires and multiplying mechanism

In case of using NiTi-springs, the multiplying mechanism will then be exchanged to also fill the space that is occupied by the NiTi-wires in Figure 13-1.

13.3 Required output

Before developing any prototype for proof of concepts, it is then necessary to specify the precise output that is required for the actuator. For the actuator to have similar capabilities to muscles, it then needs to obtain similar values as described in Table 4-1; actuation stress from 0.1 to 0.35 MPa, strain from 20 to 40 % and a specific power from 50-284 W/kg. Due to limited project time, the methods to obtain a similar high operational frequency as skeletal muscles have then been excluded from the project. Furthermore, the efficiency of NiTi materials is far lower, which is unlikely to be improved.

Considering the actuator's task, it was then considered suitable to create a flexor for the elbow joint. This is in the human body performed by the muscles biceps brachii, brachialis, brachioradialis and pronator teres (Neumann, 2002, p. 157). The desired output of the prototype therefore needs create a similar output as these muscles.

Before specifying the actuators' output, it was then first necessary to investigate the required torque. Considering the overall prosthetic's function, it was then found suitable that the actuator [MF] could lift a 5 kg object [LW] in the prosthetic's hand (Figure 13-2 A). This should enable the user to lift even the heaviest everyday objects. The movement should be performed in maximum 1 second.

This required lifting force can through simple biomechanics help specify the required force output of the flexor muscles and thereby the actuator. However, there is for this movement used one actuator similar to the biceps brachii for the project. It is therefore calculated that the entire load is lifted by one element; biceps brachii (Figure 13-2 A), rather than four sub muscles.

The next step is to create a force diagram (Figure 13-2 B), where only the load's weight [LW] is known. The lower arm's segmental weight [SW] has been generally estimated to reform a force of 17 N (Neumann, 2002). Opposite to these forces is the muscle force [MF]. These forces are stabilised in the elbow joint, where the torque also is created. It is generally estimated that the muscle's connection is 5 cm away from the elbow joint [IMA], the weight centre of the lower arm segments is 15 cm away [EMA_1], while the handheld object is 35 cm away [EMA_2]. This makes it possible to calculate the forces interacting:

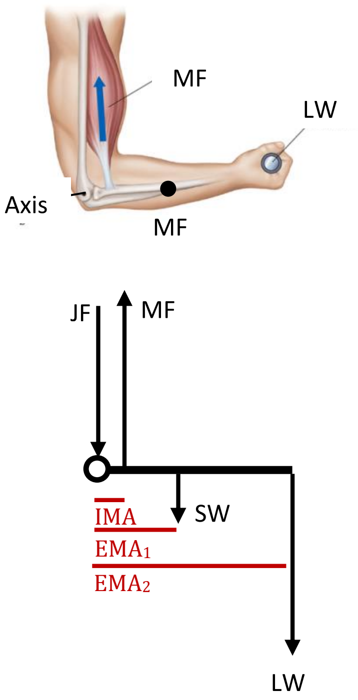


Figure 13-2: Force diagram of the The element interacing during elbow flexion in a human is in this case (A) the biceps [MF], joint force [JF], the weight of the lower arm [SW] and a handheld object [LW]. This is also illustrated in a force diagram (B) (Human Kinematics, 2014)

$$MF * IMA = (SW * EMA_1) + (LW * EMA_2) \qquad (9)$$

$$MF = \frac{(17\ N * 0.15\ m) + (5\ kg * 9.82\frac{m}{s^2} * 0.35\ m)}{0.05\ m}$$

$$MF = 394.7\ N$$

The calculations show that the NiTi elements need to create an output of 394.7 N; however, the output is set to 400 N for simplicity.

13.3.1 Required elements

Hence, the actuating NiTi elements need to create a tensional force of 400 N and a minimum strain of 20 %. With this knowledge, it is then possible to calculate the specific requirements and output information of the system. Nylon 6.6 was included in these calculations, as it has similar capabilities as NiTi-wires and it might be of interest.

The wire diameter [D] of the intelligent material elements was first provided. The dimensions for the NiTi-wires were found through: (Dynalloy, Inc, 2014), while the dimensions of NiTi-spring's were found through: (Euroflex, 2014).

The required multiplication factor [k] is then specified, which describes what multiplication factor the intelligent material needs, in order to obtain skeletal muscles typical strain of 20 % (Table 4-1). This is done by dividing the intelligent materials strain percentage [ε_{im}] with the percentage of skeletal muscles [ε_m]:

$$k = \frac{\varepsilon_{im}}{\varepsilon_m} \qquad (10)$$

$$= \frac{\varepsilon_{im}}{20\ \%}$$

The required cross sectional area of the intelligent material to reach 400 N output is then calculated [A_{400}]. This is done through the known actuation stress [σ] performed by the materials (Table 5-2). The NiTi-wires' actuation stress is set to 42 MPa rather than 200 MPa, as it is recommended from the producers (Dynalloy, Inc, 2014):

$$A_{400} = \frac{400\ N}{\sigma} \qquad (11)$$

The force output of each NiTi element was found through the producers for the NiTi elements (Dynalloy, Inc, 2014) (Euroflex, 2014), while it was calculated for Nylon 6.6 wires by using the actuation stresses (Baughman, et al., 2014) and the dimensions [D]:

$$F = \sigma * ((D * 0.5)^2 * \pi) \qquad (12)$$

This made it possible to calculate the number of elements [N] needed to create a force of 400 N:

$$N = \frac{400\ N}{F} \qquad (13)$$

Next was the focus of the operational frequency [f]. The frequency depends on reaction time [R] and passive cool down time [C]. The reaction time is determined of how fast the element can be heated, which for NiTi elements depend on the electrical current and can be as low as 0.1 seconds (Lagoudas, 2008). For Nylon 6.6 it depends on the heating fluid and has been measured to be 0.1 seconds (Baughman, et al., 2014).

Finally was a factor calculated, which describes how much energy is needed to be stored compared to what is used [E_S]. This factor depends on the energy efficiency [E_f] given in Table 5-2, which is compared to a 100 % usage:

$$E_S = \frac{E_f}{100\ \%} \tag{14}$$

These values is summated into the Table 13-2

Table 13-2: Defining the actuator characteristics
All individual values describing the material's capabilities in Table 5-2 have been reformatted to describe requirements to obtain same output as a biceps brachii, here; the dimensions [D], required multiplication factor [k], required cross sectional area to obtain 400 N [A_{700}] with given stress, factor considering required energy compared to actual output [E_S], stress produced [F], required elements to obtain 400 N of force [n], reaction time [R], *passive* cooling time [C_P] and operational frequency [f]

Class	Subclass	D [mm]	K	A_{400} [mm^2]	F [N]	n	R [s]	C_P [s]	f [s]	E_S
SMA	Wire	Ø0.10	5	9.4	1.4	1,489	0.1	0.18	10	20
		Ø0.25	5	9.4	8.8	239	0.1	5.4	10	20
		Ø0.51	5	9.4	35	58	0.1	16.8	10	20
		Ø1.00	5	9.4	134.4	15	0.1	~50	10	20
	Spring 1.2	Ø24.30	0.5	57,440	3.2	61	0.1	?	10	20
	Spring 2.17	Ø34.76	0.5	34,140	11.1	18	0.1	?	10	20
Nylon 6.6	Spr. In 1.1	Ø0.50	2	5.7	55	15	0.1	?	5	92.6
		Ø1.00	2	5.7	220	4	0.1	?	5	92.6
	Spr. In 1.7	Ø0.50	0.9	19.1	16.5	22	0.1	?	5	92.6
		Ø1.00	0.9	19.1	66	6	0.1	?	5	92.6

It was chosen to work with Ø0.51 NiTi-wires, as they both can provide a high tensile output, while not having a too severe cooling time either. Any lower diameter than 0.5 mm will require a too high number wires, in order to obtain the correct output. This would also prove difficult to attach.

13.4 Hydraulic

13.4.1 Individual piston design

The first step in developing a hydraulic fluid pump was to detail a pump (Figure 13-3).

