Development and design of a vest for a wearable soft robotic arm lifting system

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Abstract

Work related injuries causes personal suffering and economic loss for both companies and individuals. Repetitive work and static postures with the arms can lead to musculoskeletal disorders (MSD) in the shoulder and neck region. This thesis set out to develop a wearable soft robotic arm lifting system using Bioservo Technologies' Soft Extra Muscle (SEM) technology. The objective was to develop a functional prototype that supports lifting the arms. The vest part of the system was the main focus of this thesis. The intended user for the system is an individual who is in the risk group of MSD in the shoulder and neck region but does not have any work related injuries beforehand.

Initially, a literature study was performed, followed by defining the user needs and product specifications. Previous prototypes had been developed at the company and they were analyzed and learned from before starting to generate concepts. Several prototypes were constructed and they were evaluated primarily through user tests and discussions with Bioservo representatives. During the development process, a heuristic approach was found the most effective since it allowed fast iterations.

The final prototype's main parts were a vest, a mechatronic system and an elbow brace. The vest served as force anchoring around the torso and it could be adjusted to fit various body types. The mechatronic system actuated a line which was connected to the elbow brace and supported the arms during motion. The recommendations for future work includes additional user tests to see if a system of this kind can prevent work related injuries.

Keywords: Wearable soft robotics, exoskeleton, human power-assist, force anchoring

Sammanfattning

Arbetsrelaterade skador orsakar personligt lidande och ekonomiska förluster för både företag och privatpersoner. Repetitivt arbete och statiska arbetsställningar med armarna kan leda till belastningsskador i axel- och halsregionen. Detta examensarbete har haft som syfte att utveckla ett mjukt bärbart robotsystem med Bioservo Technologies Soft Extra Muscle (SEM) teknik, som ska ge assistans vid lyft av armarna. Den avsedda användaren för systemet är en individ som är i riskgruppen för belastningsskador i axel- och halsregionen men som inte har några arbetsrelaterade skador i förväg.

Inledningsvis genomfördes en litteraturstudie som följdes av att definiera användarbehov och produktspecifikationer. Företaget hade tidigare utvecklat liknande prototyper, vilka kunde analyseras och delvis användas som grund innan alternativa koncept genererades. Flera prototyper byggdes och utvärderades främst med hjälp av användartester och diskussioner med representanter från Bioservo. Under utvecklingsprocessen användes en heuristisk metod då den uppfattades som mest effektiv eftersom den tillät snabba iterationer.

Den slutliga prototypens huvuddelar var en väst, ett mekatroniskt system och en armbågsskena. Västen fungerade som kraftförankring runt bålen och det kunde justeras för att passa olika kroppstyper. Det mekatroniska systemet aktiverade en lina som var ansluten till armbågsskenan och gav stöd till armarna under rörelse. Rekommendationerna för framtida arbete innefattar ytterligare användartester för att se om ett system av detta slag kan förhindra arbetsrelaterade skador.

Nyckelord: Bärbart mjukt robotsystem, exoskelett, mänsklig kraftassistans, kraftförankring

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Lund, January 2017

Svante Fredin and Martin Ascard

Table of contents

List of acronyms and definitions

CAD	computer aided design
FEA	finite element analysis
ICR	instantaneous center of rotation
IMU	inertial measurement unit
LEB	line exit backplate
MSD	musculoskeletal disorder
Mechatronic system	actuators, microcontrollers, tendon load cells, IMUs and batteries
PID	proportional integral derivative
SEM	soft extra muscle
TIP	tower insertion point
Vest	entire product to be developed, including the shoulder part and the elbow brace, excluding mechatronic system

1 Introduction

This chapter covers the background to the thesis and the company it was conducted at. It also covers a description of the previous system which was developed at the company. Further, the objectives, the research questions and the intended user are defined and delimitations are stated. Finally, it contains a state-of-the-art literature study.

1.1 Background

In 2014, Bioservo Technologies started the development of a device which would assist elderly people with reduced arm strength when lifting their arms. The work was conducted both by master theses students and by employees at Bioservo [1-4]. The result was a wearable soft robotic system which actively assisted the lifting of an arm using the company's Soft Extra Muscle technology. The system consisted of a vest, a mechatronic system and an elbow brace. Approaching 2016, Bioservo choose to change the focus of the device from elderly people to industry workers with normal arm strength. The motivation was that industry workers who perform a lot of repetitive or static tasks with their arms are more prone to work related injuries such as musculoskeletal disorders (MSD).

Exposure to repetitive hand and arm movements is a major physical risk factors for workers in the European Union, where 62 % are exposed to this during their work time Moreover, 42% are reported to be exposed to tiring and painful positions [5, pp. 41-42]. This exposure increases the risk MSD, which causes personal suffering and economic loss for affected individuals and companies. The system was developed to reduce the risk of MSD in the shoulder and neck region for people working in these risk groups.

1.2 Previous system

This thesis will in part continue the development from the previous work conducted by master theses students at Bioservo. The previous system which they developed was intended to assist elderly and only lifted one arm. In contrast, the system developed in this thesis was intended for the defined risk group and for lifting of both arms. To understand where this thesis sets out, an explanation of the previous system will be presented. An illustration of this system can be seen in figure 1.1.

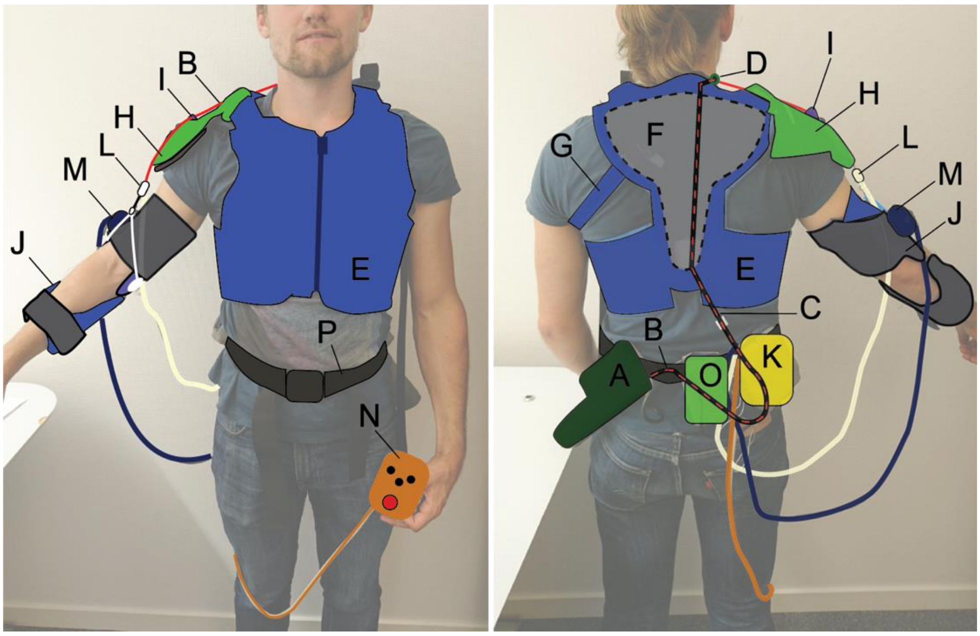


Figure 1.1 Previous prototype

The purpose of the soft robotic system is to assist the user when lifting the arm rather than replacing the arm function. The system is designed to detect the user’s intended arm movement and to deliver a supporting force as a function of the angle of the upper arm. It is designed to automatically support the arm during dynamical lifting or static holding and to reduce the supporting force when the user lowers the arm. The force is produced by an actuator (A) that is pulling a line (B) which is connected to the arm. The line is threaded through a Bowden cable (C) which runs from the actuator to the Line Exit Back (LEB) (D). The purpose of the Bowden cable is to transfer the force from the actuator to the LEB. The vest (E) contains a rigid backplate (F) which anchors the forces to the torso. Straps (G) are used to increase the force anchoring. The shoulder part (H) guides the line through a tower (I) over the shoulder. The elbow brace (J) serves as an attachment point for the line on the arm. The microcontroller (K) is programmed with a proportional–integral–derivative (PID) controller to regulate the torque of the actuator. A tendon load cell (L) is used to calculate the line force at the elbow brace. The Inertial Measurement Unit (IMU) (M) is used to calculate the angle of the upper arm using a gyroscope. The microcontroller is fed inputs from the tendon load cell and IMU to calculate a force-angle relationship and generates an output signal to control the torque and direction of the motor. To activate the system and to regulate the force level a control unit (N) is used. The electronic components are powered by a battery (O). The mechatronic system is kept on a belt (P) around the waist.

1.3 Objectives

The main goal of this thesis is to develop a functional vest prototype for a wearable soft robotic system to support lifting of the arms. Secondary goals are to develop other parts of the system and to integrate it with the previously developed parts of the system. To obtain this the aim was to:

- Understand the user needs and the context where the system is intended to be used.
- Design, construct and test prototypes in an iterative way.
- Formulate recommendations for future development.

1.4 Research questions

From the objectives, a set of research questions are set up to provide an overall focus of the work. These questions are the ones to be answered throughout the thesis and are defined as:

- Which forces occur in the system and where should they be anchored to the body?
- How can the vest be designed to allow high level of mobility and comfort?
- How can the vest be adjusted to fit various body types and sizes?
- How can the mechatronic system and elbow brace be integrated to obtain a functional prototype?

1.5 Intended user

Based on the European Union statistics and Bioservo’s collaborations, the intended user is defined as a person who is exposed to repetitive work with hands and arms and that is either working within blue-collar occupation, i.e. people working with manufacturing and assembly, or healthcare. The intended user is presumed not to have work related injuries in their shoulders, neck or arms.

The sectors which have most exposure to ergonomic risk factors in the European Union are those within construction, agriculture and blue-collar occupations. The exposure to physical risk for repetitive work with hands and arms are distributed almost equally between men and female. However, when it comes to tiring and painful positions, men are of slightly higher risk (Eurofound, 2016, s. 45).

Within the frame of this thesis, Bioservo has collaborations with companies and stakeholders within two main sectors; industry and healthcare. The first of which have a large workforce within manufacturing and assembly, often referred to as blue-collar occupations. Within the healthcare sector, there are many professions which perform repetitive work with hands and arms such as surgeons and nurses.

Based on the data from the European Union and Bioservo's collaborations, the intended user was defined as a person who is exposed to repetitive or static work with hands and arms and that is either working within blue-collar occupation or healthcare. The intended user is of normal strength and does not have any work related injuries such as MSD in their shoulder and arm region.

1.6 Delimitations

- The focus of the development was the vest and its associated parts. Development of mechatronics system will be limited to the extent of getting the whole system functional.
- The purpose of the system is to prevent work related injuries. However, the tests needed to verify this is outside of the scope of this thesis.
- The product is intended as a gravity compensating system. This means that the product will lift and support part of the weight of the user's arms but will not give any additional power beyond this.
- The system is not intended for rehabilitation or as a medical aid.
- The prototypes are developed as proof-of-concept which means they will not be a representation of a finished product from Bioservo.
- All results based on user tests are performed by the authors, unless stated otherwise.

1.7 State-of-the-art

Research describing wearable soft robotic systems intended for lifting the arms has often been made for rehabilitating purposes or as assistive robotics [6-9]. This section will introduce some of these systems and point out some differentiators from the system developed in this thesis. Illustrations of all systems described can be seen in Appendix B.

The meal assistive exoskeleton is intended for individuals suffering from polymyositis [9]. The disease is a type of chronic inflammation of the muscles and the most common symptom is muscle weakness [10]. The use case is limited to support eating with one hand while the other one controls the movements with a switch. It uses two Bowden cables to allow elbow and shoulder flexion respectively. These are actuated using a driving system with DC motors. By using soft materials for the force anchoring and bands which ties the system together the result is lightweight and compact. Moreover, the soft materials make the design more user-friendly because of easier donning and doffing. The design is intentionally restricted to lifting the arm from a table to the mouth, which means the range of motion is limited. Moreover, it does not allow movement with the arm outstretched.

Research conducted by Kesner et al. describes a soft robotic system similar to the prototype developed at Bioservo [6]. However, it is intended to be used for stroke rehabilitation and was not designed to lift the arm more than 90 degrees. Their work focused on ways of avoiding misalignment between brace (shoulder part) and body. Error in alignment will result in unwanted forces and torque which in turn will lead to discomfort for the user. A misalignment might occur because of anatomical variations as well as incorrect placement of the system on the body. Their proposed solution is to have two cables with separate actuators on either side of the shoulder. This decreased the probability for a twisting torque on the arm because of brace misalignments. However, adding another actuator together with the control needed for them to work well increases the complexity, size and weight of the system. Another factor they cover in the design considerations is the fixed insertion point of the cable on the upper arm brace. Based on their simplified model of the biomechanics of the shoulder, they concluded that the insertion point should be slightly higher up than the elbow joint in order to minimize the cable tension. This insertion point was also valid in order to minimize the force on the shoulder joint which does not result in a rotating torque around the glenohumeral joint.

Galiana et al. based some of their research on the results from Kesner et al. as described in the previous paragraph [7]. In similarity, the project is aimed at stroke rehabilitation by compensate for gravitational forces acting on the arm. This is done with two lines lifting the arm on opposite sides. These two lines join at a mutual point on top of a shoulder part and this point is chosen to be able to correct any linear or angular misalignments of the arm while lifting. The lifting angle does not continue above a horizontal plane, so the conditions for force anchoring to the torso is different. On the topic of vest design, they promote the use of soft materials over rigid elements due to its ability to adapt to anatomical variations. Moreover, cables actuated with electric motors are deemed superior over pneumatics because of energy density in lithium ion batteries compared to compressed air.

Gopura et al. points out relevant future work needed in the field of upper-limb exoskeleton robots [11]. First, more development is needed of the mechanisms to overcome the misalignments between the center of rotation of the shoulder complex and the robot joint. Solutions which exist for this today are primarily for rehabilitations purposes and more work is needed for human power-assist purposes [12]. Secondly, existing exoskeletons have rarely been designed to be worn permanently and can in fact often cause discomfort for the user. Therefore, the designer of systems which should be used for a prolonged period of time must carefully consider the comfort for the user.

2 Theory

To design a vest which is worn on the body and affects the users shoulder complex and arm region, an understanding of corresponding anatomy and biomechanics is important; thus, this chapter will first give a basic description of the anatomy of the arm and shoulder complex. Lastly, basic theory of relevant biomechanics is described.

2.1 Anatomy

Anatomy describes the structure of the human body and can be used to understand the origin of motion of movements. For this reason, it has a key role in building realistic and useful biomechanical models of the musculoskeletal system and its motions [13].

The human shoulder complex consists of three different bones; clavicle, scapula and humerus. These are mainly connected through four different joints; glenohumeral joint, acromioclavicular joint (AC joint), sternoclavicular joint and scapulothoracic joint [14]. Of which the glenohumeral joint is often referred to as the shoulder joint. As seen in figure 2.1, this system of bones and joints are anchored to the thorax which provides its base.

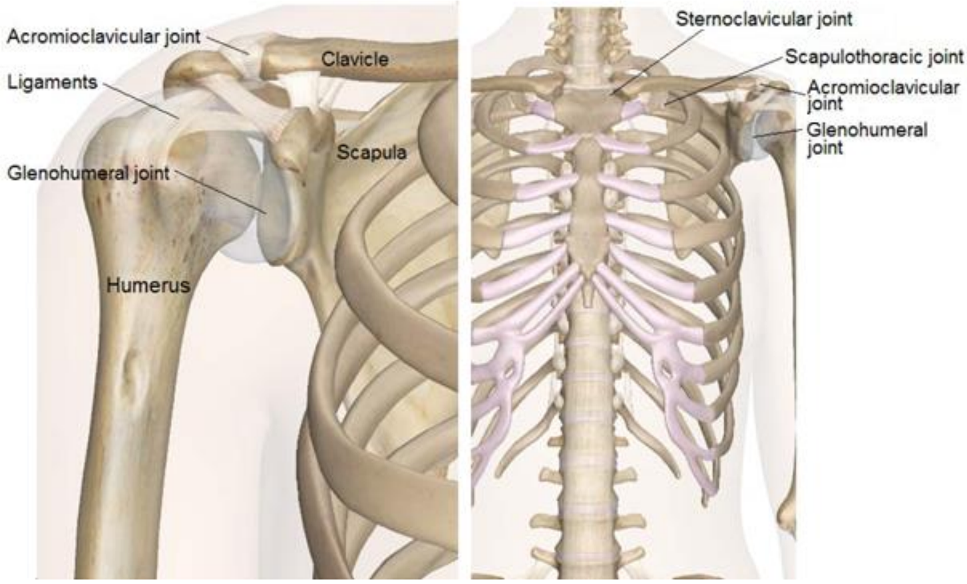


Figure 2.1 Anatomy of shoulder complex

Because of this advanced structure of joints, ligaments and muscles, the shoulder has a wider range of motion than any other joint in the human body. Furthermore, the movement during arm elevation is very complex. In short, the motion can be divided into three phases where the first phase starts from the arm resting and the last phase ends with the arm lifted to a vertical position [14].

The first phase is where most of the elevation is enabled through rotation in the glenohumeral joint. The rest of the shoulder complex is more static during this phase. During the second phase the instantaneous center of rotation (ICR) of the shoulder complex migrates from the glenohumeral joint towards the AC joint as the scapula starts to rotate. The ICR is the point in the plane around which all other points of a system are rotating. At the same time as the ICR moves, the elevation of the clavicle is increasing. The third phase occurs when the clavicle has reached its maximum elevation level and is restricted by ligaments. At this point the powerful scapular muscles continues to rotate the scapula in order to elevate the arm to its final position, about 180˚ rotation from the starting position [14].

As seen in figure 2.2, the three largest section of the spine consists of the, from top to bottom, cervical, thoracic and lumbar region. The last vertebra of the cervical region - C7 - is relatively easy to pinpoint since it is protruding when the head is tilted forward. Therefore, it can be used as a reference point on the back. Additionally, the center line of the back is defined at a axis along the spine, as seen to the right in figure 2.2. The angle the vertebra can tilt in relation to the next one vary in the different sections. Among the lower lumbar region there is more movement than in the upper thoracic region. This needs to be taken into consideration when designing products that attach to the back.