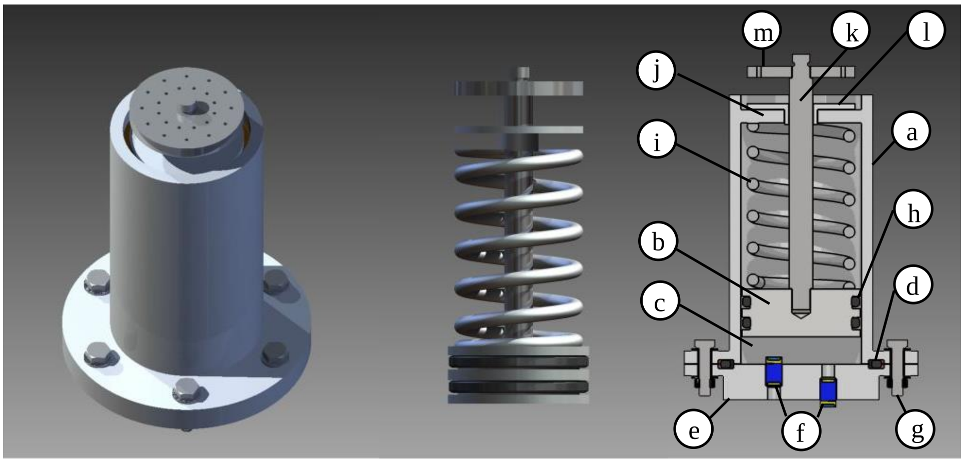


Figure 13-3: Setup for single hydraulic piston
The hydraulic piston consists of a set of components, which are the cylinder barrel [a], piston [b], hydraulic liquid [c], sealing o-ring [d], end-cap [e], check-valves [f], bolts [g], dynamic seals [h], compression spring [i], cylinder cap [j], metal rod [k], plastic bushing [l] and attachment plate [m].

The setup has a cylinder barrel, which contains piston and liquid. An O-ring between the cylinder barrel and the end-cap creates a seal that prevents leaks. Two miniature check-valves (Figure 13-4) from *Altec Products Ltd.* are attached to the end cap with different directions. Six bolts are used to merge the end cap together with the cylinder barrel. Two dynamic *Lionsele®P* seals (Figure 13-5) from *James Walker* are attached to the piston in order to prevent leaks of the fluid (James Walker, 2014). One constant *1803 compression spring* from *Lesjöfors Stockholms Fjäder AB* (Figure 13-6) is put in between the piston and the cylinder cap. A metal rod extending through the cylinder cap is screwed onto piston. A plastic bushing is used to stabilize the metal rod and lower its friction when travelling. An attachment plate with several Ø0.7 mm holes for the NiTi-wires is locked onto the top of the metal rod, using a lock-ring.

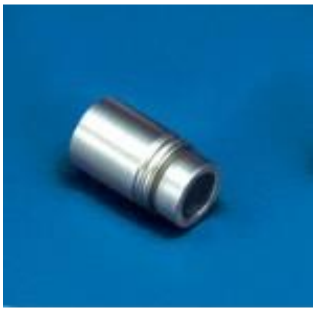


Figure 13-4: Miniature check valve
(Altec Products Ltd, 2014)

Figure 13-5: Dynamic seal Lionsele®P
(James Walker, 2014)

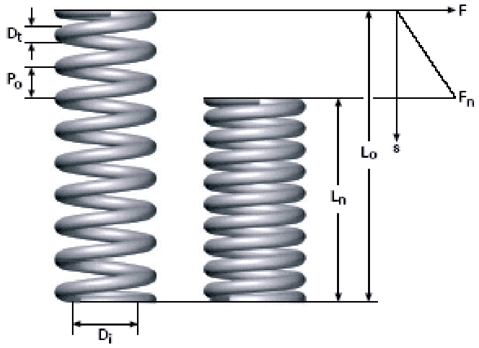


Figure 13-6: Schematics of spring 1803 (Lesjöfors Stockholms Fjäder AB, 2014)

Dt	4
Di	28
L_0	55
nt	6,3
P_0	10,6
Ln	31,4
Fn	376
c	16

Table 13-3: Parameters of spring 1803 (Lesjöfors Stockholms Fjäder AB, 2014) Suitable to be opposite force of NiTi-wires

13.4.2 Complete design

Six of the previous described pistons were used in the final design (Figure 13-8). Here they are arranged in a circle. In the centre of this circle is the actuating piston located. Thus, the output from each of the pumping pistons is guided to the actuating piston. Instead of building the pistons separately, the pistons were then merged into one aluminium block. This makes the design easier to produce and more compact.

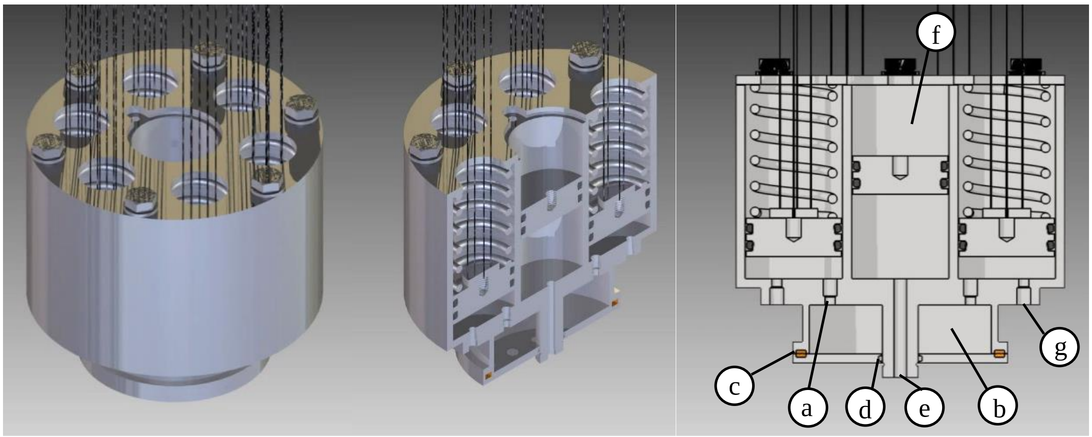


Figure 13-7: Final design for hydraulic pump using NiTi-wires
The hydraulic pump have a set of features as the *inlet check-valves* [a], a fluid reservoir [b], an o-ring sealing the lid's outer rim [c], another o-ring sealing the lid's inner rim [d], an air-releasing tube [e], outlet check-valves [g] and fluid chamber of the actuating piston [f].

The overall structure has a diameter of 136 mm and is 134 mm tall. Each piston has an inlet check-valve that is connected to a room in the bottom of the multiplier (Figure 13-7). This room functions as a reservoir for the fluid. It has two O-ring to seal the lids outer rim and tube going through the centre. The tube is used to release air beneath the actuating piston, for when the hydraulic fluid is guided into the top. The pistons' outlet check-valve is connected to the actuating piston via tubing (not shown in the figure).

The pumping pistons have the same cross sectional area as the actuating pistons. This means according to formula (5) that the force acting on the pumping piston (by the NiTi-wires) will be of the same size, when transferred to the actuating piston (no reduction). This means that each pump only will deliver little movement (4 % of the overall length of the setup). A higher strain is obtained by using the 6 pumps in series, as their movement of the actuating piston will, added together, obtain up to 24 % of strain ($4\% * 6 = 24\%$).


Figure 13-8: The hydraulic design separated

13.4.3 Status – DISCARDED

The design was ultimately discarded, as it was far too large, bulky and heavy compared to the application. Hence, the actuator will not only distort the shape of the prosthetic, but it will also be heavier than the prosthetic itself in most cases. It was calculated that the setup will weigh more than 7 kg.

This significant increase in dimensions was due to the implementations of the constant compression springs, as their performed stress was rather low compared to the occupied space. This meant that compared to the high force generated by a set of Ø0.51 mm NiTi-wires, it was then necessary to use springs that were 30 mm in diameter and up to 55 mm high. This decreased the overall stress (N/mm^2) created by the setup load to an output much poorer than muscles, which can be observed in Table 14-1. Furthermore, it was also a challenge to ensure proper seals of each piston.

13.5 Linear Inchworm

The failure of the first design led to the development of the second highest scored idea for multiplying mechanism; the Linear Inchworm (section 12.3.1). This concept uses up to 8 pairs of NiTi-wires of Ø0.5; where the wires are actuated in series in order to gain more strain.

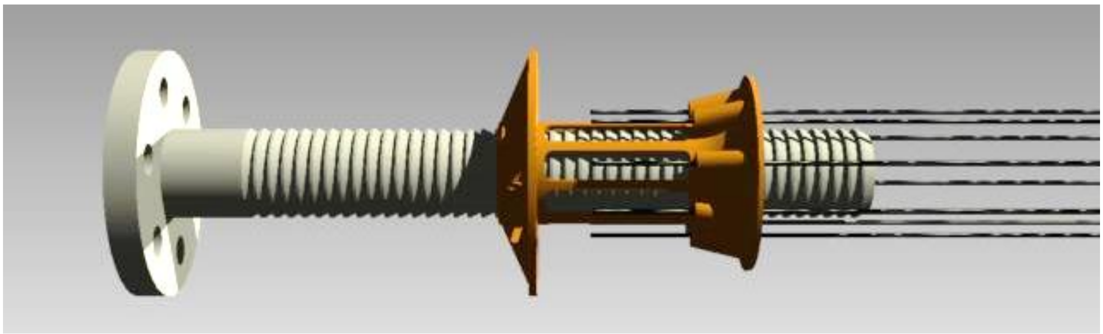


Figure 13-9: Concept of the Linear Inchworm multiplier
The Centre-rod resembled in grey is of stainless steel. The Guider in orange is a flexible piece of plastic.

13.5.1 Centre-rod

As mentioned in the description of the idea (section 12.3.1), there are two main components; the C*entre rod* and the G*uider* (Figure 13-9). The Centre-rod is 95 mm long (where 80 mm is for travel range), 11.6 mm in diameter, and has six Ø4 mm holes for its attachment to the lower arm (Figure 13-1).

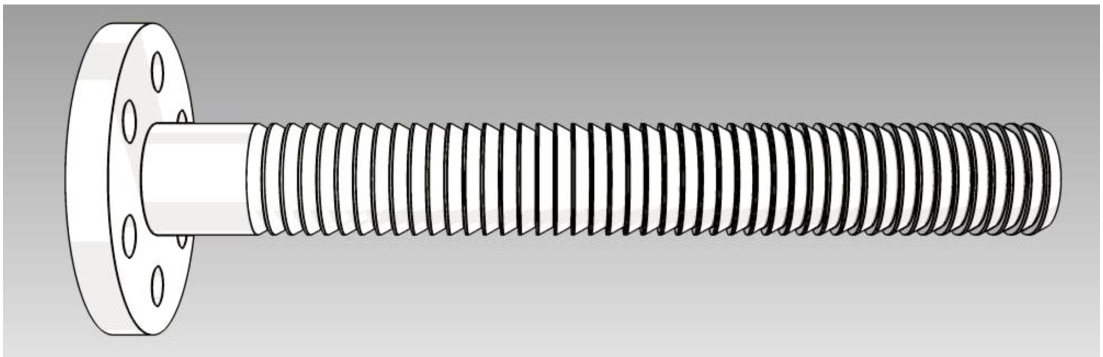


Figure 13-10: Design of the Centre rod
Holes in the base enable attachment of the rod, while gear teeth along the length creates grip for the ratchets.

It was considered to implement flexibility in the Centre-rod for later designs. This could be done by segmenting each circular gear-tooth and enable them to slide on each other. The segments could then be locked together by running a wire through the centre and fix it at each end. This reminds of the design for a pulley system (Figure 12-10 B).

13.5.2 The Guider

The gear teeth along the Centre-rod enable the *Guider* to let the NiTi-wires connect with the *Centre-rod* via its ratchets. The Guider itself is made of plastic (Figure 13-11), is 29 mm long and 25 mm in diameter. The eight holes in its front are meant for guiding the NiTi-wires to the ratchets (Figure 13-11 C and D). Eight rectangular punctures are made into the Guider (Figure 13-11 B). These punctures give the ratchets space to connect with the Centre-rod. A set of rectangular holes were made into the radial surface to attach elongation springs for positioning the ratchets (Figure 13-11 A)

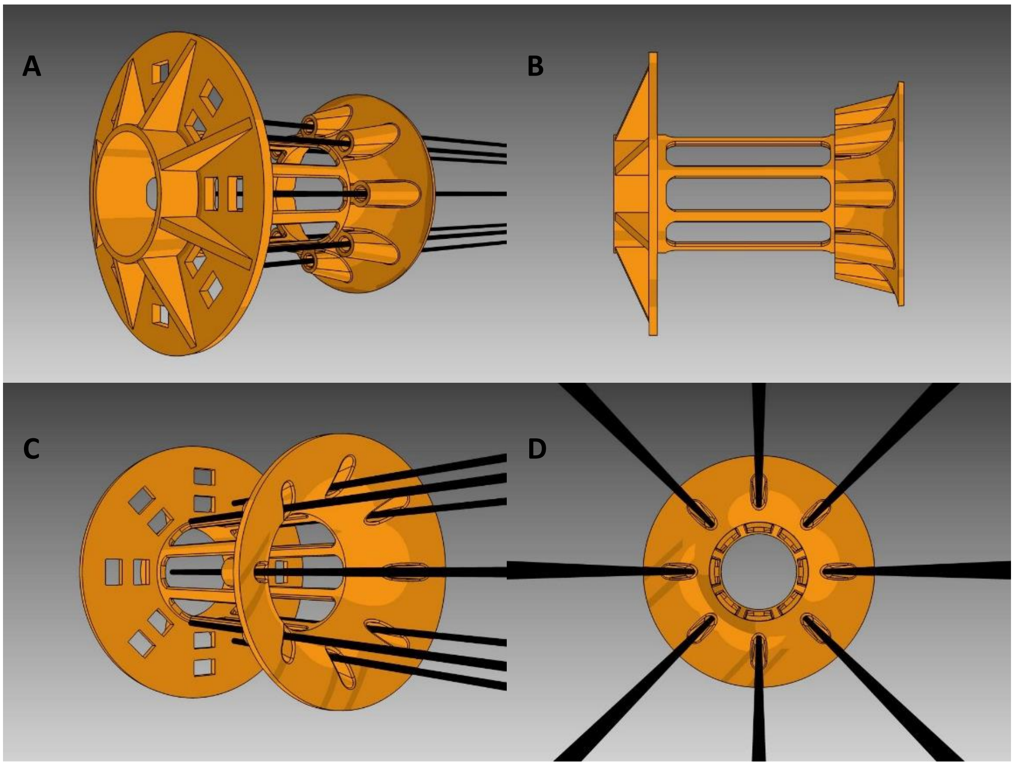


Figure 13-11: Rotational view of the Guider
There are three major details of the design. The radial backcover is used to attach the clamping mechanism of the ratchets (A). Rectangular punctures along the shaft give space for the ratchets to connect with the Centre-rod (B). Holes in the front guide the NiTi-wires to the ratchets (C and D). The front is shaped as a funnel, which help guiding the Centre-rod to the Guider in case the rod is bended (C).

13.5.3 Inchworm

The inchworm mechanism is dependent on the ratchet, which the NiTi-wire is connected to (Figure 13-12). For the inchworm to work it then needs to fulfil a four step mechanism. This is illustrated in Figure 13-13, where the pathway of the ratchet according to the Centre-rod is shown. Each of the paths requires a different mechanism and is resembled by an arrow; 1) first the ratchet connected to the Centre-rod by the *Clamp mechanism,* 2) the

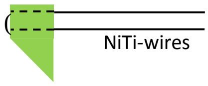


Figure 13-12: NiTi-wire looping through ratchet

NiTi-wire then contracts and pulls the centre rod along, 3) a *release mechanism* is afterward used for finally 4) having an elongation spring stretch the NiTi-wire and return the ratchet to its start.