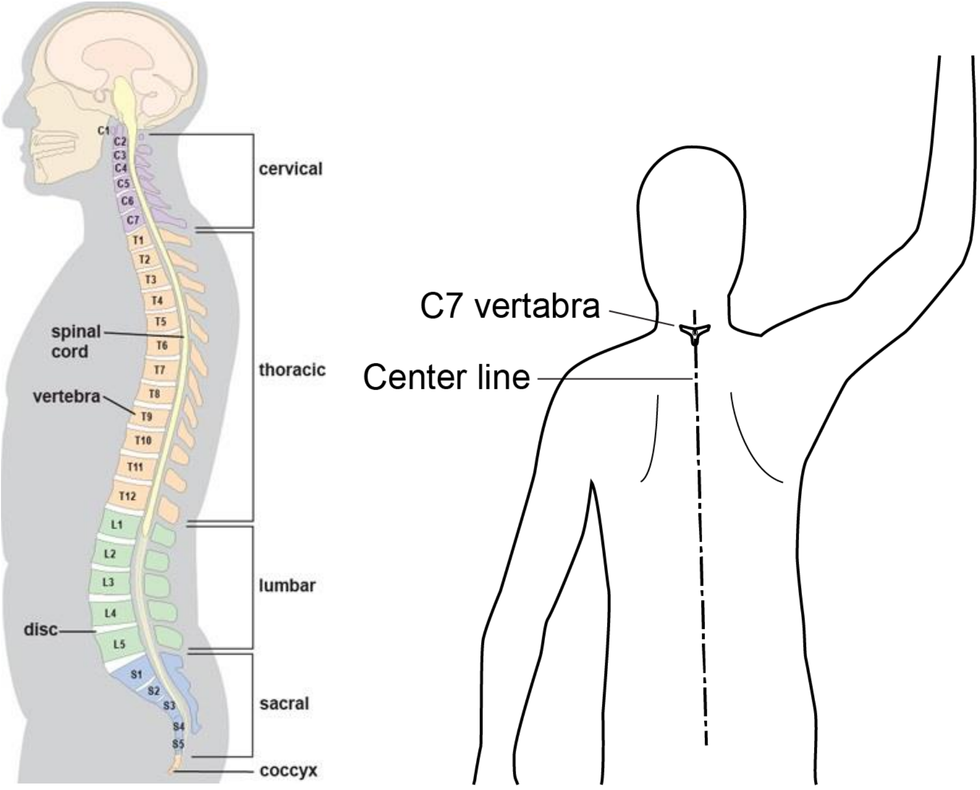


Figure 2.2 Left: Human spine, right: center line and C7 vertebra

In addition to the theory above, it is convenient to define the terminology for some primary motions of the arm. The motions are illustrated in figure 2.3 and are categorized in pairs as flexion–extension and abduction–adduction.

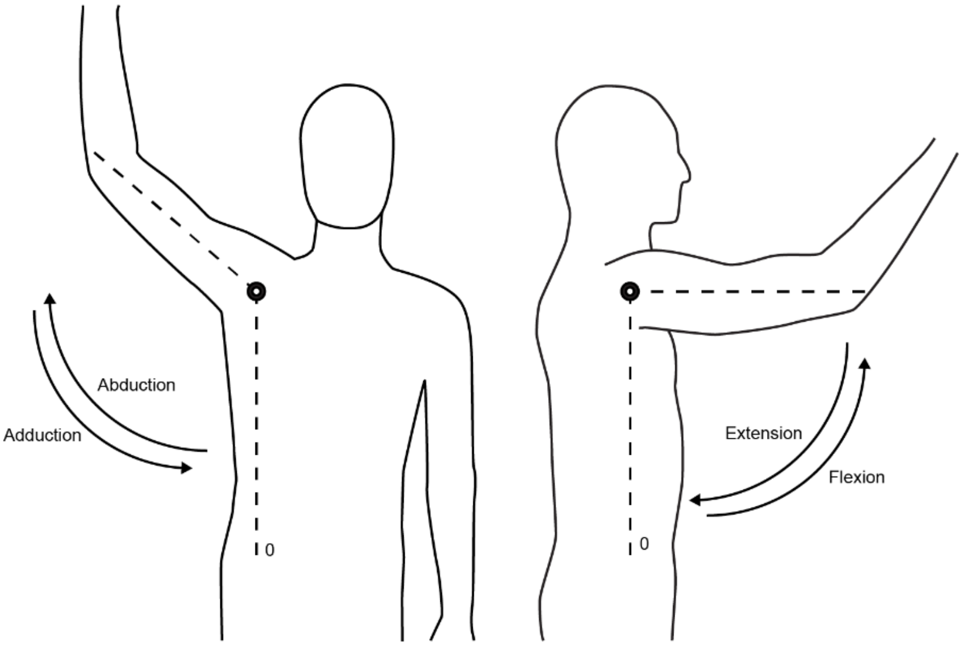


Figure 2.3 Primary motions of the shoulder and arm

Lastly, definition of anatomical planes and axes can be seen in figure 2.4. The planes and axes transect the human body and will be used to describe the orientation of motions, torques and forces. The longitudinal axis will also be referred to as the vertical centerline, or simply the centerline, of the back.

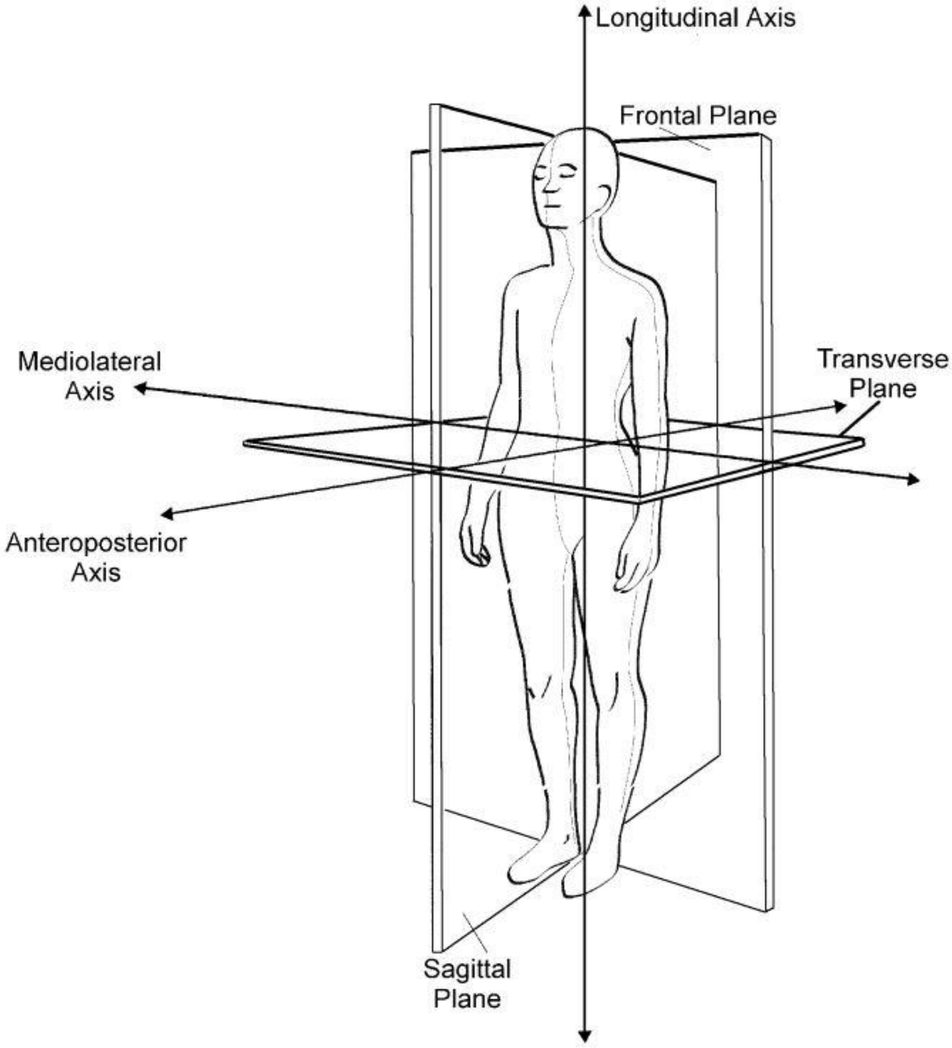


Figure 2.4 Anatomical planes

2.2 Biomechanics

Biomechanics describes the study of motion of living things and the forces that creates this motion. It applies the field of mechanics to biological systems and is therefore a powerful mathematical tool for understanding motion and forces acting on the human body [13].

Due to the complexity of the shoulder anatomy it is difficult to create biomechanical models that can provide accurate and useful information [15]. For this reason, the model presented in this chapter is a simplified shoulder joint model of the same sort as used by Knudson [13]. An illustration of this model can be seen in figure 2.5.

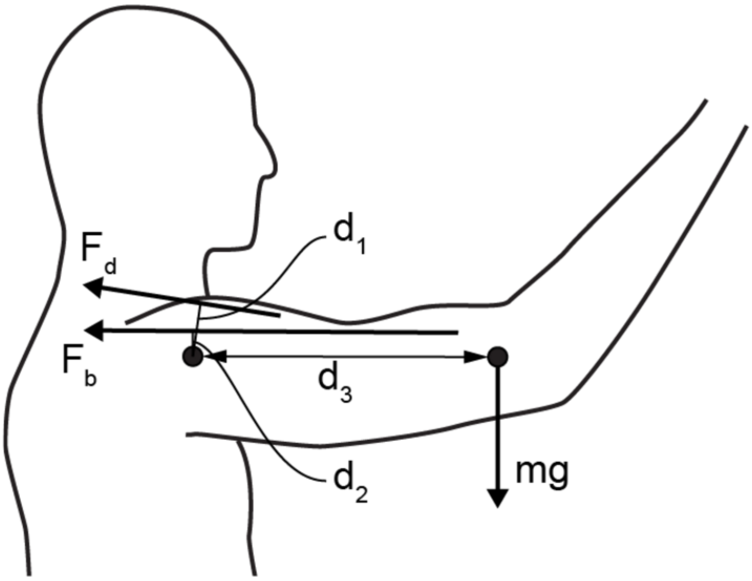


Figure 2.5 Simplified biomechanical model

In this model, F_d and F_b are muscle forces created by the anterior deltoid and long head of the biceps respectively. The weight of the arm is represented by the force mg and the quantity of force is given in Newton. Three arbitrary distances d_1 , d_2 and d_3 are also used.

The fundamental point of this model is that lift of the arm, or the rotation of the humerus, depends on the balance of torques created by the forces acting on the arm. If the forces and torques are assumed to be in static equilibrium and the shoulder joint is approximated as a frictionless ball joint the following moment equilibrium equation is valid:

$$mg \cdot d_3 = F_b \cdot d_2 + F_d \cdot d_1 \qquad (2.1)$$

This simplified model of the shoulder joint will be the theoretical foundation used for biomechanical calculations in the thesis.

Since the focus of this thesis is on development of a vest to be part of a robotic system to support lifting of a person’s arms, there will also be biomechanical problems related to the interaction between human and robot. One of the main problems with this interaction occurs as a result of anatomical differences between individuals since this requires a robotic system that can be fitted and calibrated to a wide range of people. Which is important since it means that the risk of misalignment between human and robot is minimized.

The risk of misalignment becomes especially problematic for the shoulder joint since the ICR is constantly moving throughout the elevation of the arm. Unfortunately, misalignment can lead to unnatural high forces and stress on muscles and joints which in a worst case can lead to injury [15]. Additionally, it can lead to discomfort for the user.

3 Material and method

The chapter presents an overview of the materials used, including information about the test users. Further, it gives a summary of the method used in the initial studies, the iterative development process and the user test which was used to evaluate the prototypes.

3.1 Material

The following prototyping materials, machines, software and test users has been used in the thesis.

3.1.1 **Software**

Solidworks	computer aided design (CAD) and finite element analysis (FEA)
Autodesk Fusion 360	CAD and FEA

3.1.2 **Test users**

Author 1	26 years, male, 174 cm, 73 kg, student
Author 2	26 years, male, 189 cm, 79 kg, student
Test user 1	29 years, male, 180 cm, 78 kg, welder
Test user 2	24 years, male, 168 cm, 80 kg, student
Test user 3	24 years, female, 170 cm, 55 kg, student
Test user 4	20 years, female, 161 cm, 54 kg, student

3.1.3 Prototyping material

- Textiles and straps
- Sheets of orthopedic thermoplastic. The sheets can be shaped after heated above 70 degrees C
- Granulate thermoplastics. The granulate can be merged and shaped after heated above 70 degrees C
- Fiber reinforced plastics
- Fishing line

3.1.4 Machines and tools

- Selective laser sintering (SLS) 3D printer
- Sewing machine
- Various hand tools
- Weights, for user tests

3.2 Initial studies

The initial studies were where the problem was analyzed and researched. First, the objectives and research questions of the thesis were defined to make sure all stakeholders agreed on the focus on the thesis. Secondly, the intended user and delimitation made it possible to narrow down the scope of the thesis and therefore end up with a reasonable development scope.

Since the system was to be used and worn on a human, an understanding of relevant anatomy and biomechanics was important to study. Furthermore, it was crucial not only to understand how the design should fit with the human body, but also to design with the user and her needs, in mind. Therefore, user context and user needs was established from various sources. First, the company employees had a lot of accumulated experience and could provide information regarding the user needs. Even though this was not a first-hand source, some employees at Bioservo are in daily contact with potential users which makes the input more reliable. Secondly, a video clip of industry workers who worked at an assembly line was analyzed and contributed to the user context and needs. Additionally, an interview with a welder gave first-hand information and comments about the potential for the system in his daily work. Input was also given continuously from a physiotherapist which had treated patients from industry occupations with work related injuries in the shoulder complex. Finally, all the input lead to a list of user needs and a function analysis. The function analysis chart lists a set of functions and rank them after relevance for the prototype. The functions were reoccurring throughout the prototyping phase and were, for example, used for concept screening.

With an understanding of the user, a state-of-the-art literature review was conducted to see what other research had been done with similar solutions. As a final step of the initial studies, the previous system was examined and analyzed. Several free body diagrams were produced which helped to increase the understanding of the force situation of the vest.

3.3 User test

A user test was created to have a standardized way of testing and evaluating the prototypes. The purpose of this was to have a more consistent and objective test that permitted a more reliable comparison between all prototypes.

The test consisted of an upper body motion scheme performed while wearing the prototype. The motion scheme was created together with a physiotherapist to simulate different static and dynamic working conditions within the user group and can be seen as a whole in appendix D.

All tests, except for the final prototype, were performed with the prototype equipped on the right arm. The prototypes before the final was only made to fit one arm because constructing it for two arms was not deemed time effective. However, the other arm was consequently used as a reference to see how the prototype affected mobility, comfort and relief.

Although the user test followed a motion scheme, a set questionnaire was not used to evaluate the prototypes. This was because focus was put on different parts when evaluating the prototypes. This made it unpractical to use a standardized questionnaire and instead, the questions were formulated to cover the points of interest for the particular prototype.

3.4 Iterative development process

The prototyping phase was conducted in an iterative way where brainstorming, discussions and bodystorming were the most used idea generating techniques. Bodystorming is a technique where the product is imagined to exist and different user scenarios is acted.

The prototypes will be presented in chronological order and each prototype chapter will cover the following parts: concept generation, concept selection, prototyping, results and discussions and conclusions. The concept selection was most often done with a comparison matrix where the concepts were graded minus (-), neutral (0) or plus (+) in comparison to one another. The prototyping was where the prototype was build and these chapters will describe how they were done. Under the results sections, the prototype will be presented and if any specific tests were done they are outlined here. The last chapter - discussion and conclusion – will mark the end of a prototype chapter.

Initially, three concepts which focused on the overall force anchoring of the vest was generated. These were complemented with eleven concepts for isolated parts and functions. Since the concepts and subconcepts of parts quickly added up, a tree diagram was created to get an overview of the parts and functions of the vest. This tree diagram served as a breakdown of the system and will be used to illustrate which concepts and problems that were put into a prototype build.

The first prototype was a modified vest prototype from a previous thesis conducted at the company [1]. This vest was continuously modified and added onto up until the final prototype, where a totally new vest was made. The first prototype incorporated a selection of the concepts from the initial concept generation. The next prototype chapter covers four shoulder part concepts where two of them were build and incorporated with the vest from the first prototype. The shoulder part was a crucial component of the vest and was deemed to demand even more work. Consequently, four additional concepts were generated and two of them were built in a second iteration of the shoulder parts. At this point, user tests were conducted where third parties got invited to test a selection of the shoulder prototypes. The user tests gave valuable input and lead to conclusions for the upcoming final prototype. Before starting the creation of the final prototype, the shoulder part, the LEB and backplate were refined to test if they could solve the problems which were raised in the user tests.

At last, the final prototype was created. It was based on the experience, tests and comments accumulated while building the other prototypes. It consisted of a backplate covered with fabric, straps and buckles, LEB, shoulder part, a mechatronic belt and cases, and elbow brace.

4 User and needs

This chapter clarifies the contexts where the product could be used and secondly it defines the user needs. Finally, a function analysis was created to map out which functions the system should own.

4.1 User contexts

The contexts in which the product was intended to be used is defined by the set of circumstances that surrounds the situation. To show the contexts in an easily understandable way, three different scenarios will be presented. The first scenario is interpreted from the video analysis (described in chapter 3.2), the second from an interview with test user 1 and the last from an interview with a person working in the healthcare sector. The results can be seen in table 4.1.

Table 4.1 Table of user contexts

Name	***Analysis type***	***Occupation***	***Context***
Scenario 1	Video interview	Assembly worker	• Line assembly of cars • Workstations where components are assembled in a repetitive way • Often hand held tools within confined spaces and with hands/arms above the head
Scenario 2	Interview	Welder	• Welding of high voltage cables • Industrial environment • Often offshore or underground work within confined spaces • Highly mobile work with a lot of movements between temporary work stations • Up to 30 minutes of static working postures with arms above shoulders
Scenario 3	Interview	Biomedical	• Ultrasonography of patients with

		physicist	heart diseases • Clinical environment • Static postures when investigating patients • Up to 10 minutes of static working postures

4.2 User needs

Based on the user contexts, interpretations of corresponding user needs and product features are set up in table 4.2.

Table 4.2 Table of user needs

Interpreted user need	***Corresponding product feature***
Work within confined spaces	Product occupy a small volume
Repetitive tasks with the arms	Product can follow user movement while maintaining its functionality
Work with arms above the head	Product is functional when user has the arm above the head
Operate a computer while wearing the equipment	Ability to turn off the mechatronics system and/or release the line force
Use in hospital environment	Product can be cleaned so that it meets hospital standards
Work where objects are hanging down	The line should be covered
Support arms in fast movements	Increase the operating speed of the actuator
Moving a lot during work	Product is mobile so that it can be carried by the user

4.3 Function analysis

Based on the analyzed user context and needs, company requirements and physiotherapist input, the product requirements were defined. A function analysis was used rather than quantified specifications such as weight, size and operation angles since the system is a proof-of-concept. Thus, the defined functions were used as guidelines for product development and their fulfillment were not analyzed as measured quantities.