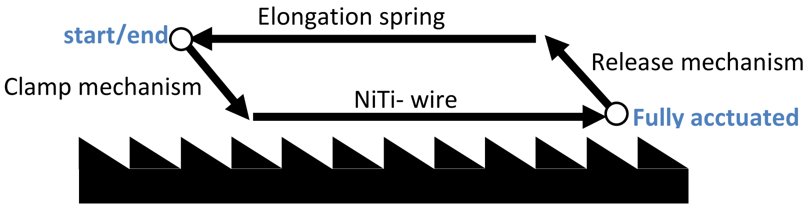


Figure 13-13: Movement of ratchets along the Centre-rod

13.5.4 Status – DISCARDED

Multiple ideas for a clamp and release mechanism were developed, where some seemed possible. However, each idea met the same problem and limitation; the limited space for the mechanism was only of a few millimetres in each direction. This did not only make it hard to develop and manufacture the mechanism, but it also made it unlikely that the mechanism would endure the high forces posed by the NiTi-wires and the elongation spring.

It also proves tricky to develop a prober attachment to the Centre-rod. This is due to the curved gears, which give less surface area for the ratchets to hold onto. Another problem with the mechanism is to disable the ratchets' attachment completely, which is needed if the Centre-rod shall move in reverse. Finally, the setup is not using the given space as optimal as it could.

13.6 Modulated inchworm

The failure of the Linear Inchworm was, among other, due to the rounded shape that complicated any ratchet mechanism. The round shape also made it difficult to put multiple modules in parallel. Thus, it was considered necessary to create a more modulated, simple and flat design. This led to a completely new concept; the *Modulated Inchworm*.

13.6.1 Base

The setup's first component is its *Base* (Figure 13-14), which is a key structure of the frame. Each module is mounted on top of the Base, which creates an actuator stack. The flat surface of the Base allows the modules' *Casings* to slide sideward, which is used for the *reverse mechanism.* The sides of the Base also function as a guide and a limiter of the reverse mechanism of the modules on top. This makes the modules able to shift 5 mm sideways.

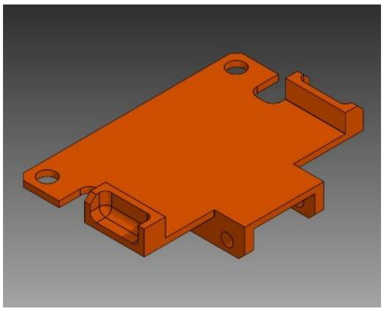


Figure 13-14: The Base of the Modulated Inchworm

13.6.2 Drag plate

The *Drag-plate* is another key in creating movement. It is also the only part, which is directly connected to the prosthetic beside the NiTi-wires (Figure 13-1), which makes it the only static rigid part of the setup. The remaining parts use the inchworm mechanism to crawl along the Drag-plate (thereby shortening the structure). The Drag-plate is 92 mm long, 52 mm wide and 4 mm thick. Along the length are 5 rows of 63 intruded gear teeth, which are used to connect with the *Slider-ratchets* (Figure 13-16).

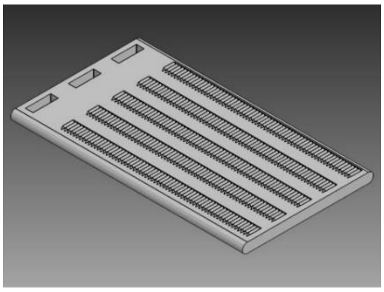


Figure 13-15: The Drag-plate

Three rectangular holes at the end of the plate are used to connect the Drag-plates from each module. This will ensure that a step onto any of the Drag-plates from the inchworm mechanisms also will move the remaining Drag-plates.

13.6.3 Slider

The *Slider* is the component that creates the setups inchworm mechanism. It is 33 mm in length, 8.6 mm wide and 5 mm high. A ratchet is located in the Slider's centre (Figure 13-16 B, orange). The *Slider-ratchet* is attached to the *Slider-house* with a small Ø2 mm axis (Figure 13-16 A). This makes the ratchet perform angular movements. A torsional spring is also attached to the axis (Figure 13-16 A and B) and is used to create a torque between the Slider-ratchet and the Slider-house, which forces the ratchets to rotate outwards (Figure 13-16 C). This rotation is used to make the Slider-ratchet interlock with the Drag-plate. This interlocking is done with the small tooth at the end of the Slider-rachet, which is angled perpendicular to rotational axis. The Slider is actuated by a single NiTi-wire, which loops around the Slider-house twice (Figure 13-16, black). The *Slider-tail* is used to narrow the wires together (Figure 13-16, yellow), so that they can travel through the centre of a compression spring (Figure 13-16 D). The Slider-tail also puts slightly pressure on the NiTi-wire, in order to fix it around the Slider-house.

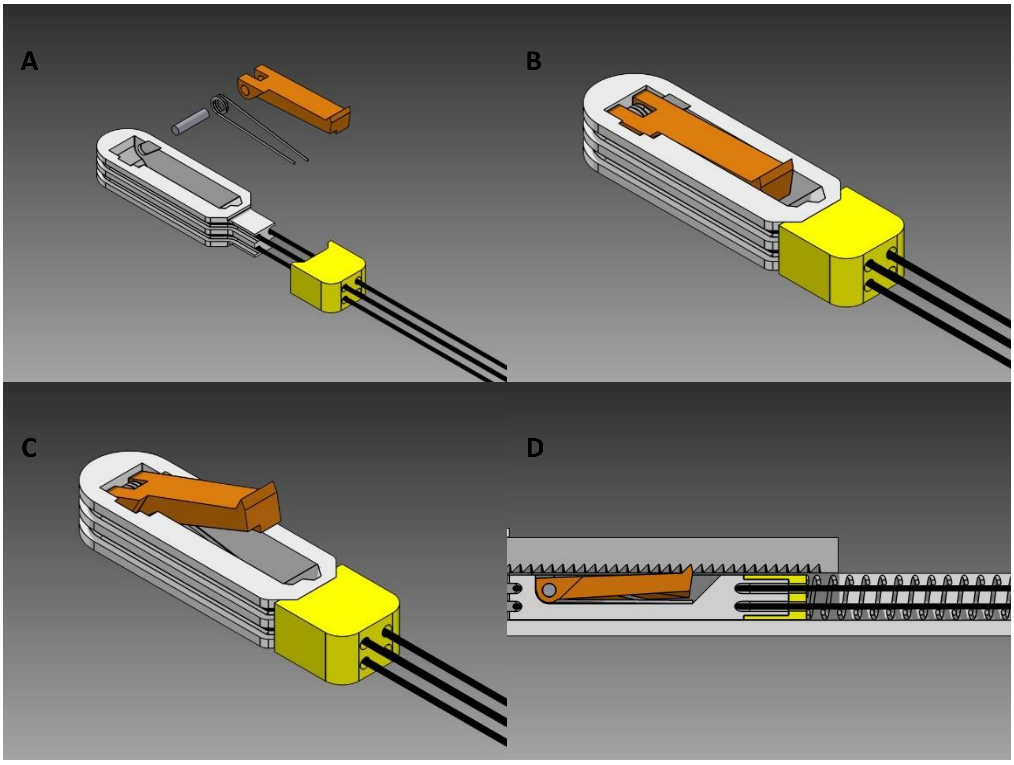


Figure 13-16: The Slider and its subcomponents

The Slider works in four phases as described in Figure 13-13; the torsional spring is used as a clamp mechanism to attach with the Drag-Plate, the NiTi-wire creates a pull, while a compression spring returns the Slider to its original position. Though, the Slider does not have any release mechanism, meaning that the ratchet always will be forced onto the Drag-plate above. Hence, the torsional spring will be pushed down by the Drag-plates' gear teeth, when returning to the original position. This is possible due to the angle between the Drag-plate's gears and the backside of the Slider-ratchet's tooth.