The function analysis chart was used to map out which functions the system should own. It is structured by functions in the format of verb + noun with an additional comment if clarification is needed. The functions are divided into classes in order of importance as *Main*-, *Necessary*- and *Desired*- functions, as seen in table 4.3. The intent of the format is to limit the functions to describing “what” should be done and not “how”.

The chart fills multiple purposes. It aids the developers to know what to build and it can also be used for the stakeholders to know what they are getting. First, many possible functions were listed. Secondly, the functions were divided into categories. Then, the functions were categorized into which type – prototype or product – it was most relevant to. The functions categorized into prototype was the most relevant for this development and can be seen in table 4.4. The additional functions can be seen in appendix C.

Table 4.3 Classes in order of importance

Class	***Abbreviation***
Main function	MF
Necessary	N
Desired	D

Table 4.4 Function analysis

	Function		***Comment***	***Class***	***Type***
Category	***Verb***	***Noun***			
Use	Support	lift	of the arms	MF	prototype
	Anchor	force	to body	MF	prototype
	Allow	adjustment	of size for anatomical variation	N	prototype
	Allow	movement	of shoulder complex	N	prototype
	Convey	comfort	when wearing	D	prototype
	Allow	sitting	while operating system	D	prototype
	Allow	laying	while operating system	D	prototype
	Minimize	weight		D	prototype

	Minimize	size		D	prototype
	Minimize	complexity		D	prototype
	Avoid	protruding	out from body	D	prototype
	Use	soft materials		D	prototype
Construction	Minimize	weight		D	prototype
	Minimize	size		D	prototype
	Minimize	complexity		D	prototype
	Avoid	protruding	out from body	D	prototype
	Offer	durability	short term	D	prototype
Safety	Include	stop function	e.g. emergency button	D	prototype

5 Analysis of forces and anchoring positions

This chapter describes the forces which are present in the previous system using free body diagrams in different planes. However, they are valid in this development as well since the same overall concept for force anchoring was used. Also, it covers the concept of misalignment in context of the previous system.

5.1 Side view of arm

Assuming a state of static equilibrium, the force situation of the arm in a plane parallel to the sagittal plane is illustrated in a free body diagram, see figure 5.1. The force F_{lift} is of vital importance since this is the force that creates the torque that rotate the humerus upwards, i.e. it generates an arm lifting torque around the pivot point located at the humeral head. This torque can be described as:

$$M_{lift} = F_{lift} \cdot L_1 \tag{5.1}$$

Where F_{lift} is a force component of the force applied to the line, called F_{line}. The latter which origins from the actuator.

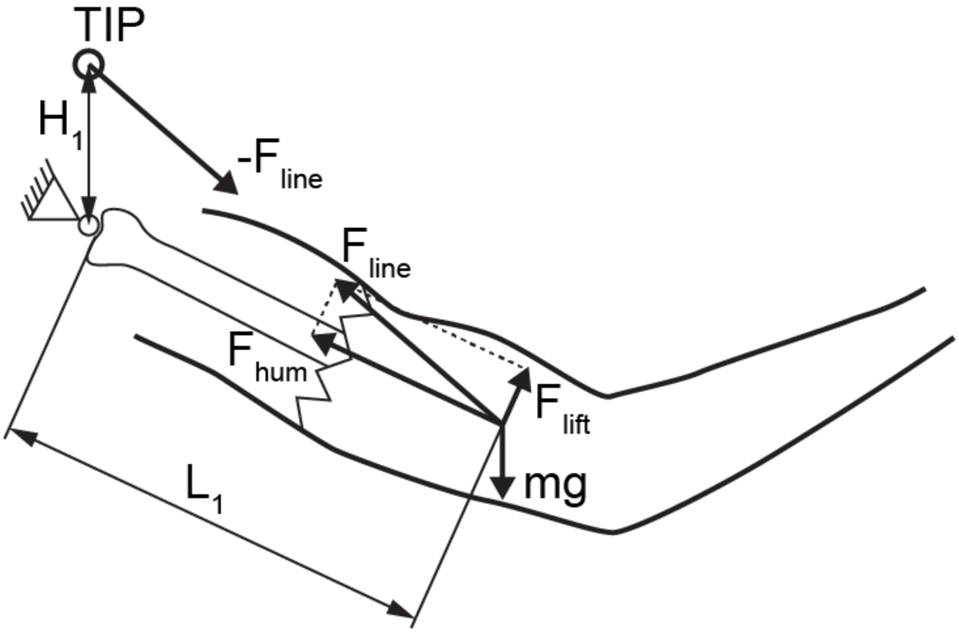


Figure 5.1 Free body diagram of side view of arm

The force F_{hum} is the other component of the force F_{line}. It acts in line with the humerus and is therefore compressing it without contributing to M_{lift}. This makes F_{hum} unnecessary from a lifting perspective and it's also a source of discomfort for the user. In this presumed state of static equilibrium, M_{lift} is balanced by an opposite and equal torque generated by the force mg .

5.2 Top view of arm and misalignment

The force situation of the arm in a plane parallel to the transverse plane is illustrated in a free body diagram, see figure 5.2.

In this thesis, misalignment refers to the relationship between the force vector from the line, acting on the insertion point of the elbow brace, and the glenohumeral joint.

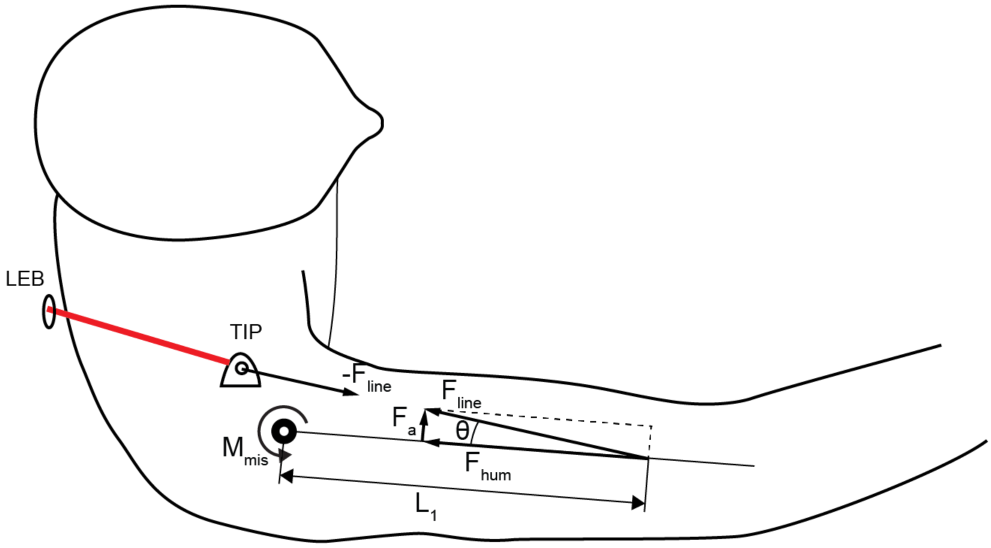


Figure 5.2 Free body diagram in an offset plane parallel to the transverse plane

In the free body diagram, a misalignment between F_{line} and the glenohumeral joint results in a torque because of the force component F_a . This torque tends to rotate the humerus towards the sagittal plane only to be stopped by an opposite torque, M_{mis} , generated by muscle action. The misalignment is undesirable since it either forces the user's arm to a not intended rotation or the user has to continuously compensate this inward rotation by muscle action.

In summary, it’s of importance to maximize F_{line} , minimize F_{hum} and keep alignment in order to develop a more optimal product.

5.3 The vest and anchoring positions

Another important factor is the anchoring of the forces and torques from the vest to the human body. This anchoring needs to be solid for the system to operate as intended and in a predictable manner. At the same time, the anchoring needs to be comfortable for the user.

Figure 5.3 shows a simplified and estimated free body diagram of the vest of the previous prototype during operation. A problem is that there are many forces and pressures between the human torso and the vest that are unknown and dependent of many factors. Some factors could be the user’s anatomy, individual preferences while fitting and strapping the vest and material properties. This means that a mechanical model could be inaccurate. However, the free body diagram is used to understand an estimated force situation and to draw conclusions about force anchoring around the torso.

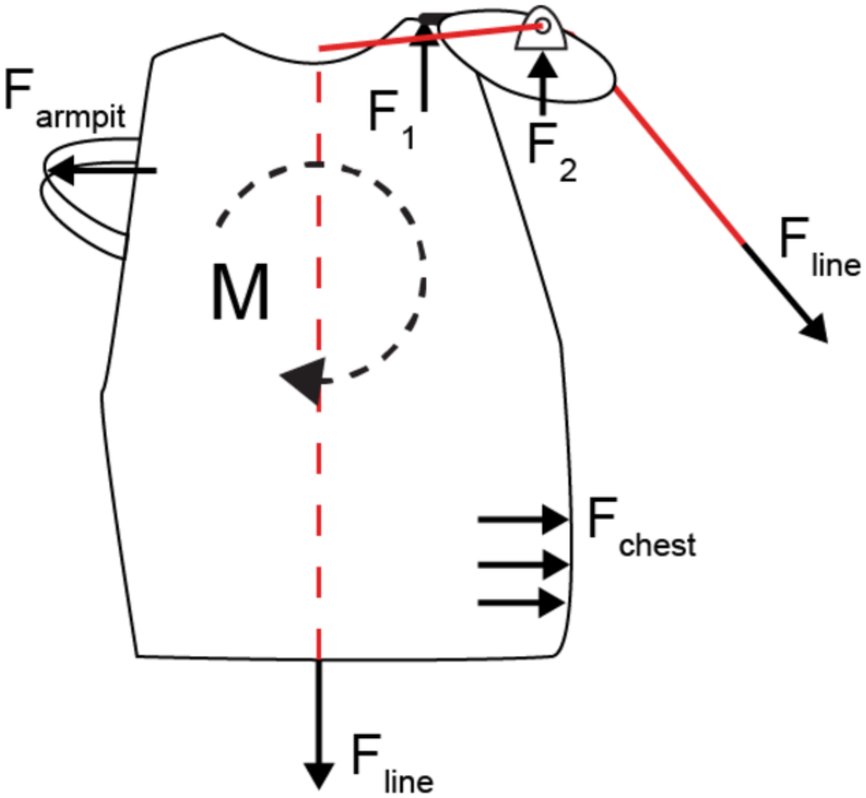


Figure 5.3 Forces acting on the vest

An important factor is that the horizontal component of the force F_{line} must be anchored by other horizontal forces. Assuming static equilibrium, these forces will also keep the vest from rotating. At the previous prototype, this was mainly accomplished by a strap underneath the user's armpit, as seen in figure 5.3.

The backplate is a rigid plate inside the vest and is used to anchor the forces. Assuming a static equilibrium, a free body diagram can be seen figure 5.4. The forces in the diagram are from the strap under the armpit, F_{armpit}, the strap around the chest, F_{chest}, the line, F_{line}, and finally the vertical forces F_1 and F_2..The latter represents the forces from the shoulders strap and shoulder pad.

In this simplified model, the line force F_{line} acts along a horizontal line, even though this is not always the case. Arbitrary distances called L_2 and L_3 are also introduced.

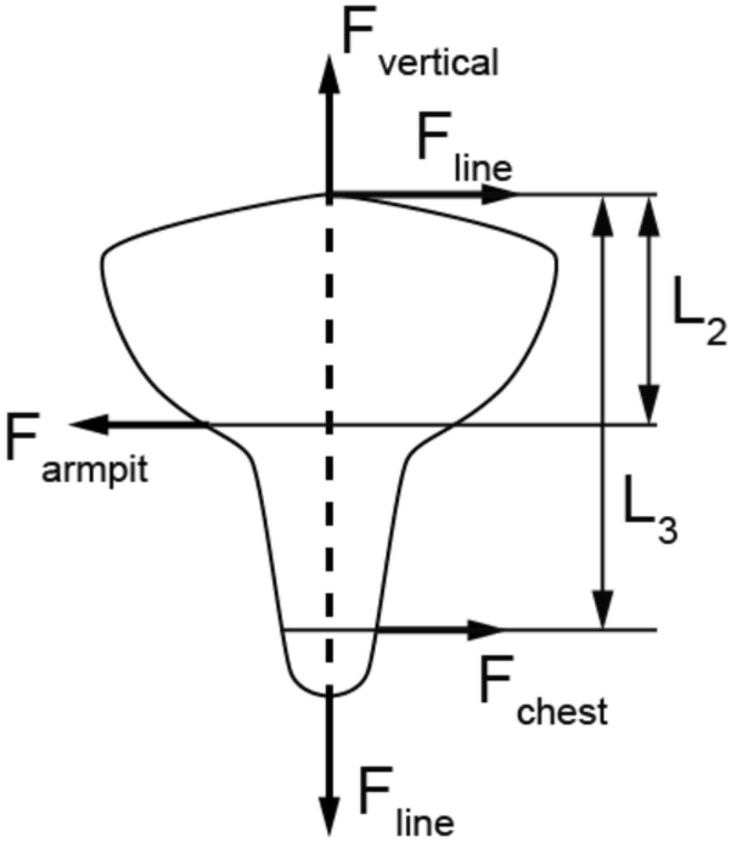


Figure 5.4 Forces acting on the backplate

Following static equilibrium equations are now valid:

$$F_{armpit} = \frac{F_{line}}{1 - \frac{L_2}{L_3}} \tag{5.2}$$

$$F_{chest} = \frac{F_{line}}{\frac{L_3}{L_2} - 1} \tag{5.3}$$

By observing Equations (5.2) and (5.3) it can be seen that a small value of L_2 and L_3 is beneficial since this reduces the magnitude of both F_{chest} and F_{armpit}.

From the vest design perspective, a small value of L_2 means that it would be good practice to anchor the force F_{armpit} as close to F_{line} as possible. Optimally, it would be anchored along the line of action of F_{line} since this would mean that no torque is being created. Thus, the vest would not tend to rotate at all.

The reason that it is beneficial with a large value of L_3 is that it provides a longer lever arm to prevent the rotation of the vest. Thus, reducing the magnitude of both F_{chest} and F_{armpit}.

Unfortunately, it’s not trivial to anchor the force F_{line} along its line of action. One reason is that the line of action is moving as a function of arm elevation and another reason is that there is no obvious position to anchor this force to the human body in a comfortable and ergonomic way. The latter also goes for a large value of L_3. As a result, trade-offs and compromises between functionality and comfort had to be made throughout the development process.

6 Initial concepts

This chapter introduces three overall concepts and eleven isolated parts and functions.

6.1 Overall vest design

These overall vest designs focus mainly on where to anchor the forces on the body. As an example, the previous system anchored the forces to the torso only.

6.1.1 **Hip anchoring**

The user wears a belt around the hip and a frame along the back. The line exits from the top of the frame down to the arms. Additional attachment on the upper body is kept to a minimum. Illustration of this concept can be seen to the left of figure 6.1.

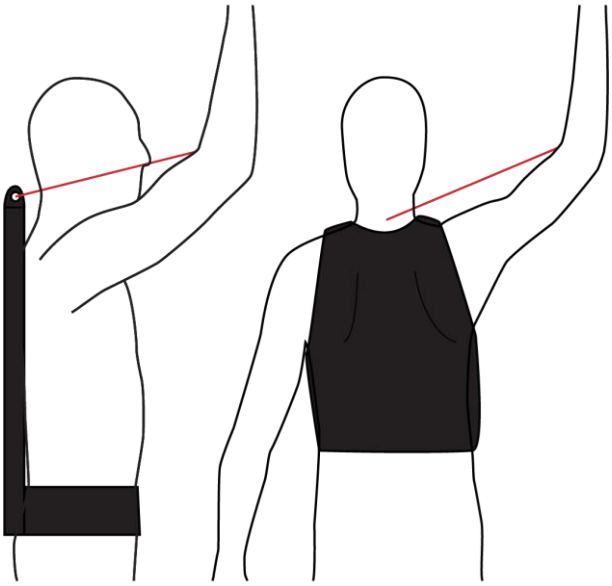


Figure 6.1 Left: Hip anchoring, left: Torso anchoring

6.1.2 **Torso anchoring**

The user wears a vest or harness which anchors the forces to the torso. A rigid backplate forms a type of frame to anchor the forces. This is the same idea which the previous system was built upon. Illustration of this concept can be seen to the right of figure 6.1.

6.1.3 **Anchoring band on side**

This is a combination of the Hip anchoring and Torso anchoring concepts. Stiff or flexible bands connects the vest to the waist. The waist part would potentially have to be designed as a harness around the crotch to anchor the force in a comfortable manner. This would be effective in countering the rotating torque of the vest. Illustration of this concept can be seen to the left of figure 6.2.

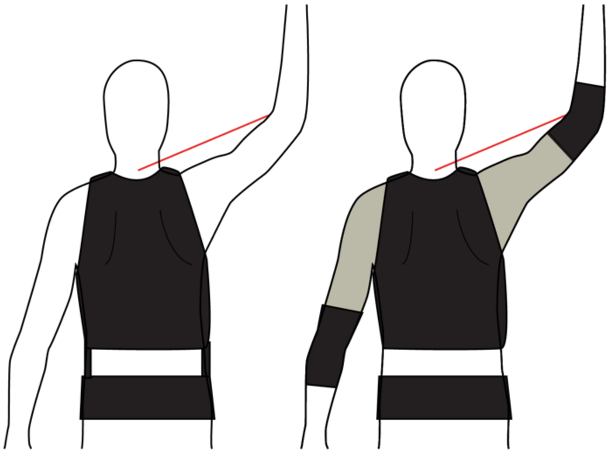


Figure 6.2 Left: Anchoring band on side, right: Fabric integration

6.1.4 **Fabric integration**

The whole system is held together with an underlying fabric or textile. The vest, mechatronic system and the elbow brace would therefore be taken on like a jacket. Illustration of this concept can be seen to the right of figure 6.2.

6.1.5 **Concept selection**

The initial concepts were screened and evaluated from a feasibility perspective. The function analysis was a useful tool in the evaluation of which concepts to realize. An important factor was also how rapid the concepts would be to build with the resources available. Hence, concepts where parts of the previous system could be used were prioritized.

Since the torso anchoring is what was used in the previous system, it was efficient to try out this concept. This design was rather effective in anchoring the forces and had potential for improvements. Additionally, it would be possible to use an earlier prototype to test additional concepts, which would be time efficient. Therefore, this concept was chosen for further development.

6.2 Isolated parts and tree diagram

Based on the concept Torso anchoring the main problem is divided into subconcepts and visualized in a tree diagram, each with a corresponding set of questions to analyze, as seen in figure 6.3. This type of tree diagram will be used throughout the prototype sections to visualize which subconcepts and questions that are focused on when building a particular prototype.

The tree diagram consists of different rows which corresponds to a certain problem break-down level. The break-down always ends at a set of subconcepts or questions. These are the ones to be analyzed and answered after testing a prototype.

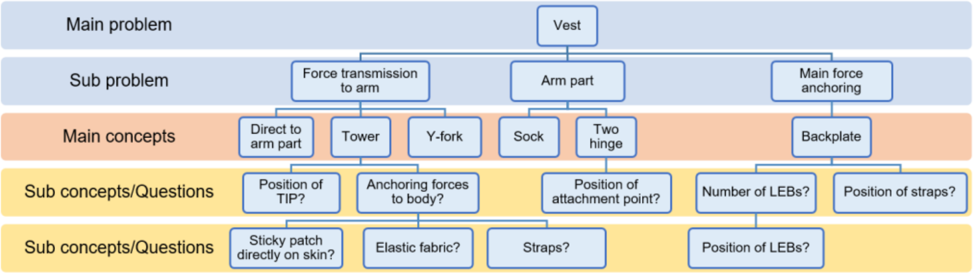


Figure 6.3 Tree diagram of the vest

In the tree diagram, there are several different main concepts, subconcepts and questions that have been generated and introduced. The main and subconcepts are described below together with an illustration and a subjective evaluation of the pros and cons associated with them. The pros and cons are used for concept selection at this initial phase.

6.2.1 **Direct to arm**

The following concept as well as 6.2.2 Tower and 6.2.3 Y-fork are subconcepts of the sub problem called Force transmissions to arm, as seen in the tree diagram in figure 6.3.

The idea is to use a direct force transmission from the LEB to the arm without any interaction with the shoulder complex. The LEB is attached to the backplate at an arbitrary position, in the figure it is placed on the side of the center line.

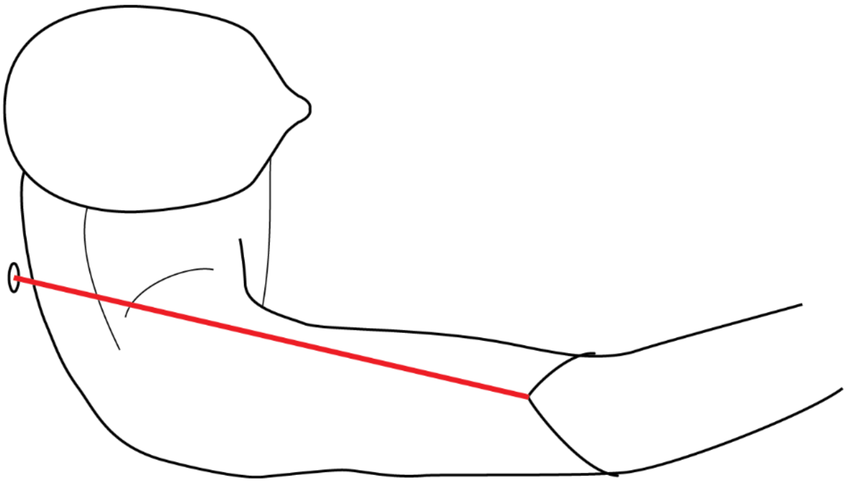


Figure 6.4 Direct to arm concept

Advantages of this concept could be that the arm experiences lift without anything pushing down on the shoulder. Additionally, it is a solution without a shoulder part, which would reduce the complexity of the vest. Disadvantages of the concept could be that the line will most likely come in contact with the shoulder when the arm is resting which can cause discomfort. To reduce the effect of this, the LEB needs to be placed in a high vertical position and this would lead to it protruding a lot from the vest, which is undesired.

6.2.2 **Y-Fork**

The idea is to use a Y-shaped part which is connected to the backplate. This Y-fork guides the line around the shoulder allowing it to move freely within the opening of the fork.

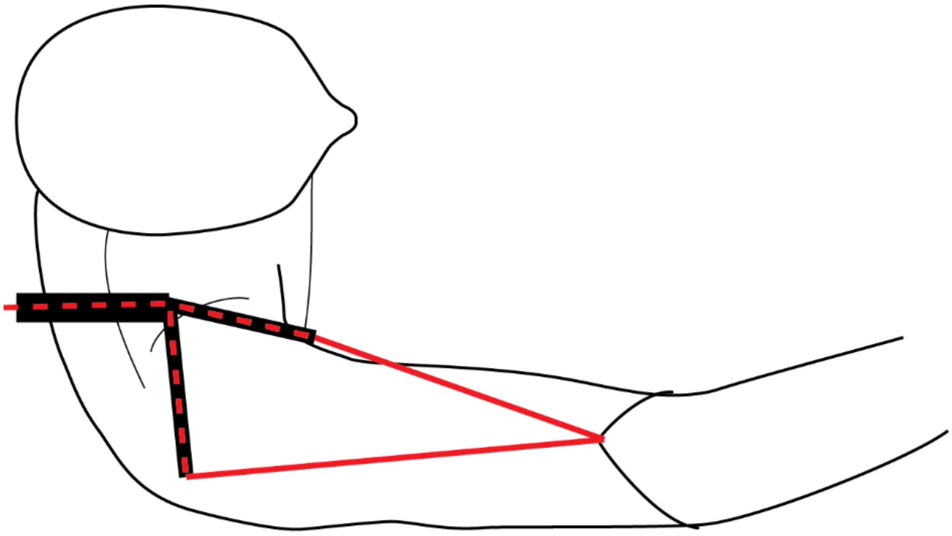


Figure 6.5 Y-fork concept

An advantage of this concept could be that it allows mobility in between the Y-shape without any interaction with the shoulder. A disadvantage is that the part would most likely get in contact with the arm at elevated arm positions where the distance between the shoulder muscles and the neck tend to get very slim.

6.2.3 **Tower**

The idea is to attach a tower part to the shoulder which would guide the line over the glenohumeral joint. This concept is used in the previous system and several of the systems in the state-of-the-art chapter.

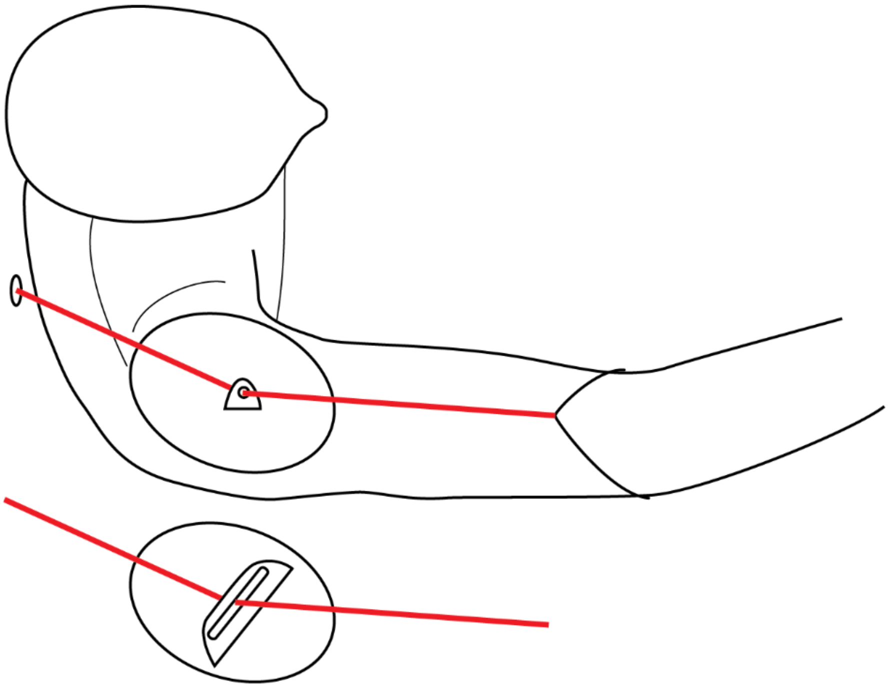


Figure 6.6 Tower concept

Advantages of this concept is that it readily follows the motion of the shoulder complex since it is applied on top of the shoulder. Disadvantages could be difficulties with keeping the tower at its position and also the fact that the tower will be pushing down on the shoulder.

The shape of the opening in the tower could have different shapes, for example a hole or a slot. A single hole could guide the line in a more predictable and fixated way but will probably experience higher forces since it is more fixed. A slot on the other hand would allow some sliding of the line which could reduce the forces on the tower but to the cost of a less predictable guiding of the line. A slot would potentially also lead to more misalignment which is undesired.

6.2.4 **Sticky patch directly to skin**

The following concept as well as 6.2.5 Elastic fabric and 6.2.6 Straps are subconcepts of Tower as seen in the tree diagram in figure 6.2.1.

The idea is anchor the tower to the body using a sticky patch which is attached directly onto the skin.

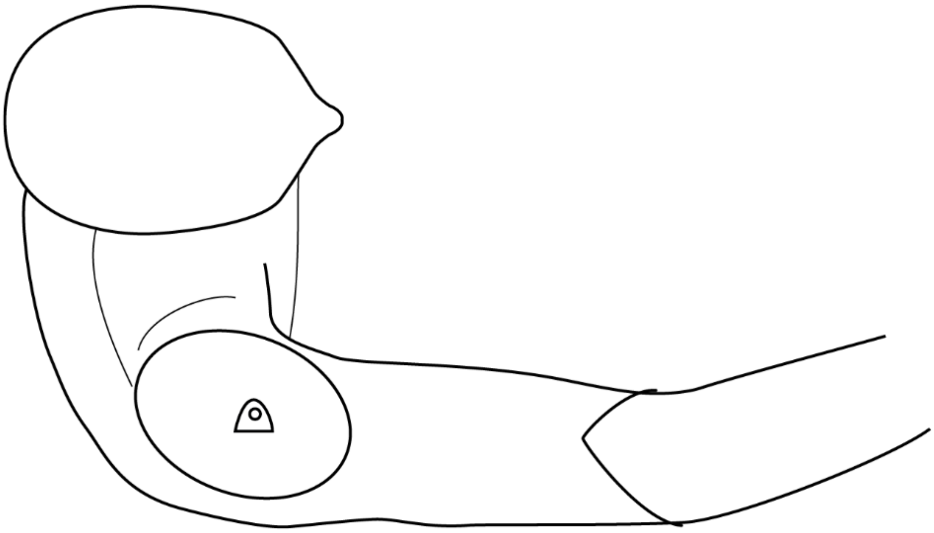


Figure 6.7 Sticky patch directly to skin concept

Advantages are that it could work good for fixating the tower and thus keeping the alignment of the line over the shoulder. It could also follow the shoulder movements exactly since it is attached directly to the skin. Disadvantages are that it could be inconvenient to apply a tower part directly to the skin and also to find the correct placement.

6.2.5 Elastic fabric

The idea is to anchor the tower to an elastic fabric which is integrated with the vest. This concept is essentially the same Fabric integration, described in chapter 6.1.4. Even though it was not chosen in the initial concept selection it can be combined with the Torso anchoring concept.

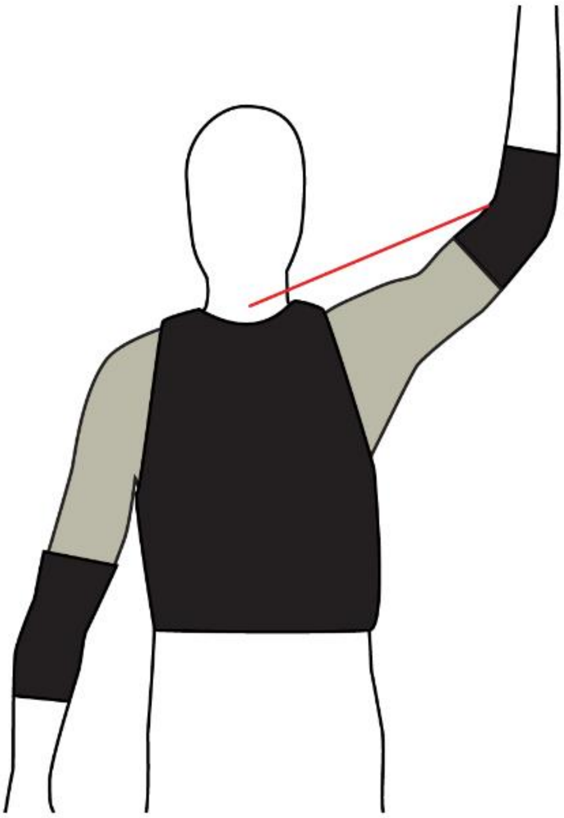


Figure 6.8 Elastic fabric concept

Advantages could be the convenience it would offer to have the entire system integrated into one piece. This would also allow for easier donning and doffing. Disadvantages could be that the tower is not fixed enough when the arm is moved or when there is a large line force.

6.2.6 **Straps**

The idea is to anchor the tower to the backplate via non-elastic straps at suitable locations. This concept is seen as a tool that could be used in combination with other concepts in order to fixate the tower.

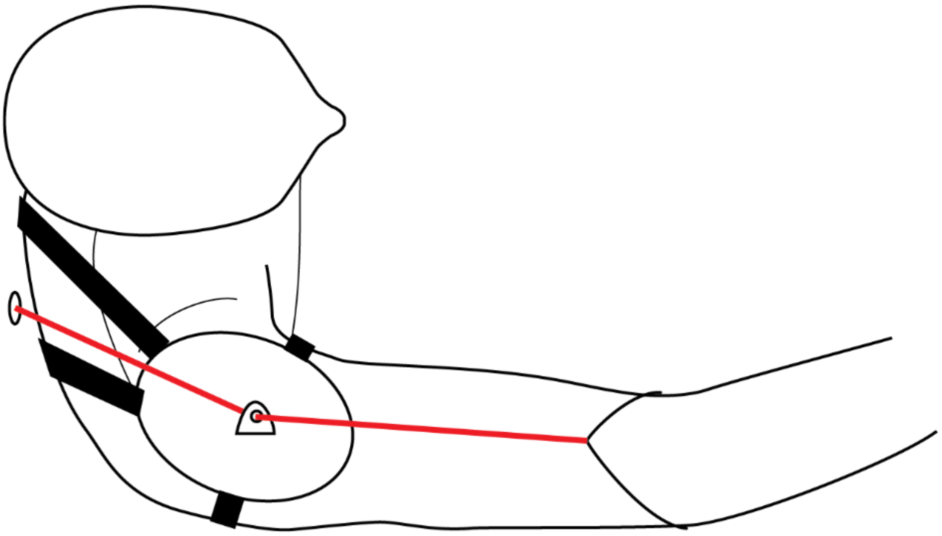


Figure 6.9 Straps concept

An advantage could be high modularity, i.e. straps can be placed at multiple positions to add necessary force anchoring. A disadvantage could be that the straps have to be adjusted manually, which means a lot of adjustments if multiple straps are used.

6.2.7 **Sock**

The following concept as well as 6.2.8 Two hinge are subconcepts of Arm part as seen in the tree diagram in figure 6.3.

The idea is to use a sock-like design to create an anchoring point of the line to the arm. The sock has a tight fit and a conic shape which provides a self-locking mechanism that prevents sliding and therefore allows force transmission to the arm.

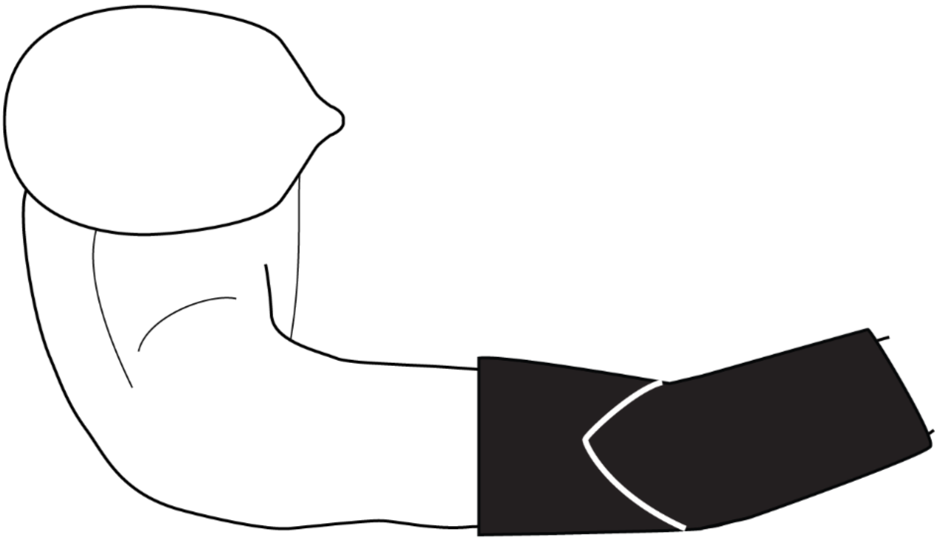


Figure 6.10 Sock

Advantages could be a comfortable fit since it is a soft construction. It is also a simple design without any joint mechanism. Disadvantages could be that it must be rather a rather tight fit around the arm to maintain its position. This can lead to discomfort during extended use. The soft design might also have difficulties to anchor the force at the line insertion point.

6.2.8 Two hinge

The idea is to use a two hinge elbow brace to create an anchoring point of the line to the arm. This is the same concept as used in the previous system.