13.6.4 Casing

The Casing is used to create pathways needed for the Sliders' inchworm mechanism (Figure 13-17), when they are being pulled by the NiTi-wires. The Casing is also a key component of the setup's frame and structure. It has four holes, which are used to connect with other modules in the stack. There are used 5 mm high spacers in between the modules (Figure 13-17), to make space for the Drag-plate. In the front of the Casing are two holes, which are used to attach the *Spring-holder* (Figure 13-17) for the compression springs.

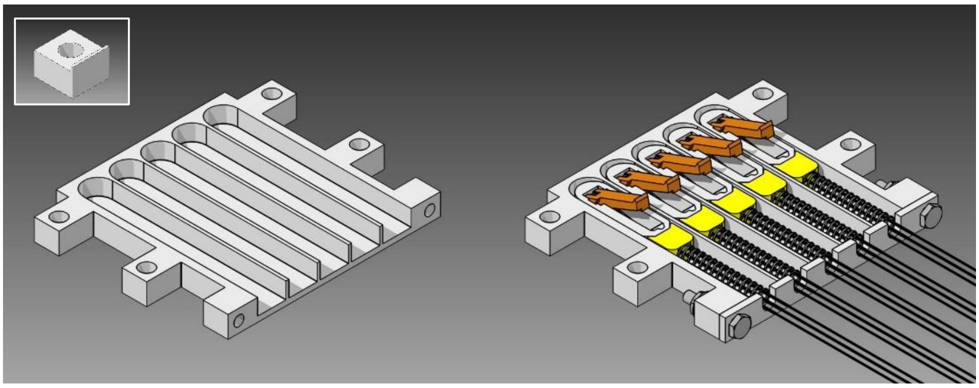


Figure 13-17: The casing

13.6.5 Plastic bushing and Pylon

In order to make the Drag-plate move smoothly according to the Sliders' inchworm mechanism, it is then necessary to implement the *Plastic-bushing*. The Plastic-bushing is made of polymer that has a very low friction against metal (also described in section 12.3.5). Furthermore, the Plastic-bushing also helps to stabilize and guide the Drag-plate.

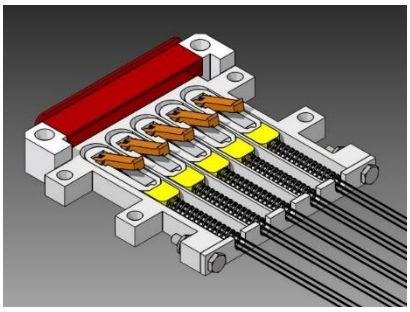


Figure 13-18: Addition of the Plastic-bushing and the Pylon

The *Pylon* is the backbone of the multiplier, as it is connecting Drag-plates of each module to the Base. The Pylon is also used to interlock the Casing and allow 5 mm of movement at the same time. This feature is used in the *reverse mechanism.*

13.6.6 Module

Table 13-4: Module parts

Part	Units
Casing	1
Spring holder	1
Pylon	1
Plastic bushing	1
Drag plate	1
Slider-house	5
Slider-tail	5
Slider-ratchet	5
Torsional spring	5
Compression spring	5

These parts can be assembled to form a module. Each module consists of 6 different general parts, while it counts for 30 parts separately (Table 13-4). To summarise; there are 3 parts significant for the frame - the *Casing*, the *Spring holder* and the *Pylon*, and 2 parts to enable motion - the *Plastic bushing and* the *Drag plate.* There are for the inchworm mechanism of each module used 5 *Sliders,* each consisting of 5 parts – the *Slider-house,* the *Slider-tail*, the *Slider-ratchet*, a torsional spring and a compression spring.

Together these parts form one module (Figure 13-19 A), which can be stacked together with others (Figure 13-19 B). The only part that is not duplicated with each module is the Base, as only one is required to assemble the actuator.

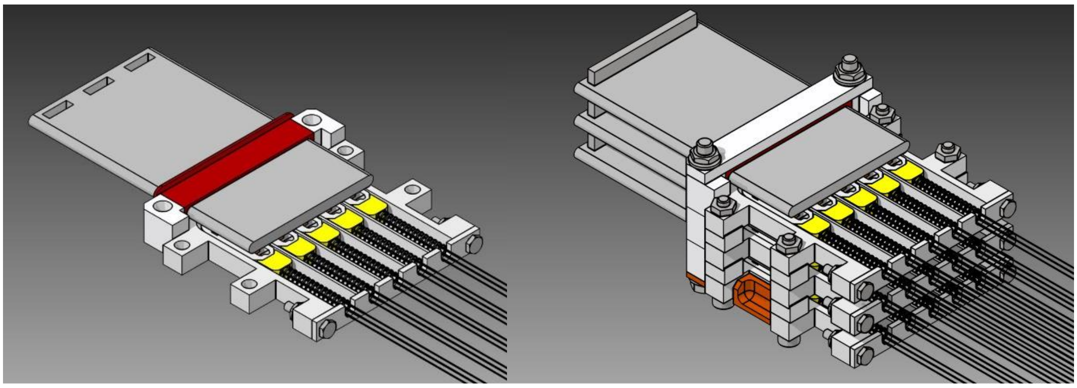


Figure 13-19: A single module and a complete Modulated Inchworm

13.6.7 Stacked Inchworm mechanism

The 5 Sliders of each module make it possible to create 20 % contraction, if they are actuated in series ($4\,\% * 5 = 20\,\%$). Hence, each module that is added to the setup provides further strength to the overall actuator. This is done by contracting the module's Sliders parallel to each other. For example, if an actuator has 3 modules stack, it will then actuate the 15 Sliders over 5 steps. This means that 3 Sliders will actuate in parallel in each step. As each Slider provides 140 N of tensional force, this then creates an overall actuation with a strain of 20 % and tensional force of 420 N. However, it is also possible to adjust the ratio between serial and parallel contraction. For instance, all the Sliders can be contracted in parallel, if it is desired to create a much higher force, which will result in an tensional force up to 2100 N ($15 * 140\ N = 2100\ N$). This will on the other hand lower the strain per actuation to just 4 %, which will significantly increase the time before 20 % is obtained, as the NiTi-wires need to cool down between each cycle.

The Modulated Inchworm (Figure 13-20) reminds to some extent of the skeletal muscle's sarcomere (Figure 13-21). The multiple layers of inchworm mechanisms have similarities to the myolin strands which in muscles create movement. Meanwhile reminds the function of the Drag-plate of actin.

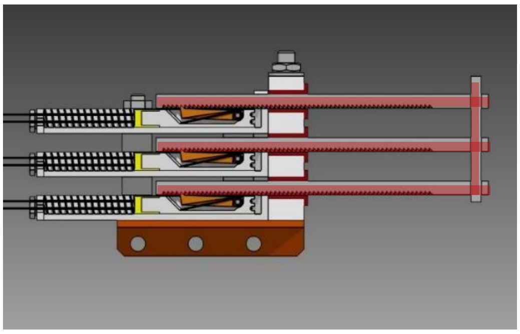


Figure 13-20: Actuator stack with three modules
The stack has been sliced in order to expose the inchworm mechanism

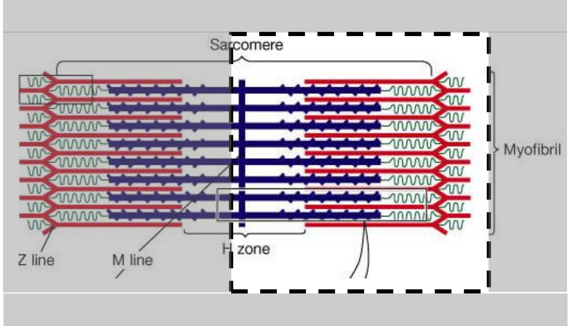


Figure 13-21: The Modulated Inchworm's resemblance to a sarcomere
The inchworm mechanism reminds of the myolin, while the Drag-plate resembles actin

13.6.8 Reverse movement

It is however also important to ensure that the actuator can extend after usage. The lack of this feature was the main downfall of the Linear Inchworm's (section 0). The reverse mechanism was obtained by enabling the Casing to slide 5 mm sideward. The sideward slide would readjust the Slider-ratchets according to the Drag-plate. When *enabled* the Slider-ratchets will then connect to the gears of the Drag-plate. However, when moving the Casing sideward, the ratchet teeth will then slide onto the smooth surface of the Drag-plate (Figure 13-15), which removes any grip and thereby *disables* the inchworm. Hence, the Drag-plate is able to reverse, as there are no longer any resistance from the ratchets.