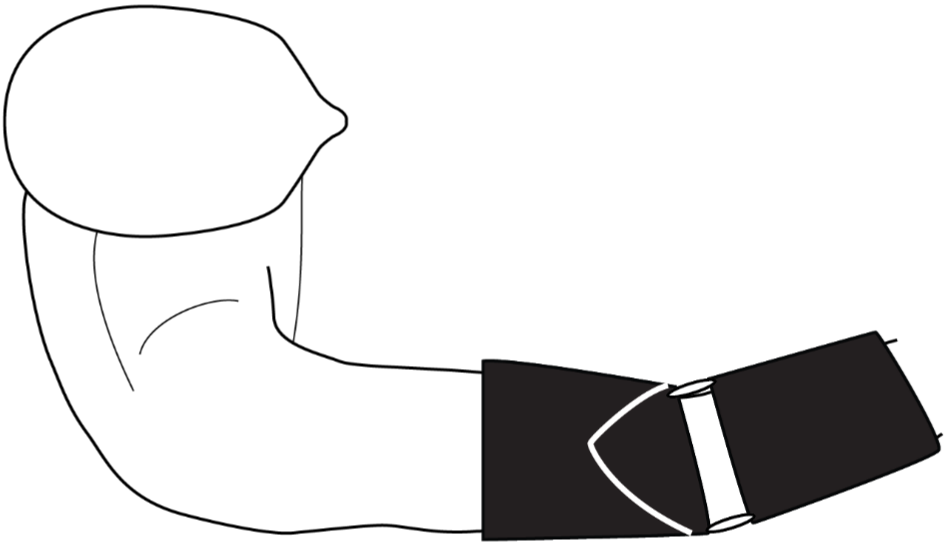


Figure 6.11 Two hinge

An advantage is that it allows mobility of the elbow while anchoring the force to the arm. It also stays in place and aligns around the elbow joint because of its design. In addition, it can be worn outside of clothing and attached with elastic bands to fit various sizes of arms. Disadvantages are that the design contains more parts and can get bulky.

6.2.9 Number of LEBs and position of LEBs

The following concept as well as 6.2.10 Position of straps are subconcepts of Backplate as seen in the tree diagram in figure 6.3.

The option is to either have the line exit back behind the neck – LEB_{center} - or to move them further to the side of the upper back – LEB_{side}. It is expected that the force situation on the vest will differ depending on the position of LEBs.

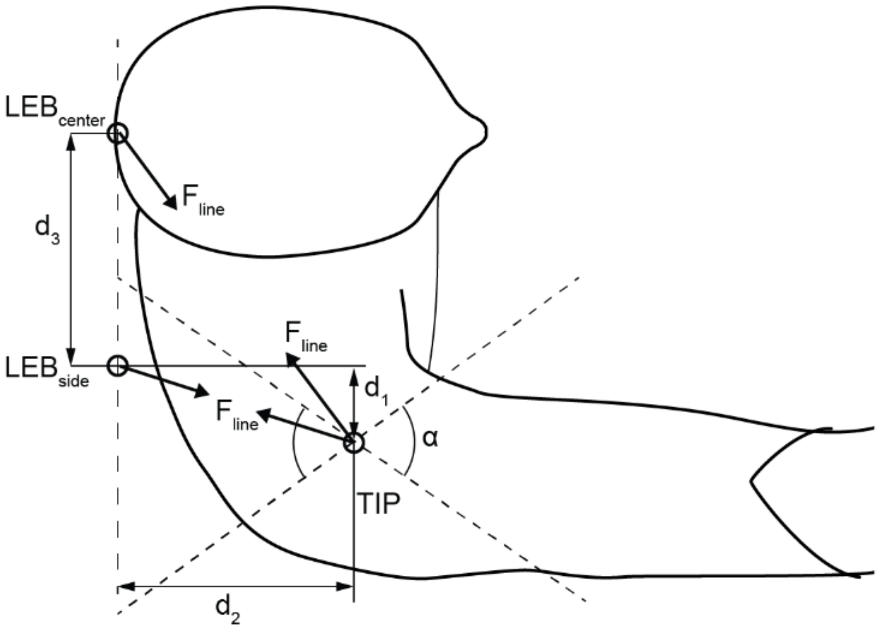


Figure 6.12 Illustration of the position of the LEB relative to the TIP

Advantages of using a LEB_{center} would be a more compact design of the vest. On the other hand, it would the make the tower have to reroute the direction of the line more than the LEB_{side}. This would lead to higher forces on the tower in a plane parallel to the transverse plane and hence require better force anchoring. Advantages of the LEB_{center} are the disadvantages of the LEB_{side} and vice versa.

6.2.10 **Position of straps**

The idea is to use straps to anchor the forces of the backplate to the torso. The concept raises questions about functional and comfortable positions of the straps.

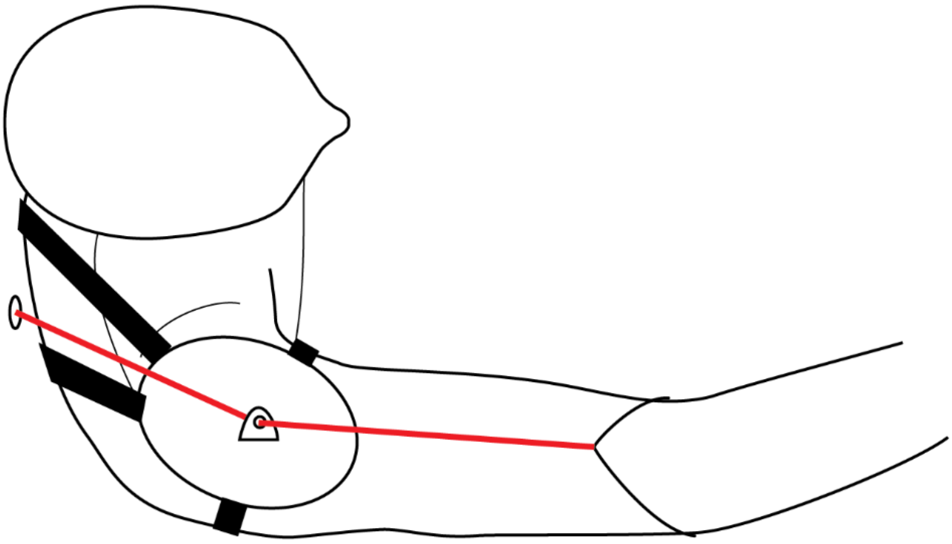


Figure 6.13 Illustration of the position of straps

Force anchoring in a comfortable and rigid way would be essential for a successful product. At the same time, it should be an easy and intuitive donning and doffing of the vest in which the backplate is integrated. Therefore, inspiration is taken from commercial backpacks and the previous prototypes at the company. Because of the complexity of the forces and torques acting on the backplate, and the subjective user experience of comfort, a heuristic approach is used to locate appropriate positions of the straps.

6.2.11 **Position of TIP**

The question corresponds to which position the line should be guided through over the shoulder. The position of the TIP includes both the perpendicular distance from the skin and the position in a plane parallel to the transversal plane as seen in figure 6.14. Previously, it has been argued that the TIP should be aligned with the glenohumeral joint to avoid causing an undesired rotating torque at the joint. However, since the ICR migrates when the arm is elevated, the initial position might be offset.

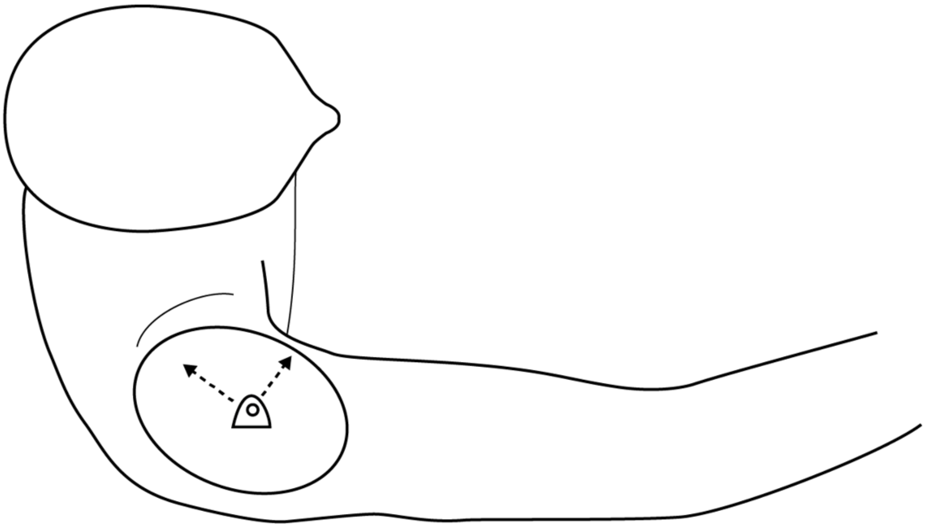


Figure 6.14 The position of the TIP in a plane parallel to the transversal plane

7 First prototype

This chapter describes the development of the first prototype. Including concept selection, prototyping, results of user tests and discussion and conclusion.

7.1 Concept selection

One of the biggest problems with the previous system was that the forces acting on the shoulder part was lead into the shoulder strap. Consequently, it pressed against the neck when lifting the arm which caused discomfort for the user.

As a result, the initial concept selection done with this critical problem in mind. After discussions with the supervisors at the company a set of concepts to be implemented into the first prototype was chosen. The available prototyping material and the estimated time to complete the prototype was also factors when selection the concepts. The concepts are listed in the estimated order of importance to overcome the focused problem:

- Position of LEBs
- Elastic fabric
- Position of TIP
- Straps to backplate
- Position of straps
- Position of attachment point

7.2 Prototyping

The green marks in the tree diagram are the concepts the previously mentioned concepts and questions which were implemented in the first prototype. A previous vest prototype was modified and built upon when creating the first prototype.

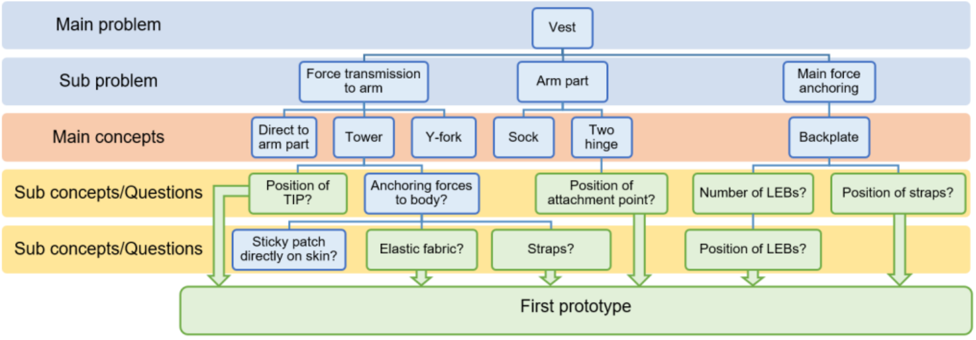


Figure 7.1 Tree diagram of first prototype

By moving the Line Exit Backplate (LEB) from a centered position behind the neck towards the shoulder there would be less force pushing the shoulder part towards the neck. In order to move the LEB, the backplate had to be extended out over the scapula. A sheet of thermoplastic was used to create a plate on which to attach the LEB. First, the plate was shaped by pressing it against the upper part of the back. Secondly, the plate was laminated using polyester and glass fiber to become rigid.

The distance from the centerline of the back as well as the height over the shoulder affects the force situation when lifting the arm. The motivation for moving the LEB further out is to reduce the angle the line is rerouted at the tower of the shoulder part. A straighter line through the tower leads to less force which wants to tilt the tower. A rail which would facilitate adjustment both horizontally and vertically was therefore created. The T-shaped rail was made of spike strips which was held together with bolts. The LEB was created using granulate of thermoplastic and attached to the rail. Three LEB was placed in a row, 60 mm apart and the height was initially 50 mm over the C7 vertebra, as seen in figure 7.3.

As previously mentioned, the shoulder part pressing against the neck was one of the main problems this prototype was meant to solve. Apart from moving the LEB, the design and the anchoring of the shoulder part was also considered since it affected the comfort. Instead of anchoring the shoulder part to the shoulder strap a new design would attach onto elastic fabric with additional straps to hold it in place. A sport shoulder support of neoprene was used as the elastic fabric since it delivered some rigidity in the material yet being comfortable to wear. A shoulder pad was made of a knee protection pad made of rubber which was glued and sewed onto the neoprene shoulder support. A tower was made of granulate of thermoplastic and attached to the shoulder pad. The Tower Insertion Point (TIP) of the tower was 50 mm over the shoulder and aligned over the glenohumeral joint. Towers with TIP of 60 and 70 mm height respectively was also created. This height affects the lever around the glenohumeral joint and hence the required line force.

Several straps were added with the purpose of anchoring forces to the body:

- Strap from the shoulder part to the backplate
- Strap from front and back of shoulder part and around armpit
- Strap from the front of the shoulder part diagonally over the chest
- Strap from shoulder part to elbow brace

The previous elbow brace was modified to test out the Two hinge-concept. The elbow brace had additional attachment points along the upper arm, 50 mm apart, as seen in figure 7.5.

Figure 7.2 Front view of prototype

Figure 7.3 Left: T-shaped rail attached to extended backplate, right: strap from shoulder part to elbow brace

Figure 7.4 Elbow brace with additional attachment points

7.3 Results

All results are extracted after performing the user test (defined in chapter 3.3) on the two authors of this report.

The force transmission to the body feels more comfortable with the LEBs moved out from the centerline of the back. If the exits are far out on the scapula region it effectively reduces the force which pushes the tower on the shoulder part sideways, so that it wants to move in an offset plane parallel to the transverse plane. This side pushing force is minimized if the line is routed in a straight line between the LEB, the TIP and the elbow brace attachment point. For most upper arm movement, this position is between 30 and 120 mm out from the center line.

The vertical position, or the height, of the LEB affects the vertical force acting on the tower and ultimately the shoulder of the user. A higher position means less force pushing down on the user's shoulder when the arm is elevated less than 90 degrees, i.e. less than to a horizontal position. When the arm is lifted above 90 degrees, the height of the LEB has no noticeable effect during the tests.

The position of the TIP should be aligned over the glenohumeral joint in an offset plane parallel to the transverse plane. This is to reduce the rotating torque of the arm in this plane. During the tests, it was often hard to keep the alignment after a few movements of the arm since the flexible textile slid over the user's skin.

The height of the TIP affected the experience of useful lifting force, F_{lift}. Even though no measurements were made the results indicated that a high TIP provided more useful lifting force. At the same time, a high TIP resulted in more rotational tilt of the tower due to increasing moments acting on the tower.

The flexible textile was comfortable to wear, yet it was rather bulky with the 3 mm thickness. There was a tendency that the tower which was attached to it could misalign over the glenohumeral joint.

The straps which were added to keep the shoulder part, and ultimately the tower, in place had different results. The strap to the backplate was effective for anchoring vertical forces. The strap under the armpit was effective at keeping the tower from lifting from the shoulder. The strap over the chest could not handle large forces because of comfort but still provided overall stability. The strap from tower to elbow brace slacked when the arm was lifted but was effective at pulling the shoulder part back into its initial position after the arm was lowered to its vertical resting position. To summarize the results of the straps, they were effective in keeping the shoulder part in place.

The position of the line attachment point of the elbow brace felt more comfortable if it was close to elbow but still on the upper arm part. A position higher up also reduces the lever (see L_1 in figure 5.1) but on the other hand increases the force F_{lift}.

7.4 Discussion and conclusion

When it came to how the LEB position affected the force transmission between vest and body, the results concluded that it was more comfortable if the LEBs were moved out from the centerline of the back. However, the design protruded more from the body than a single exit and of course even more if two LEBs were used instead of a centered one. Especially when those two were positioned far out towards the user's shoulders. This was not in line with company interests and user needs of a slim design with limited protrusion that would work better in confined spaces. Thus, it was concluded that compromises had to be made in order to satisfy different interests in upcoming prototypes.

Results showed that the height of the LEB didn't have any noticeable effect for the user. But from a biomechanical perspective it is likely that a high LEB position could increases the useful lifting force F_{lift} if the TIP allows the line to be straight between the LEB and the elbow brace. However, as it was undesired that the LEBs are protruding, the vertical position was decided to be kept below 70 mm from the backplate's top edge. To summarize, the LEBs was kept in a position moved out from the centerline and at a limited vertical position but the measurements will be decided after more tests.

As seen in the results, the position of the TIP was preferred to be centered over the glenohumeral joint to minimize misalignment. But when it came to the height of the TIP it was less clear. The results showed that if its position was higher it provided more useful lifting force, F_{lift}, but it also protruded more from the body and tilted more due to high moments when forces acted on the TIP of the high tower. The latter also affected the user experience since a higher moment on the tower could be felt as a changed pressure distribution on the shoulder. Conclusion was made that the downsides of having a TIP higher than 50 mm was greater than the upside, so the TIP was kept at that height or lower.

The textile material used had a major problem which was to anchor the forces acting on the tower. Especially when the tower was given a high design which resulted in the increasing moments on the tower. The straps provided necessary anchoring of the forces and moment acting on the tower and ultimately the shoulder part and user. But it was time consuming and impractical to mount and adjust so many straps to the specific user. Thus, it was concluded that forces and resulting moments on the tower had to be limited so less straps could be used for the prototype to be functional.

When it came to the elbow attachment point the conclusion was made to keep it closest to the elbow in the coming prototypes. The reason for this was simply because the results showed that it was the most comfortable setup.

Based on experience from the first prototype the main focus is being put on generating concepts and solutions to the most critical problem; the shoulder part.

8 First iteration of shoulder part

This chapter describes the first development iteration of the shoulder part. Including generation of four shoulder part concepts, concept selection, prototyping, results of user tests and discussion and conclusion.

8.1 Concept generation

8.1.1 **Rigid link**

The concept anchors the forces of the shoulder part through a rigid link to the shoulder strap. This is how the shoulder part of the previous system was constructed. Although the shoulder part of the previous system caused discomfort during the lift, the concept behind it could be used and improved. The motivation for this concept was its high potential to anchor the forces from the tower.

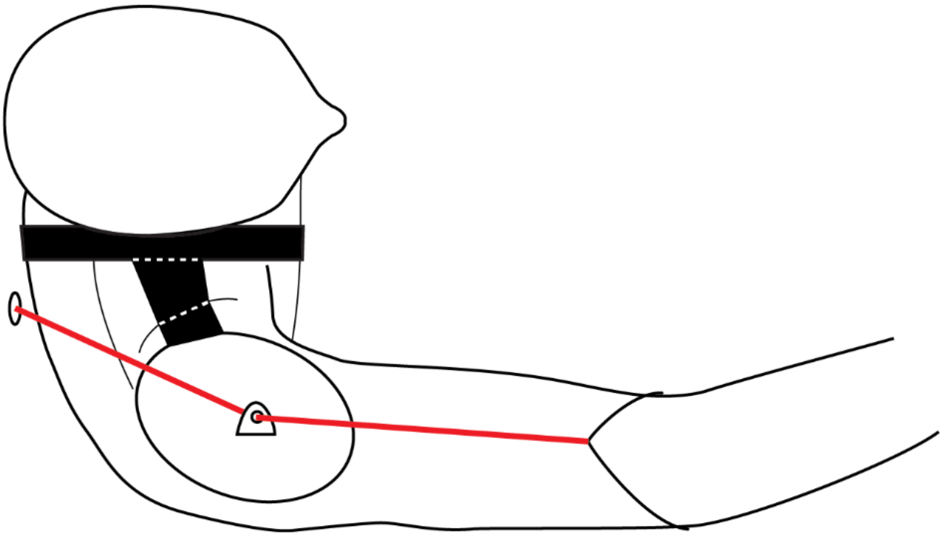


Figure 8.1 Rigid link

8.1.2 **Flexible plate**

The concept is similar to the proposed rigid link concept but the hinges and plates are replaced by a softer polymer plate. The advantage is that it is fewer parts and that the material can bend more organically, compared to the rigid link.

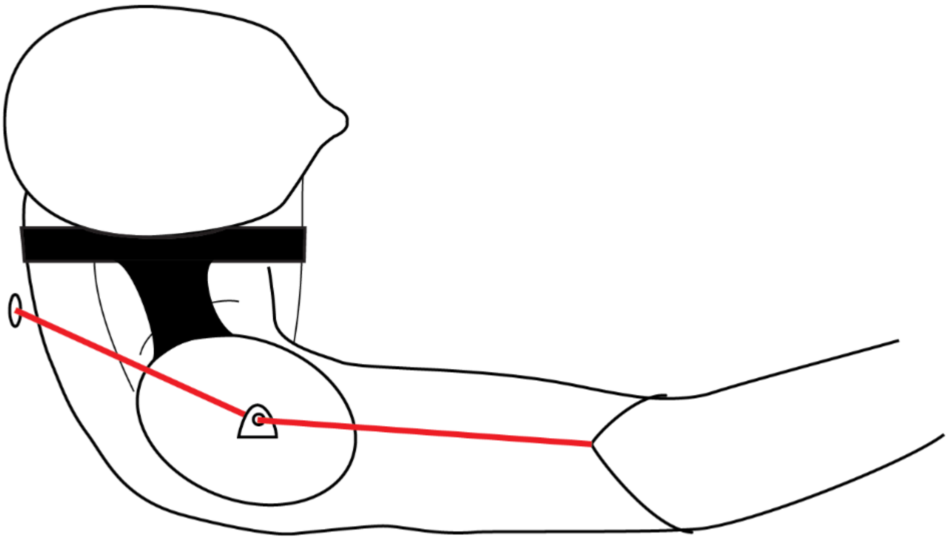


Figure 8.2 Flexible plate

8.1.3 **Soft attachment**

This is an iteration of the elastic fabric concept from the previous chapter. The improvement would be to use a thin and tight fitted shirt instead of the thick neoprene material used previously. The tower at the shoulder part would also be improved by making it lower. The shoulder part needs to be kept in place with either straps or alternative attachments.

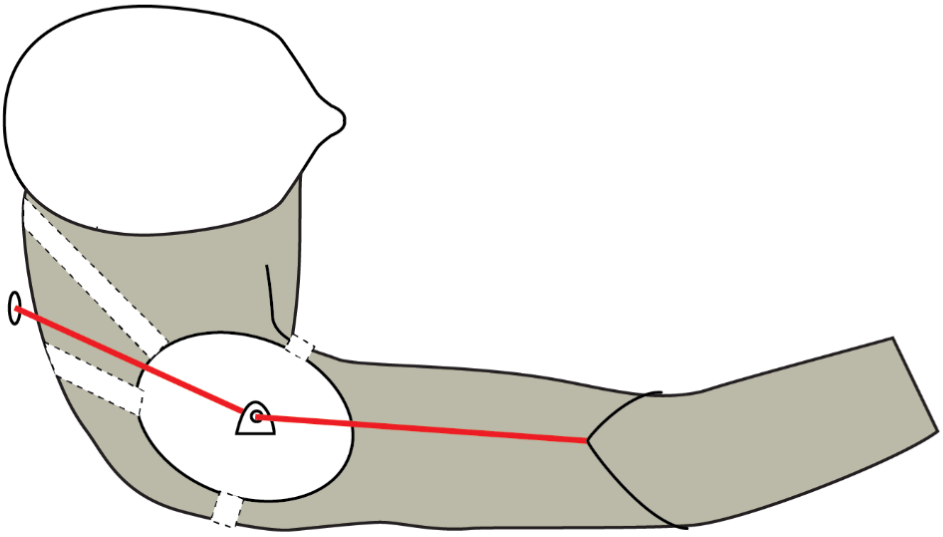


Figure 8.3 Soft attachment

8.1.4 Clavicle aligned support

The concept would use a stiff rod which is aligned with the clavicle to keep the shoulder part in place. The idea behind the rod being aligned with the clavicle was to try to mimic its guiding function of the shoulder. The concept would be combined with the Soft attachment to keep the shoulder part correctly align on top of the shoulder.

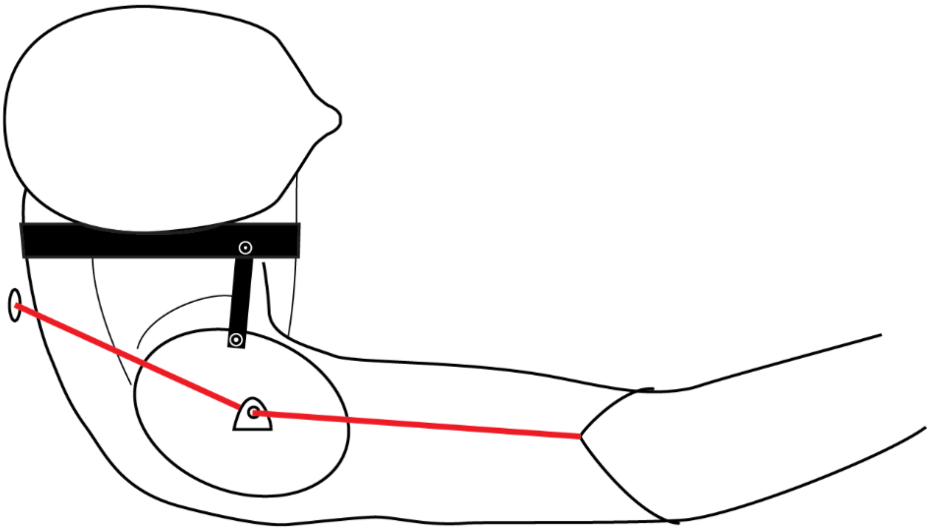


Figure 8.4 Clavicle aligned support

8.2 Concept selection

The shoulder part concepts are evaluated in the concept scoring matrix seen in table 8.1.

Table 8.1 Concept scoring matrix

	Rigid link	***Flexible plate***	***Soft attachment***	***Clavicle aligned support***
Force anchoring	+	0	-	0
Comfort	-	0	+	0
Mobility	-	-	+	0
Continue development	NO	NO	YES	YES

8.3 Prototyping

The green marks in the tree diagram, as seen in figure 8.5, are the concepts and questions which were implemented in the prototype. The vest and T-shaped rail from the first prototype continued to be used and improved in this prototype.

Based on the scoring matrix in table 8.1 and discussions, the Soft attachment and Clavicle aligned support was combined and constructed.

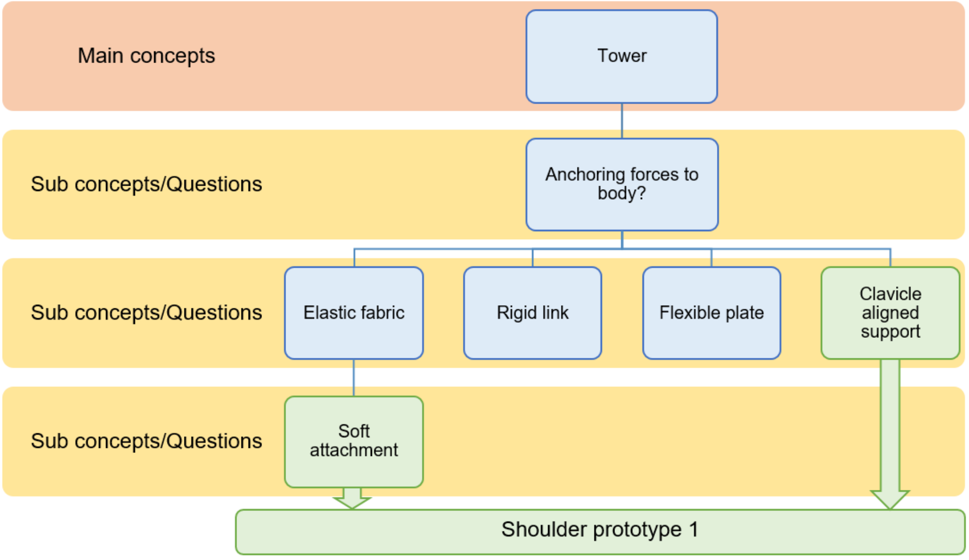


Figure 8.5 Tree diagram of first iteration of shoulder prototypes

A thin, tight fitted sport shirt was used as the base to create the Soft attachment and Spring support concept, which can be seen in figures 8.6. A foam protection pad was attached to the shoulder of the shirt using Velcro. The Velcro attachment made it possible to adjust the position of the shoulder part therefore accommodate for anatomical variations. A tower was made of polymorph and attach to the pad. The TIP was positioned 40 mm over the shoulder, which is lower than the first prototype. This was done to make it more stable and reduce the risk of tilting. The Spring support was created with a wooden rod, a polymorph socket and pocket inserts at the shoulder strap of the vest.

Based on the experience from the first prototype, straps were added under the armpit (A), diagonal to the shoulder strap (B) and to the backplate (C), which can be seen in figures 8.7-8.8.

Figure 8.6 Front view of the prototype

Figure 8.7 Clavicle aligned support as wooden rod with straps

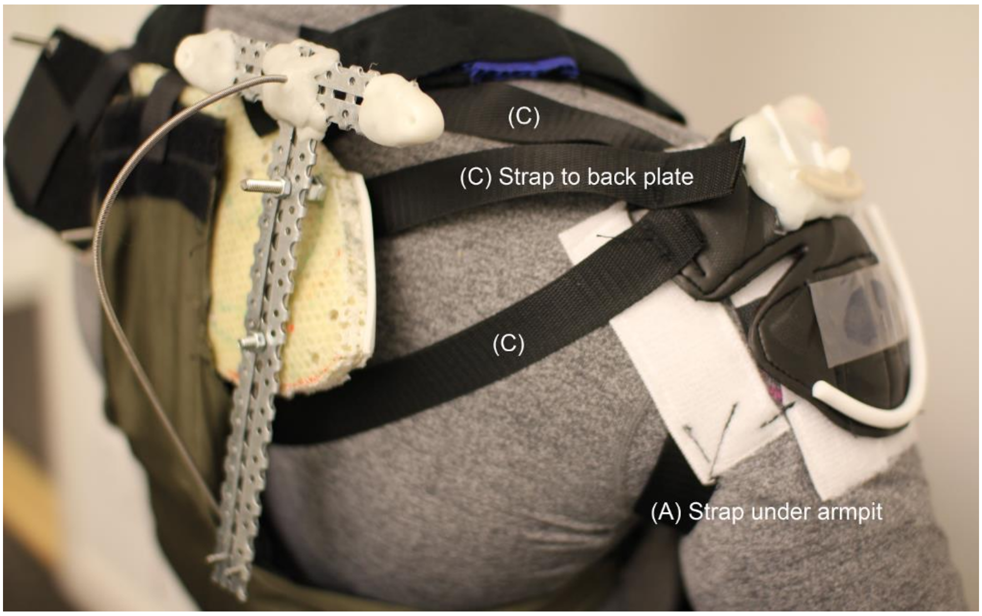


Figure 8.8 Soft attachment concept with multiple anchoring straps

8.4 Results

All results are extracted after performing the user test (defined in chapter 3.3) on the two authors of this report.

The Soft attachment concept, which was built upon the tight sport shirt, was comfortable to wear under operation. However, the alignment of the TIP was unpredictable when tested on different tests subjects. This was because the shoulder part moved and didn’t show a consistent and predictable behavior. It demands that the length of the straps is adjusted precisely to the user.

The anchoring straps provided different results. The most effective one was the diagonal straps over the chest. It effectively kept the shoulder part from sliding towards the backplate during movements. The strap under the armpit pulled the shoulder part down into its initial position when the arm was lowered but did not anchoring the forces very well. The straps from the shoulder part to the backplate were effective at stopping it from sliding forward but only when multiple straps, covering different angles, were applied at the same time.

The Clavicle aligned support was tested without any additional straps for anchoring the shoulder part. It succeeded in keeping the tower from ending up close to the neck when the arm was elevated, but was uncomfortable under operation. It could mimic the function of the clavicle if it was placed high up on the shoulder strap, but then it pressed into the chest or neck when the arm was lifted above 90 degrees. In this prototype, a stiff wooden rod was tested as a first step.

8.5 Discussion and conclusion

Even though the Soft attachment concept was comfortable to wear, the many straps attached to the concept made it unpractical. Especially, donning and doffing could not be made in an easy manner since every strap had to be individually fitted. But since the straps only were added to handle the external forces acting on the tower, and ultimately the shoulder part, it could be possible to figure out another way to handle those forces. A way that would be more practical than adding another strap.

The Spring support concept didn't deliver as hoped. Even though it could anchor some of the forces acting on the shoulder part, and lead those forces to the shoulder strap of the vest, it couldn't anchor them in a comfortable way. The main reason for this was that the magnitude of the force was too great to handle for the shoulder strap which collapsed under to load and pushed hard on the users' chest or neck.

Also, it was difficult to align the rod with the clavicle to mimic its behavior. This was the main idea since it was expected to follow the motion of the shoulder part in a natural way and anchor forces in the same way as the clavicle does in the human body. Instead, it didn't follow the clavicle and became a motion restrictive experience for the user when trying to lift the arm.

Granted that the Spring support concept would have showed more promising results, a compressible spring would have been tested instead of a stiff rod. But due to its results, the Spring support concept was abandoned after the initial tests.

9 Second iteration of shoulder part

This chapter describes the second development iteration of the shoulder part. Including concept selection, prototyping, results of user tests and discussion and conclusion.

9.1 Concept generation

The idea generating continued and new concepts were sketched. The first two describe concepts which anchors the shoulder part to the backplate, which was possible with the extended backplate of the vest.

9.1.1 **Rigid link to backplate**

The Rigid link to backplate concept consists of rigid shoulder part with two degrees of freedom. Being rigid would make it easier to route the forces acting on the tower to the backplate.

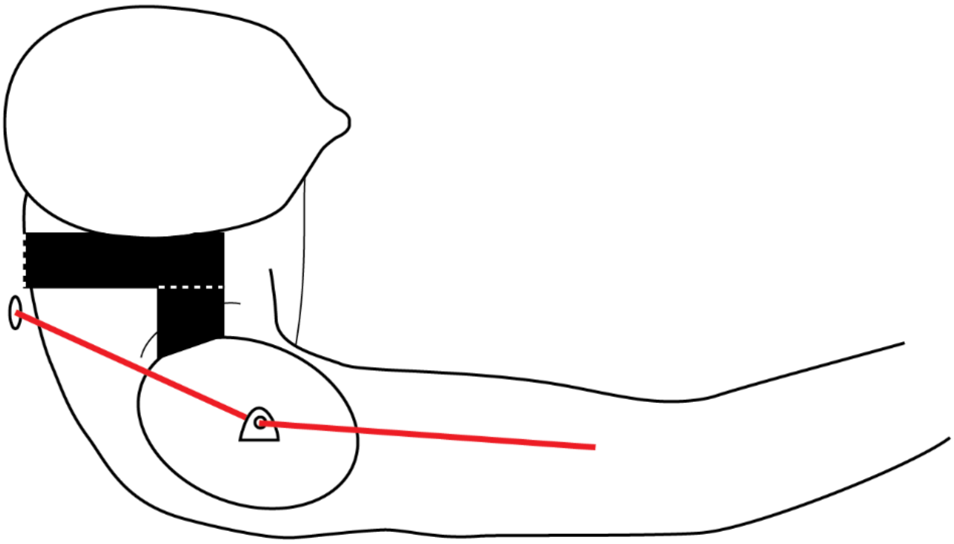


Figure 9.1 Rigid link to backplate

9.1.2 Flexible plate to backplate

The concept is similar to the Rigid link to backplate concept in the way that it is anchored to the backplate. The difference is that the shoulder part is made of a flexible material such as a polymer and will bend without using any hinge.

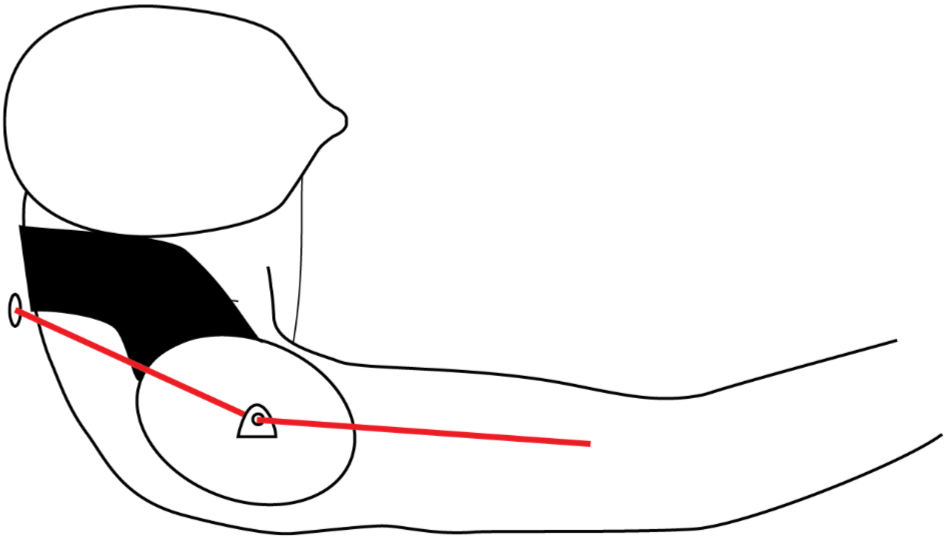


Figure 9.2 Flexible plate to backplate

9.1.3 **Foam**

A piece of foam will anchor the shoulder part the shoulder strap. The foam needs to be able to compress yet offer resistance when the shoulder part presses against it. The rebound effect of the foam is supposed to push the shoulder part back into place.