13.6.9 Status – PROTOTYPED

The design was overall satisfactory and it was of interest to investigate how well it would work in practice. This led to a 3D printed prototype.

CHAPTER 6: OBSERVATIONS

14 Theoretical investigation

14.1 Physical and output

The capabilities and physical parameters of the three main concepts have been summarized and put together in Table 14-1. There are for each concept stated the specifications of a single unit/module, and the specifications of the number of units/modules required to obtain a serial contraction (20 %) of minimum 400 N.

Table 14-1: Summary of the three concept's capabilities and attributes
It is specified for each of the three concepts; how many units or modules are needed to challenge the human elbow flexor muscles. The valuated attributes are the volume of all the setup parts [V_{True}], the overall boxed dimension occupied by the actuator [V_{Space}], mass [m], density [D], the stress generated with cross sectional area filled by the NiTi-wires during *serial*- [$\sigma_{N.S}$] and *parallel* actuation [$\sigma_{N.P}$], stress generated with the cross sectional area of the entire structure during *serial*- [$\sigma_{E.S}$] and *parallel* actuation [$\sigma_{E.P}$], the strain percentage during one cycle of serial- [ε_{Serial}] and parallel contraction [$\varepsilon_{Parallel}$], newton generated compared to the mass during serial- [$T_{max.S}$] and parallel contraction [$T_{max.P}$], the specific power [P_k] and energy density [u].

		Hydraulic pump	Linear Inchworm		Multiple Inchworm	
Units		(Alone)	(Alone)	4	(Alone)	3
V_{True}	[cm^3]	959	15	58	45	157
V_{Space}	[cm^3]	3139	161	643	96	465
m	[kg]	7.48	0.1	0.4	0.07	0.32
D	[g/cm^3]	7.8	6.87	6.87	1.7	2
F_{Serial}	[N]	750	105	420	140	420
$F_{Parallel}$	[N]	-	560	2240	700	2100
$\sigma_{N.S}$	[N/mm^2]	0.08	0.36	0.18	1.27	0.37
$\sigma_{N.P}$	[N/mm^2]	-	1,78	0,89	6,34	1,86
$\sigma_{E.S}$	[N/mm^2]	0.07	0.14	0.12	0.15	0.15
$\sigma_{E.P}$	[N/mm^2]	-	0,70	0,59	0,77	0,73
ε_{Serial}	%	26	32	32	20	20
$\varepsilon_{Parallel}$	%	-	4	4	4	4
$T_{max.S}$	kN/kg	0.10	1.05	1.05	2	1.31
$T_{max.P}$	kN/kg	-	5.60	5.60	10	6.65
P_k	kW/kg	0.04	0.31	0.31	0.57	0.37
u	kJ/m^3	83	195	195	408	252
Eff.	%	<5	<5	<5	<5	<5
Cycles		>10^5	>10^5	>10^5	>10^5	>10^5

14.2 Critical elements

The ratchet is the most critical element of the setup, as it is the part which undergoes the highest load. It was therefore decided to investigate, if the structure could endure the stresses. Autodesk Inventor was used to generate a stress analysis. Stainless steel was chosen as material, which has a yield strength of 250 MPa (Table 14-2), which the created stresses need to be lower than.

Table 14-2: Material properties of stainless steel

Name	Stainless Steel	
General	Mass Density	8 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	193 GPa
	Poisson's Ratio	0,3 ul
	Shear Modulus	74,2308 GPa
Part Name(s)	Teeth, V2	

A compression force of 140 N (four NiTi wires load) was put onto the edge of the ratchet (Figure 14-1 A). The supporting surfaces were then specified to be the axis (Figure 14-1 B) and the rear surface of the ratchet (Figure 14-1 C).

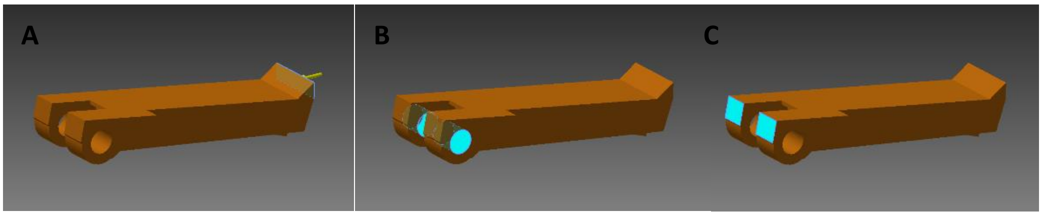


Figure 14-1: Fixation and compression areas of the ratchet
Illustrated are compression site (A), the radial fixation site (C) and the planar fixation site (B)

The reaction forces were calculated with respect to the two attachment sides (Table 14-3), which revealed that the axis was going to absorb significant more force, than the rear end.

Table 14-3: Reaction forces and moment of step

Constraint Name	**Reaction Force**		**Reaction Moment**	
	Magnitude	**Component (X,Y,Z)**	**Magnitude**	**Component (X,Y,Z)**
Plannar constraint	38,6215 N	-35,4063 N	0,0115183 N m	-0,00571279 Nm
		15,4111 N		0,00679962 Nm
		-0,71763 N		0,00733488 Nm
Axial constraint	162,943 N	51,9486 N	0,0716141 N m	-0,0697002 Nm
		-154,438 N		-0,0164456 Nm
		0,728057 N		0 Nm

14.3 Von Mises Stress

The stress analysis resulted in a Von Mises data model (Figure 14-2). This model helps to highlight the critical areas of the ratchets. It can be found that the areas under highest stress are just at the base of the ratchet's tooth. Here is the stress reaching as high as 129.9 MPa (Figure 14-2). Though, this is still far below the yield strength of 250 MPa (Table 14-2), which indicates that the Slider-ratchet is capable of enduring the highest stresses that are posed by actuating the NiTi-wires. The stress analysis has been summarised into Table 14-4.

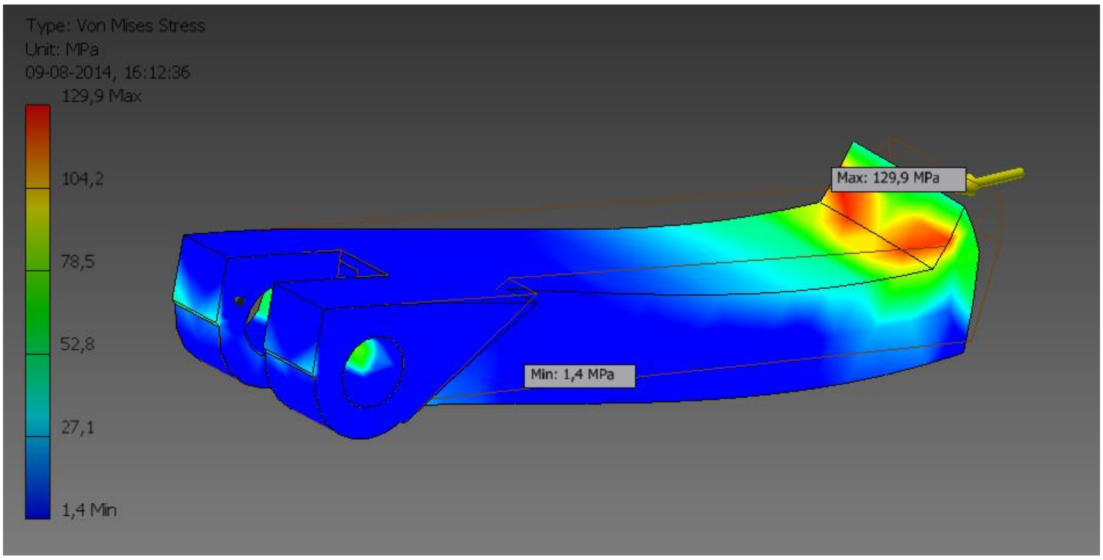


Figure 14-2: Von Mises stress analysis

Table 14-4: Summary of the stress analysis

Name	**Minimum**	**Maximum**
Volume	143,786 mm^3	
Mass	0,00115028 kg	
Von Mises Stress	1,36321 MPa	129,909 MPa
1st Principal Stress	-21,5076 MPa	75,6404 MPa
3rd Principal Stress	-150,515 MPa	4,30092 MPa
Displacement	0 mm	0,00504523 mm

15 Practical investigation

15.1 Prototype

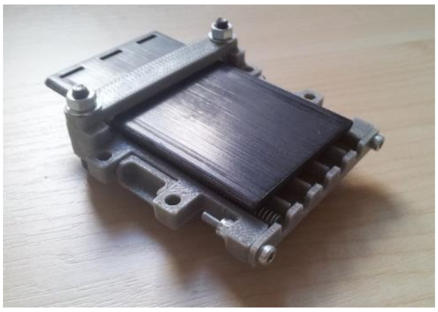


Figure 15-1: The assembled prototype

It was without any troubles possible to assemble the prototype (Figure 15-1), which proved that the tolerances had been of correct values. However, only one Slider was manufactured for the prototype, because of the high manufacturing costs. The prototype was of rough resolution and not made of the correct materials. No NiTi-wires were available and it was therefore not possible to test the actuation. How well the prototype's different mechanics functioned was therefore investigated instead.

15.1.1 Slider

The 3D print of the Slider was of satisfying quality (Figure 15-2 A); however, some of the areas around the rotation axis had been too thin for printing. This did not cause any troubles, as the torsional spring still worked as planned. It created the desired pressure onto the ratchet, rotating it when it is under no pressure (Figure 15-2 B).

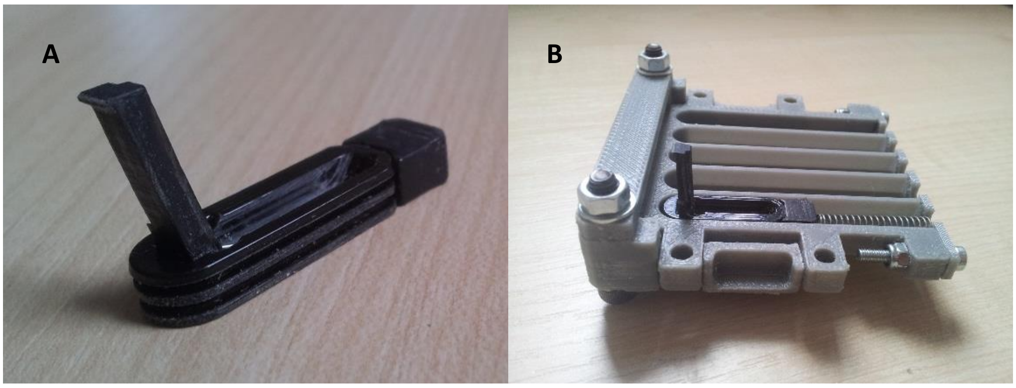


Figure 15-2: The slider isolated and under no pressure

Wear

The material of the 3D print showed to not be durable enough, as the tip of the ratchet teeth after few cycles began to wear down and become rounded.

Noise

Noise emission was registered from the ratchet, when it travelled along the gears of the Drag plate. It can be imagined that the noise only will be amplified with more ratchets.

15.1.1 Ratchet plate

The 3D print of the Ratchet plate was of a satisfyingly high quality (Figure 15-3). The linear gears of the plate did not seem to have any troubles enduring the stresses, as they successfully locked together with the ratchet.

Figure 15-3: The Ratchets plate

15.1.2 Bushing to guide and lower friction

The bushing was not of the correct low friction material and had been printed in too low quality. Furthermore, the plastic bushing was also meant to slide against stainless steel, rather than the plastic the Drag-plate was made of. Hence, this made the friction between the bushing and the Drag-plate high (Figure 15-4).

Another problem was the bushing ability to stabilise the Drag-plate. Sadly, as the Drag-plate only had one guiding point, the bushing was then able to go astray. This often made it get stuck temporarily.

Figure 15-4: The Drag-plate positioned in the plastic bearing

15.1.3 Reverse mechanism

The Reverse mechanism that disengages the ratchets from the Drag-plate worked as planned. The sliding from the engaged- (Figure 15-5 A) to the disengaged position (Figure 15-5 B) occurred without problem. Though, it could be troublesome to maintain the Casing in one position. Hence, there is needed a steady switch, which can maintain the Casing better in each position. From the start, it has been anticipated that this could be done by a small control actuator, such as a RC-servo.

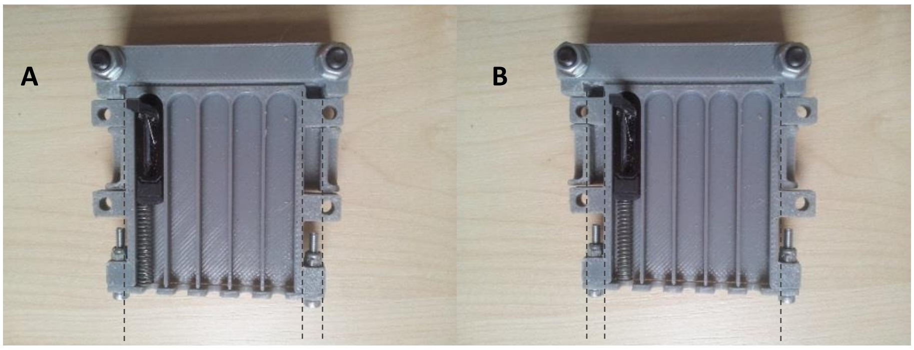


Figure 15-5: Reverse mechanism
Showing how the Casing can shift between being (A) engaged and (B) disengaged

16 Discussion

The final design, the Modular Inchworm, has greatly decreased its volume compared to previous designs. Though, it is still the constant springs that determine the overall size. In this case it is the torsional springs that increase the width of the sliders and grippers. The spacing between each set of wire is therefore increased more than what would have been necessary otherwise.

Actuation

The actuator of the setup has multiple unique features. One of these is its ability to be electrically geared between actuating the Sliders in series or parallel. This will theoretically create the choice of either creating tensile force up to 420 N with 20 % strain or a tensile force of 2100 N with just 4 % per cycle (it is even possible to run more cycles to increase the strain). This is a unique feature which is not found often in any other commercial actuators.

Another special feature is the actuator's longitudinal flexibility. This makes it possible to attach it more easily to structures with a more organic shape. However, this flexibility is also one of the actuator's main issues, as it limits it to actuate in only one direction. Hence, the actuator is only able to create tensile force. Due to this, a prosthetic is then only able to turn its joint in one direction, and as such it then needs separate actuators for both flexion and extension. This then requires a high amount of intelligent materials to perform complete motion. This may not add much extra weight to the design, but it still has a high material cost.

It may be considered to transfer the Modulated Inchworm into the hydraulic domain, as this will create a pump, which can control more than one actuator by using valves. However, this transfer is likely to minimize or remove the electrical gearing option. It is also questionable how much the design's mass and volume will increase. Thus, if future developers select this path, they will then need to keep wary of using elements that can dramatically increase the volume of the setup.