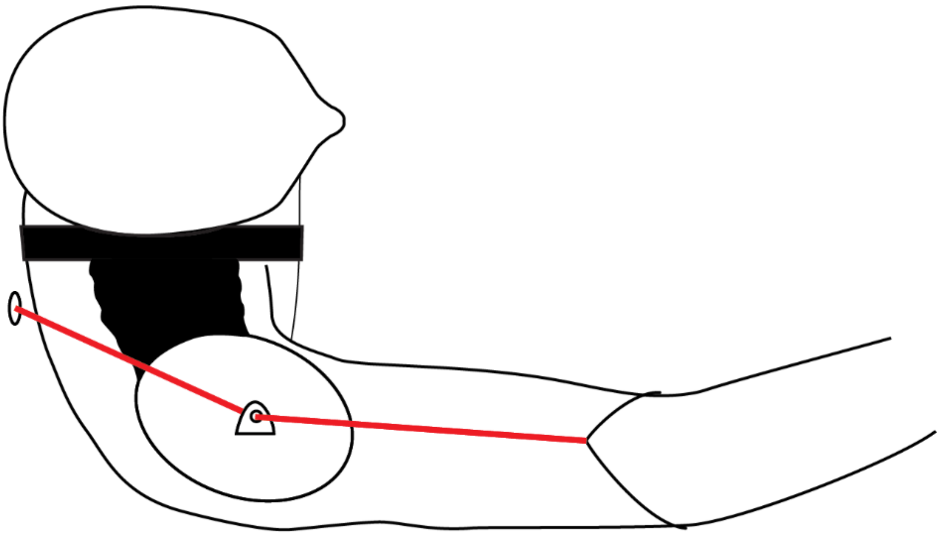


Figure 9.3 Foam

9.1.4 **Spring**

Similar to the foam concept, but it uses a mechanical spring to push the shoulder part in place. The spring would not lay in the same plane as the compression, so it would allow for greater compression of the space between the shoulder and the back.

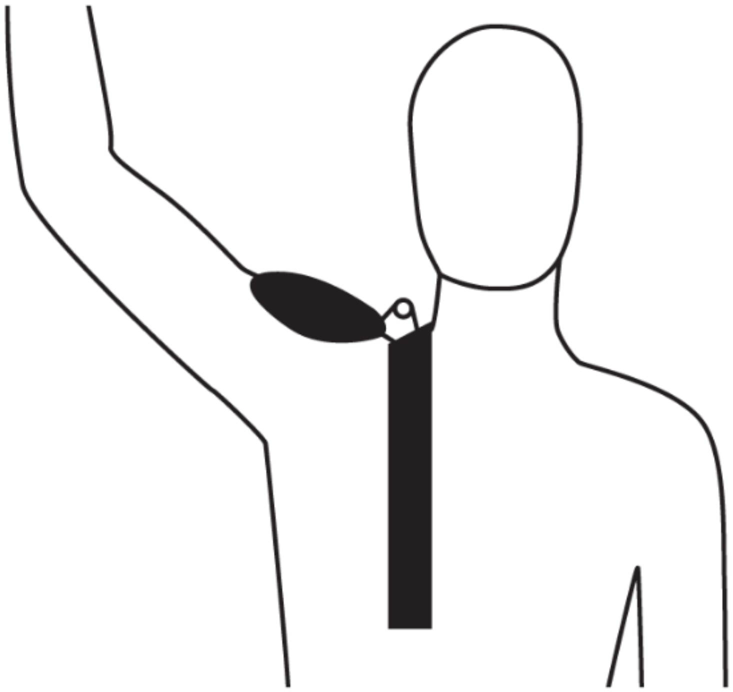


Figure 9.4 Spring

9.2 Concept selection

The concepts are compared in relation to one another using the concept selection matrix seen in table 9.1. In addition to the concept scoring matrix used in chapter 8.2, this one includes simplicity and compactness.

Table 9.1 Concept scoring matrix

	Rigid link to backplate	***Flexible plate to backplate***	***Foam***	***Spring***
Force anchoring	+	0	0	0
Comfort	0	0	0	0
Mobility	+	-	-	-
Simplicity	0	+	0	-
Compactness	-	0	0	0
Continue development	YES	YES	NO	NO

9.3 Prototyping

The green marks in the tree diagram, seen in figure 9.5, are the concepts and questions which were implemented in the prototype. Based on previous experience and the scoring matrix from figure 9.1, the two concepts which anchor forces directly to the backplate were chosen.

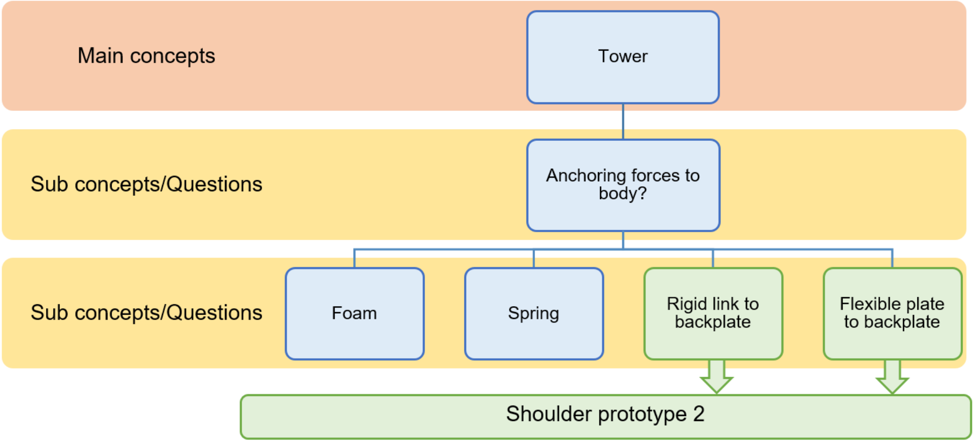


Figure 9.5 Tree diagram of second iteration of shoulder prototypes

First, paper models were made to test out the angle and dimensions of shoulder parts for the two concepts. Secondly, metal plates were cut in and joined together with hinges for the Rigid link concept and a sheet of thermoplastic for the flexible plate concept. Shoulder pads was made of foam and the towers out of granulate thermoplastic, just as in previous prototypes.

Initially, the metal pieces in the Rigid link prototype was connected with two hinges. However, after testing the prototype, the hinge closest to the backplate was removed because it did not add more mobility to the arm movement. In addition, by having two hinges, the shoulder part was more unstable in some positions. Therefore, the back hinge was exchanged to a rigid metal piece which attached to the backplate. The Flexible plate and Rigid link to backplate prototypes can be seen in figures 9.6 and 9.7 respectively.

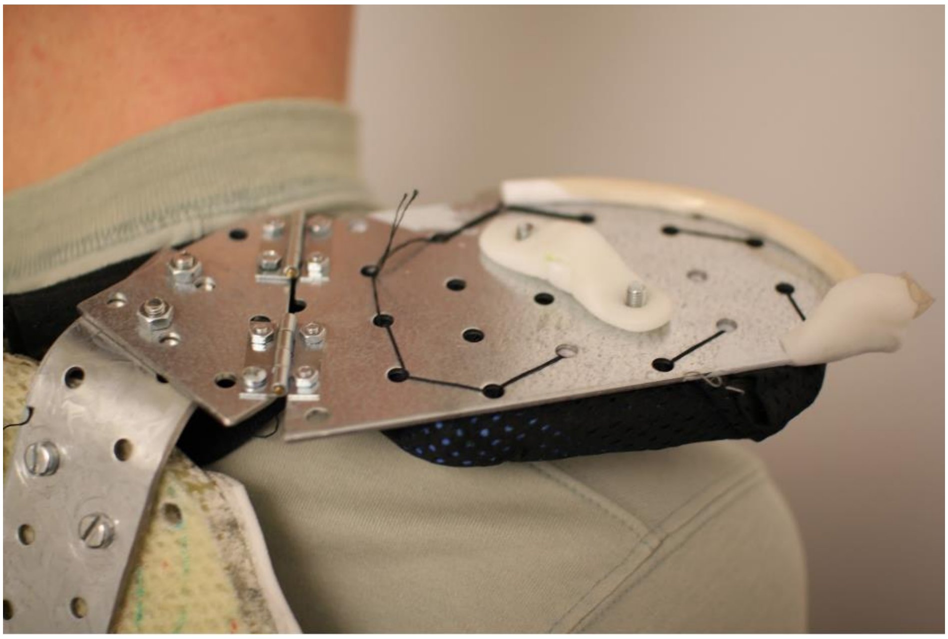


Figure 9.6 Prototype of the concept Rigid link to backplate

Figure 9.7 Prototype of the concept Flexible plate to backplate

9.4 Results

All results are extracted after performing the user test (defined in chapter 3.3) on the two authors of this report.

The Rigid link concept showed good results when it came to anchoring the forces acting on the tower. As expected, the shoulder part was constrained to only one degree of freedom and behaved in a consistent and predictable manner. But since the material was stiff and the degrees of freedom was limited it had problems following the motion of the user's shoulder complex. It also proved to become very restrictive to some shoulder motions if the user didn't fit it to the body properly.

The Flexible plate concept showed similar results as the Rigid link concept. It could anchor the forces acting on the tower even though material deflection due to these forces were noticeable. A problem was that it restrained the arm from lifting since it did not have a hinge to bend at but depended on deflection of the material itself. But since it bent more gradually over its deformation zone compared to hinge of the Rigid link concept, the users experienced a more organic feeling.

A key finding from the testing of the prototypes was that a small area at the trapezius, seen in figure 9.8, was beneficial for placing a fixed plate to anchor forces. This area did not move or compress considerably when the arm was lifted.

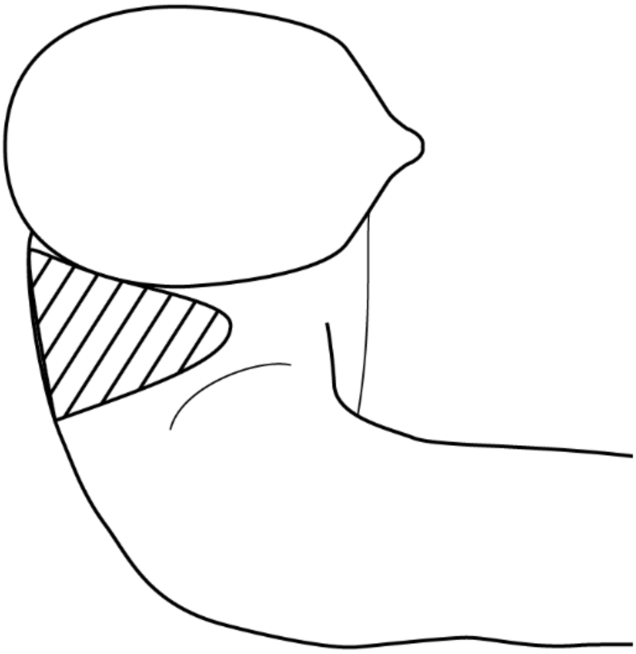


Figure 9.8 The small area at the trapezius that was beneficial for placing a fixed plate

9.5 Discussion and conclusion

The Rigid link concept proved to be a very solid solution to the problem of anchoring the forces acting on the tower. But its non-flexible material and mechanical hinge could give a stiff exoskeleton feeling not in line with the company interests of a smooth, soft and organic solution. The stiffness also had the downside of not being very forgiving to misfits while putting it on which could become a problem if the user, for any reason, can’t fit it properly. Then it could become uncomfortable to wear of even lose its functionality.

The Flexible plate concept had the advantage of a more smooth, soft and organic feeling since the material itself deformed and followed the shoulder complex. This was in line with the company interests while still being able to anchor the forces acting on the tower. But as the results showed, a problem was that the force required to bend the polymer pushed down on the shoulder while lifting the arm. This was unwanted but to some extent necessary since the polymer needed to have some stiffness to withstand the forces acting on the tower.

The key finding of the small area at the trapezius was valuable since a major design problem up until this point had been that the distance between the shoulder and the neck compresses a lot when the arm was lifted. This made it difficult to locate any position where the forces of the shoulder part could be anchored without restraining or restricting the motion of the shoulder complex. Especially as the forces of the shoulder part had proven to be of a magnitude above what previously developed concepts could handle in a satisfying way.

Another aspect is that a force anchoring in this area could open the possibility of a more simplistic design. This means a design that is more intuitive and easy to use and hopefully requires less adjustments when donning and doffing, i.e. increased usability.

At the same time, clear company direction stated that the product should be experienced by the user as soft and organic which was more in line with the previously developed softer prototypes. This also had to be considered during further development.

In conclusion, it was effective to anchor the forces of the shoulder part to the backplate and the area at the trapezius was suitable for anchoring these forces while maintaining mobility of the shoulder complex. Both prototypes were therefore kept to undergo user tests.

10 User tests of shoulder part prototypes

This chapter presents a description of the user tests of selected shoulder part prototypes. Followed by its results and discussion and conclusion.

10.1 Descriptions and details of user tests

User tests, as described in chapter 3.3, were performed on test users 1 and 2, the first was a welder in manufacturing industry and the second was a student in the biomedical field. The tests were mainly performed to gather information for decision support in selecting a final shoulder part concept to develop. Focus was put on this problem since it was considered the most critical one for developing a successful prototype.

In addition to the user test, the test persons filled in a user grading of the perceived mobility, comfort, relief and overall impression.

The user test and grading were made between the three shoulder part anchoring prototypes with the highest potential of success; Soft attachment, Rigid link to backplate and Flexible plate to backplate. These concepts were subjectively chosen after consultation with the company management.

In addition to the user test with resulting grading, the test also had the purpose of gathering information about the perceived usability, ergonomics and level of intuition to use the product in the intended way. These user inputs were also taken into consideration for further development even though they are not explicitly formulated in the upcoming grading system and final concept selection.

The final concept selection of the concepts was done by combining two types of grades:

- User grading from the user tests combined with a weight factors
- Additional criteria that are solely graded by the authors

Both of which are described in more detail and presented with their respective results in the upcoming sub chapter.

10.2 Results

10.2.1 **Grading with weight factor**

The results from the user tests were extracted from a visual analog scale that was filled in by the test persons. One analog scale was used for each of the four tested criteria; mobility, comfort, relief and overall impression. The results from the scales were discretized into a corresponding number between 1-10 and the mean value of the test persons grading were then multiplied by a weight factor called *Weight of Development Potential* (Weight DP) that was set by the authors. The visual analog scales that were filled in by the test persons can be seen in appendix D.5.

The weight DP is a factor that is introduced by the authors. The factor used to compensate for different maturity levels of prototypes. For example, the Rigid link to backplate prototype had been given only half of the development time given to the Soft attachment prototype, which especially affected the comfort refinements. As such, it is also likely to have negatively affected the test persons grading of the comfort of the Rigid link prototype. Therefore, comfort of the Rigid link prototype is positively weighted using the weight DP factor.

Subjectively applying this methodology to the three concepts result in table 10.1 below.

Table 10.1 User tests grading with weight factor

User tests	***Soft attachment***		***Flexible plate to backplate***		***Rigid link to backplate***	
	Mean test persons	***Weight DP***	***Mean test persons***	***Weight DP***	***Mean test persons***	***Weight DP***
Mobility	7	+ 0%	6	+ 10%	6	+ 0%
Comfort	8	+ 0%	7	+ 10%	6	+ 20%
Relief	5	+ 0%	5	+ 5%	6	+ 0%
Overall impression	6	+ 0%	5	+ 0%	4	+ 0%

As seen in the matrix, the soft concept has a weight DP factor of magnitude 0 % in all criteria. The reason for this is simply that the soft prototype has the highest level of maturity of all present prototypes and is therefore used as the reference.

10.2.2 **Additional criteria and final grades**

Since the user tests only could cover a limited number of criteria, while still keeping the duration of the test within reasonable limits, additional criteria and grades that are considered to be of importance are added. These criteria are simplicity and compactness.

Compactness is defined as not having parts protruding from the body. Simplicity is defined by two parts; simplicity from a construction perspective and simplicity from a functional perspective. The latter means that the functions of the construction elements and their interconnections are readily understood. This is important since it means that the engineering team has a better understanding of how the product works which creates a solid foundation for further development.

This system results in the selection matrix system seen in table 10.2 below. Note that the sum of the total points has been rounded to the nearest integer.

Table 10.2 User tests grading with weight factor and additional authors grading

User tests	***Soft attachment***		***Flexible plate to backplate***		***Rigid link to backplate***	
	Mean test persons	***Weight DP***	***Mean test persons***	***Weight DP***	***Mean test persons***	***Weight DP***
Mobility	7	+ 0%	6	+ 10%	6	+ 0%
Comfort	8	+ 0%	7	+ 10%	6	+ 20%
Relief	5	+ 0%	5	+ 5%	6	+ 0%
Overall impression	6	+ 0%	5	+ 0%	4	+ 0%
Authors tests	***Authors***		***Authors***		***Authors***	
Simplicity	4		6		7	
Compactness	6		7		7	
Total points	36		38		37	

As seen, the concept with the highest total score is the Flexible plate concept. Consequently, this is the shoulder part concept to be integrated in the final prototype.

10.2.3 User comments

Even though the final concept is chosen, the most prominent and important user comments are provided in this subchapter.

The most commented user experiences had to do with the mechatronic system and can be summarized as two points:

- The actuators of the mechatronic system pull the line in too slow to supporting lifting of the user’s arms during faster dynamic movements.
- The mechatronic system should not assist as much when the arms are lowered. I.e. it should allow the user to readily lower the arms without having to push them down.

Beside the mechatronic system, other important user input had to do with the comfort of the vest. Users commented on regions of the vest that produced an uncomfortable pressure on the back during operation. Those regions were mainly located in the area of scapula motion since it couldn’t move freely enough and also because of sharp curvature of the backplate. A more neutral and flat shape of the backplate was preferred by the users.

The level of intuition of the straps was also commented on. The users preferred a strap setup similar to other well established strap systems, e.g. the ones used on backpacks.

10.3 Discussion and conclusion

The user tests provided invaluable input about the user experience of using the prototypes. Even so, uncertainty of the tests could be high.

One reason is that only two user tests were performed because of time limits within the project. More user tests would have provided more reliable data. Another uncertainty can be seen within the grading system. The user graded the prototypes performance in reference to their non-hooked-up arm but since it could be differences between a person's arms, this could also be misleading.

Another very prominent factor was the mood of the test person. During testing of the first prototype the user seemed to be in a more energized and positive state of mind, which could result in a positive bias towards the prototype tested at that moment. At the end of the user test, about one hour later, the test persons seemed less energized and positive, which resulted in a negative bias towards the prototype tested at that moment. To prevent this effect, the order of the prototypes to be tested was inverted between the two test persons. But it still demonstrates how subjective and uncertain these kind of user tests can be.