Lifting capability

Through the project there were uncertainties of the desired lifting capability the prosthetic should have. It was initially chosen that the prosthetic should be able to lift 10 kg in the hand. This transferred into a requirement that the actuator needed to create 750 N of tensile force. The first concept, the Hydraulic pump was dimensioned and designed according to these forces, which can be seen in Table 14-1. However, it was later found that 10 kg of lifting force was an unnecessary large power output. The lifting requirement was therefore decreased to 5 kg for the following concepts. Hence, this may make it unfair to compare the following concepts' physics and output with the hydraulic setup. Though, the concept for the hydraulic setup's capabilities is so considerably poor that it not even can be considered close to concept 2 and 3. It was even tried to scale concept 2 and 3 up to the same force output, but even then the capabilities were far apart. For example, the hydraulic pump can lift 750 N over 20 %, while it weighs 7.8 kg and occupies 3138 cm^3. Meanwhile, a Modulated Inchworm with 6 modules can generate 840 N over 20 %, while it just weighs 0.4 kg and occupies 870 cm^3.

Observation

The noise emission from the ratchets during movement is of concern. It was observed that the noise will only be amplified with more modules. This noise emission can lead to an unsatisfactory experience for the user when compared to a conventional actuator. It might therefore be necessary to avoid using torsional springs in the designs. A solution could be to use small electromagnets to compress the torsional spring, when the NiTi-wire is not actuating. Though, this would add further complexity to the design.

It was observed that the Modulated Inchworm will have troubles creating stacks larger than 4 modules, as the used Ø4 mm bolts do not have sufficient length to lock all the modules together. This might make it necessary to reconsider the modules' interlocking mechanism.

Another issue is that some of the length of the NiTi-wire is lost when implementing a multiplying mechanism. From the beginning it was anticipated that the NiTi-wire would contract 4 % of the overall length, and that the multiplier's task were to increase this five-fold in order to reach 20 % overall actuation. However, the NiTi-wires' contraction has become less than 4 % of the actuators entire length, due to the space taken by the multiplier. It is unsure if it is possible to solve this problem through remodelling the design, or that an entirely new concept will be needed.

The uncertainty of the wire length is also amplified when considering the Slider. It is impractical that the slider needs to travel in a grove in the Casing, as it creates potential for it to get stuck. Furthermore, the Casing length was also created specifically to the purpose of flexing the elbow. Hence, it may prove difficult to apply the same structure to other joints, as they do not have the same specific dimensions as the elbow flexor.

Nylon 6.6

Implementing a strain multiplying mechanism proved to decrease the specific power of the intelligent material and introduce a new set of issues and challenges. This does not happen in the case of artificial muscle setups. Hence, artificial muscles may still seem more suitable if it is possible to overcome the strain limitations. This is why the Nylon 6.6 was of interest; as it had both a high specific power and strain. This makes it seem as though it is the best candidate to follow or even outperform skeletal muscle. However, sadly its main issue was a very low energy efficiency, which meant that an inordinate amount of power would be required. This ultimately makes it unsuitable for prosthetic use, as a portable energy source is needed. However, it might still have other purposes where a more constant power source is supplied.

Energy efficiency

It is questionable, that even a fully developed NiTi inchworm actuator is capable of fulfilling the task as a prosthetic actuator. This is due to its low energy efficiency, which decreases the operation time dramatically. Hence, any future researchers might need to reconsider what intelligent material is best for the task.

Specific power

It can be noted that the theoretical specific power of the Modular Inchworm is of 0.37 to 0.57 kW/kg, which can be considered high compared to other conventional actuators. The motor 3274E from *Phidgets* (Figure 16-1) weighs for instance 2 kg and has a rated voltage of 24 V DC together with a planetary gearbox with a gearing factor of 168:1, which enables a power output of 30 W (Phidgets, Inc., 2012). Hence, the motors specific power can be calculated to 0.015 kW/kg, which is up to *38 times less* than that of the Modular Inchworm.

Figure 16-1: The 24 V DC motor *3274E* (Phidgets, Inc., 2012)

CHAPTER 7: CONCLUSION & FUTURE DEVELOPMENT

17 Conclusion

Through development of the theoretical model and the prototype, it is then considered possible to use intelligent materials to create new prosthetic actuators which have previously unseen capabilities. The proposed actuators are lighter, smaller and can obtain a higher specific power than many conventional and modern actuators. It also creates an opportunity for electrical gearing rather than mechanical gearing, which gives more control opportunities.

However, the usage of intelligent materials still poses different problems and challenges depending on the specific material used. Many of these have been proven possible to overcome through mechanical multipliers.

Hence, in terms of proof of concept, the research presented in this paper indicates that these new actuators can be constructed using current intelligent materials and mechanical multipliers. However, such multiplying mechanism still needs a great amount of development in order to improve their effectiveness and limit any other issues being introduced with their parts and function. Issues observed are mainly noise emission, friction and control.

18 Perspective

18.1 Optimization

The prototype's design was quite rough, and should obtain significant optimization. By using stress analysis, it should then be possible to minimize the individual parts to their minimum size. Furthermore, each slider has four strands of NiTi-wire attached to it. By minor adjustments it should then be possible to have another loop to it, giving a total of six strands of NiTi-wires. The stress analysis also indicates that the materials should be able to endure the force; though, some reinforcements could be necessary. By adding another loop each slider would then achieve a 50 % increase in tensile force, which would lower the required number of modules and thereby the cross sectional area. Thus, it is anticipated that the actuation stress could be increased with as much as 30-40 %.

18.2 Inchworm

The most complex part of the Modulated Inchworm is the slider mechanism. It is considered possible to dramatically simplify the design and decrease the number of parts by replacing the Slider. This is preferred as the current sliding mechanism adds severe complexity, size, vulnerability and room for errors.

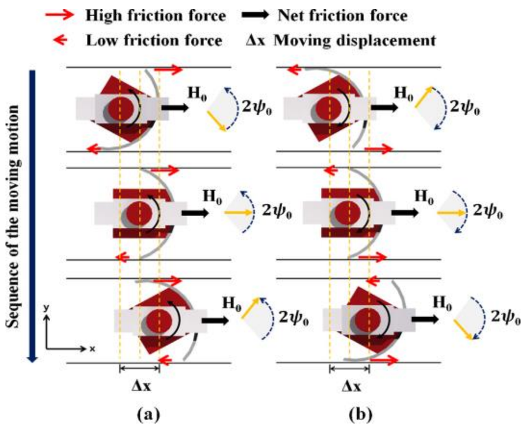


Figure 18-1: Crawling micro-robot
Other studies has created rectilinear forward movement for crawling micro-robot. Electromagnets was used to induce (a) counter-clockwise rotating motion and (b) clockwise rotating motion. These rotations uses flaps to connect to the sides and push itself forward (Nam, et al., 2014)

An alternative is to use a single rigid element with ratchet/flaps on each side, which enable rectilinear movements. This is used to lock onto gears positioned on both sides (Drag-plate) and push the element forward. The setup was inspired by studies, which used a similar mechanism to make a micro-robot crawl inside tubes (Figure 18-1). This resembles the Modulated Inchworm's movements along the Drag-plate.

The moving element is made able to rotate by placing an axis in its centre. Rotations in both directions are made possible by looping a NiTi-wire around the element on each of the axis's. Hence, during actuating the NiTi-wire will then turn the element towards it. Furthermore, the ratchets/grippers will during this movement connect- and pull the linear gears beside the element. As one wire contracts, it will then also stretch the wire on the opposite side, back to its starting position. This is similar to the micro-robot in Figure 18-1, which uses electromagnetism instead.

Hence, a setup that reloads without spring can then be made, by pairing the NiTi-wires together around one moving element. Less parts simplifies the design and can decrease the overall volume of the setup. Only few parts remain, which creates a setup with similar size and shape as the Casings alone (section 13.6.4).

18.2.1 Release mechanism

The missing *release mechanism* of the Modulated Inchworm created an issue, as it resulted in both noise and resistance. It is considered possible to obtain a release mechanism by using small electromagnets, as they can be used to pull the ratchet of the gears of the Drag-plate.

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