Focusing on the results, the user tests showed that the main concerns of the users were the performance of the mechatronic system and not the vest itself. This problem was important to address to company management but was not to be solved within the scope of this thesis since it mainly focused on the development of the hardware parts of the vest.

As seen in the grading table 10.2, it was almost a tie between the prototypes. Especially between the Flexible plate and Rigid link concepts, only differing 0,35 points if neglecting the round of. But after additional discussions with company representatives it stood clear that the more organic Flexible plate concept was more in line with the company interest. Contributing to the decision of continuing its development.

The input about uncomfortable pressure zones on the back while using the prototype was prioritized and lead to a reshape of the backplate in the upcoming chapters. The main ideas were to flatten out the sharp curvature of the backplate and shorten the length of the backplate, but also to open up the scapula region to promote mobility.

11 Refinements of concepts

Before starting the construction of the final prototype the shoulder part, the LEB and backplate were refined to see if a number of improvements could be implemented. This process is described in this chapter.

11.1 Prototyping

In order to obtain a correct alignment between the TIP and the glenohumeral joint, a shoulder part which could be adjusted was created. This would facilitate variations in shoulder width and position of the shoulder to the torso. To obtain the possibility of adjustment while still maintaining a soft, organic and smooth product appearance, as asked for by company management, it was decided to use a Velcro attachment with a strap lock as seen in figure 11.1-2.

In addition, the LEB was redesigned with a fixed position. The position was chosen by combining two methods. First, a heuristic approach to find the position that gave the most comfortable pressure distribution on the back combined with the most efficient and rigid force anchoring of the vest. The latter is of importance since it both provides a more solid product feeling and a more predictable product performance.

Secondly, by measuring the loss of force in the line as a function of different LEBs positions. This loss is due to friction while the line passes through the system, namely when the Bowden cable is bent. The test was limited to only change the LEB position and arm elevation angle while keeping the TIP position constant and served the purpose of getting a brief understanding of how the position of the LEB affected the force loss in the line.

Figure 11.1 Adjustable shoulder part using Velcro as attachment

Figure 11.2 Shoulder with Velcro attachment.

11.2 Friction test setup

The setup of the friction test can be seen in figure 11.3. A weight of 3 kg was hung in one end of the line and a digital dynamometer was used to measure the force (in kg) at the other end of the line.

The test person held his arm at different angles while the force in the line was measured. Both a centered position of the LEB and a displaced position (6 cm towards the shoulder) was analyzed. Also, a relative change in the height of the LEB was analyzed, called high and low positions.

Figure 11.3 Friction test setup

11.2.1 **Results**

Table 11.1 Results of the line force at different arm angles. Applied force was 30 N.

Arm position	***Abduction/adduction***		***Flexion/extension***	
LEB horizontal position	***Center***	***Side (6cm)***	***Center***	***Side (6cm)***

45 degrees	17 N	19 N	17 N	20 N
90 degrees	17 N	21 N	18 N	21 N
135 degrees	24 N	21 N	21 N	21 N

Arm positions	***Abduction/adduction***		***Flexion/extension***	
LEB vertical position	***Low***	***High***	***Low***	***High***
45 degrees	21 N	23 N	22 N	25 N
90 degrees	2,2 N	2,2 N	2,2 N	2,4 N
135 degrees	2,1 N	2,1 N	2,2 N	2,2 N

11.3 Discussion and conclusion

As seen from the results in table 11.1, the position of the LEB clearly affects this loss. A LEB positions further out towards the shoulder decreases the undesirable loss of force in the line and vice versa.

The difficult part when choosing the position of the LEB was to find the best balance between the subjective user experiences and the task of minimizing the frictional loss in the system.

From user tests, input about uncomfortable pressure zones on the back were considered by flattening out the sharp bowl-shaped curvature of the backplate. Also, material was removed in the scapula region of the backplate to provide a more comfortable pressure distribution as well as enhanced mobility for the user.

12 Final prototype

This chapter includes the making and tests of the final prototype which incorporated the experience gained from previous prototypes.

12.1 Overview

The final prototype can be divided into six parts; backplate, straps, LEB, shoulder part, mechatronic cases with belt and elbow braces as seen in figure 12.1-12.3.

Figure 12.1 Front view of the final prototype

Figure 12.2 Back view of the final prototype

Figure 12.3 Side view of the final prototype

12.2 Backplate

The backplate acts as the fundament of the prototype. It contributes with stability, rigidity and capability to anchor forces in the system.

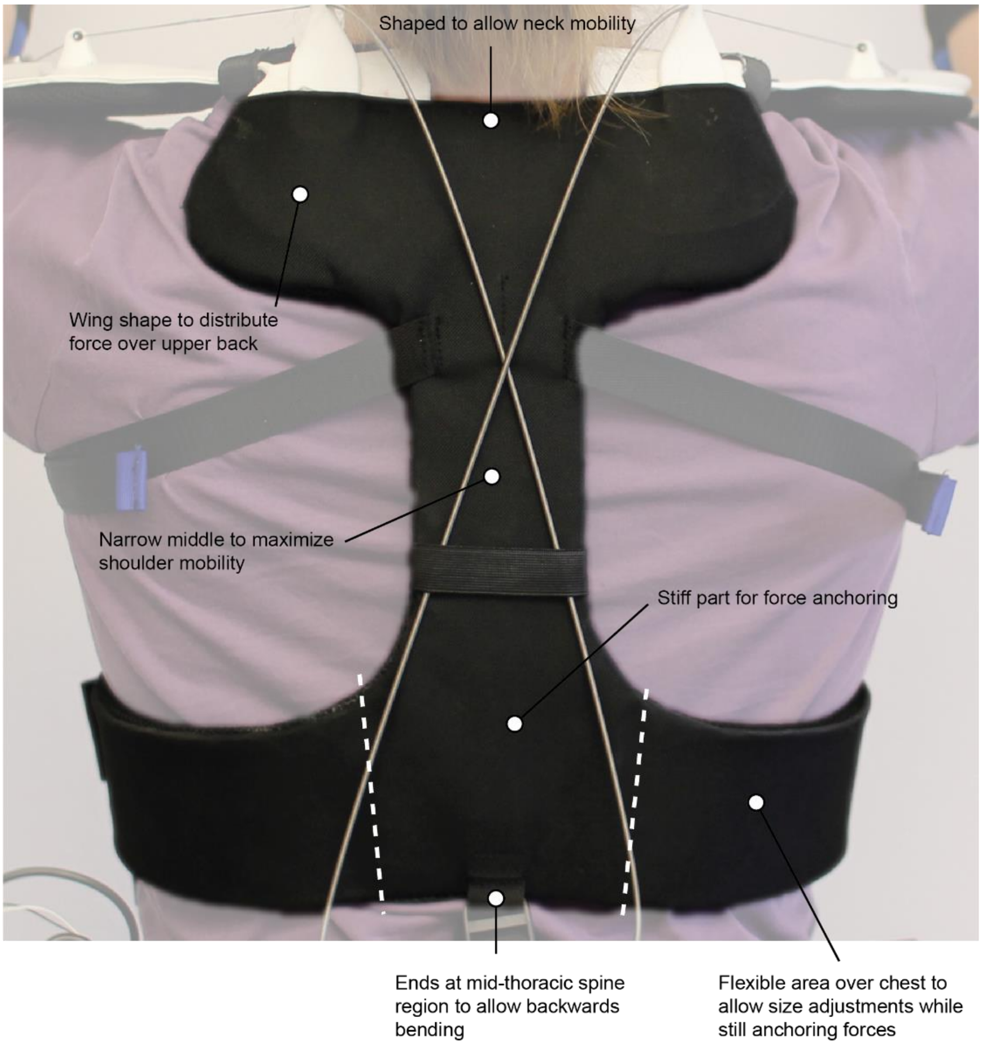


Figure 12.4 Detailed view of the backplate of final prototype

It was created by first cutting and forming a thermoplastic matrix. It was then reinforced using glass fiber and polyester before applying a stiff synthetic fabric on the back to enhance force transfer from the straps to the backplate. Finally, a soft memory foam covered with a mesh fabric which was applied on the front to enhance comfort.

12.3 Straps

The main functions of the straps are to provide individual adjustment possibilities and to provide force transmission between the body and the vest. Both of which are important for product functionality and user comfort.

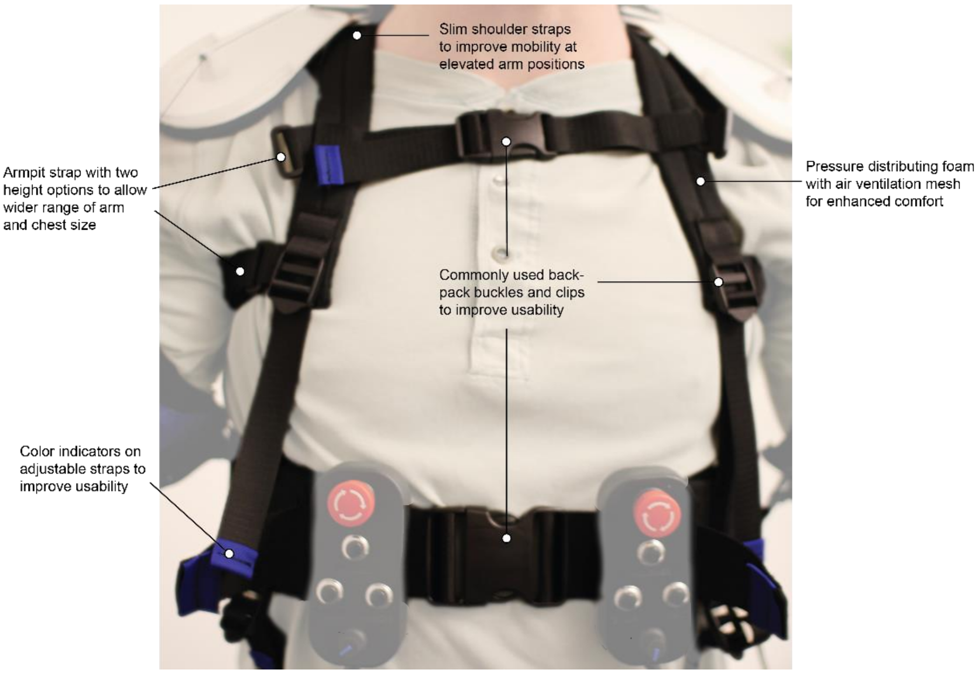


Figure 12.5 Detailed view of the straps of the final prototype

The straps were created by cutting and sewing non-elastic polymer straps directly to the stiff fabric covering the backside of the backplate. The pursued stiffness was used to ensure rigid force anchoring between body and vest. Suitable plastic buckles and Velcro were added to lock the straps, provide intuitive use and user comfort.

Finally, the shoulder straps, which were exposed to high forces, were sewed using a combination of foam, mesh and stiff fabric. The first two materials were used to enhance comfort for the user while the stiff fabric provided the force transmission capability.

12.4 Line exit back

The LEB is used to regulate the exit positions of the lines coming from the actuators to the shoulder. Its position is important for the function of the product since it affects the forces and moments acting on the vest and ultimately the user.

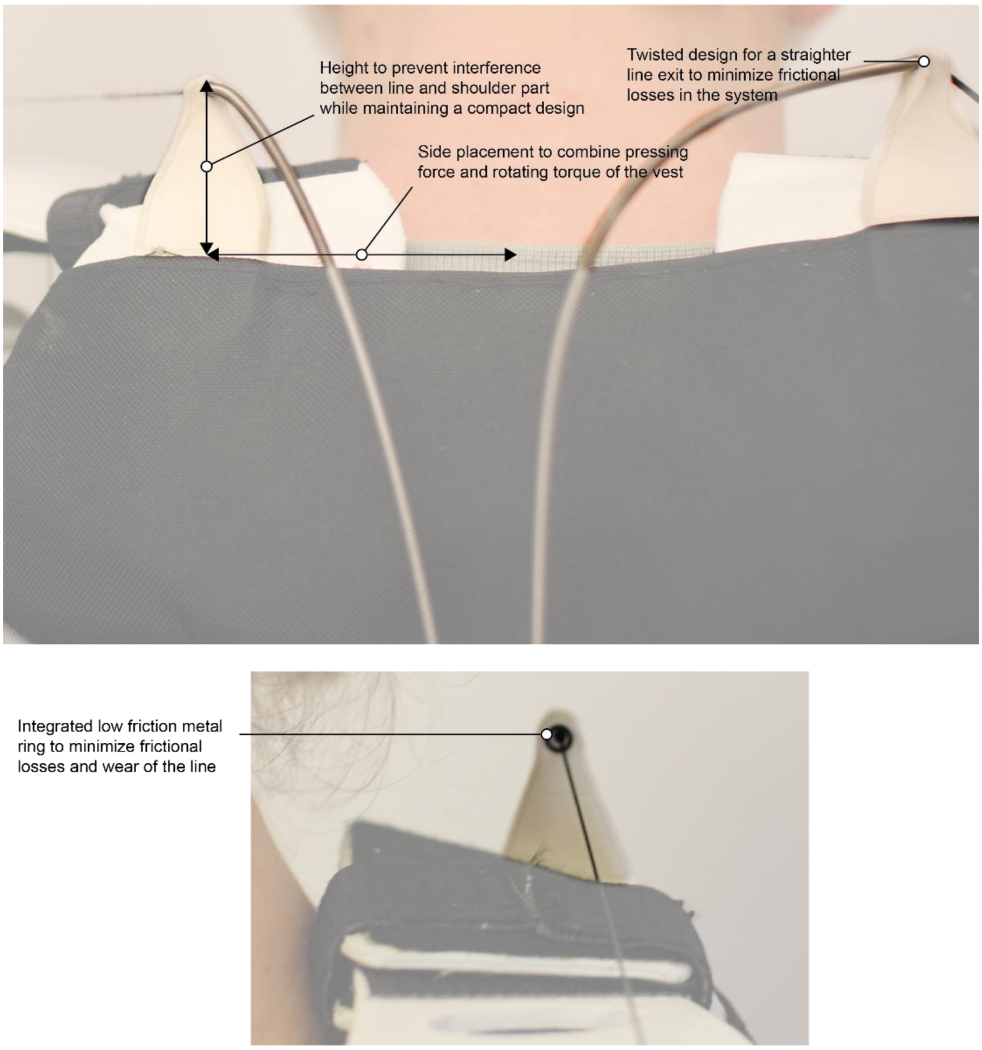


Figure 12.6 Detailed view of the Line exit back of the final prototype

The LEBs were design using 3D CAD and was then manufactured using SLS of a nylon polymer. Later, they were attached directly to the composite material of the backplate using an epoxy based glue to produce a rigid force transferring joint.

12.5 Shoulder part

The shoulder part had the main function of guiding the line over the shoulder and to the elbow brace so that the force from the actuators reaches the arms. It is also used to align TIP with the glenohumeral joint to prevent potential injury of the user.

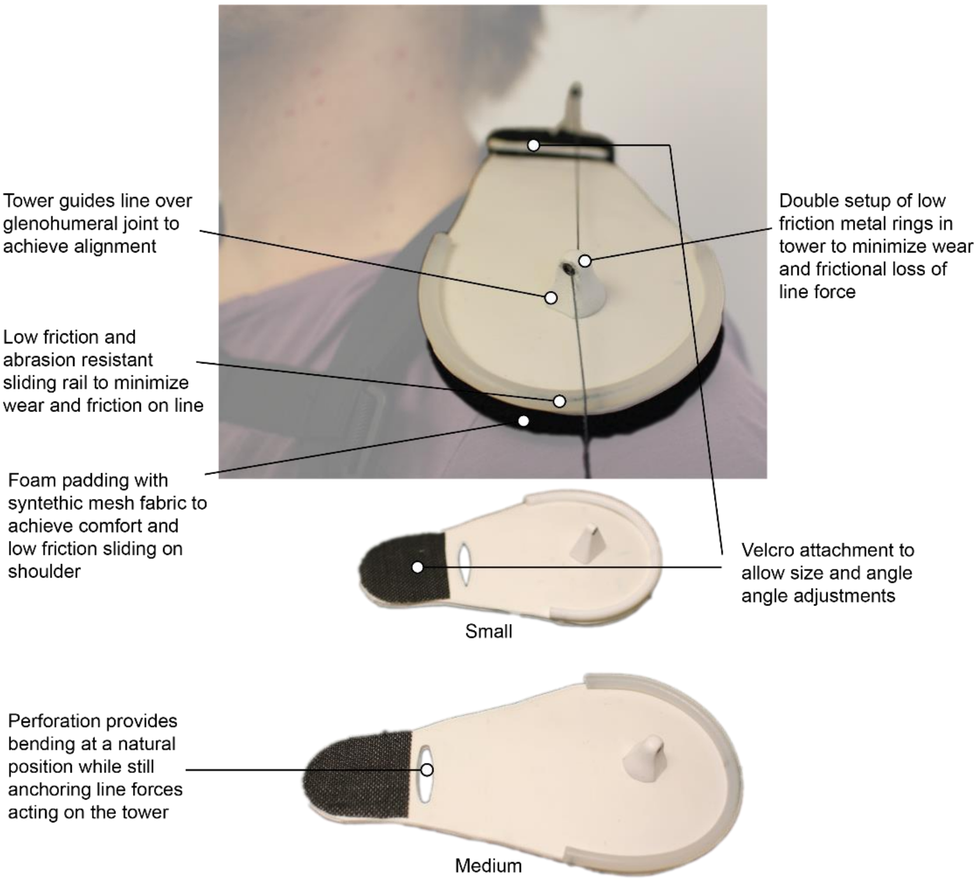


Figure 12.7 Detailed view of the shoulder part of the final prototype

The shoulder parts were created by cutting, forming and perforating a thermoplastic plate. Then the towers were designed using 3D CAD and manufactured using SLS of a nylon polymer. Low friction metal rings were fixated at the entrance and exit holes using epoxy based glue. The towers were attached to the thermoplastic plate using screws through the bottom of the plate.

The screw heads were later covered by adding the foam padding which was covered in low friction mesh. Finally, the sliding rails were cut and screwed in place to cover regions where the line would slide over the shoulder part.

12.6 Mechatronic cases and belt

The main function of the mechatronic cases and belt are to provide a wearable integration between the vest and the mechatronic system. The cases also acts as protection for more sensitive electronics, such as the microcontrollers.

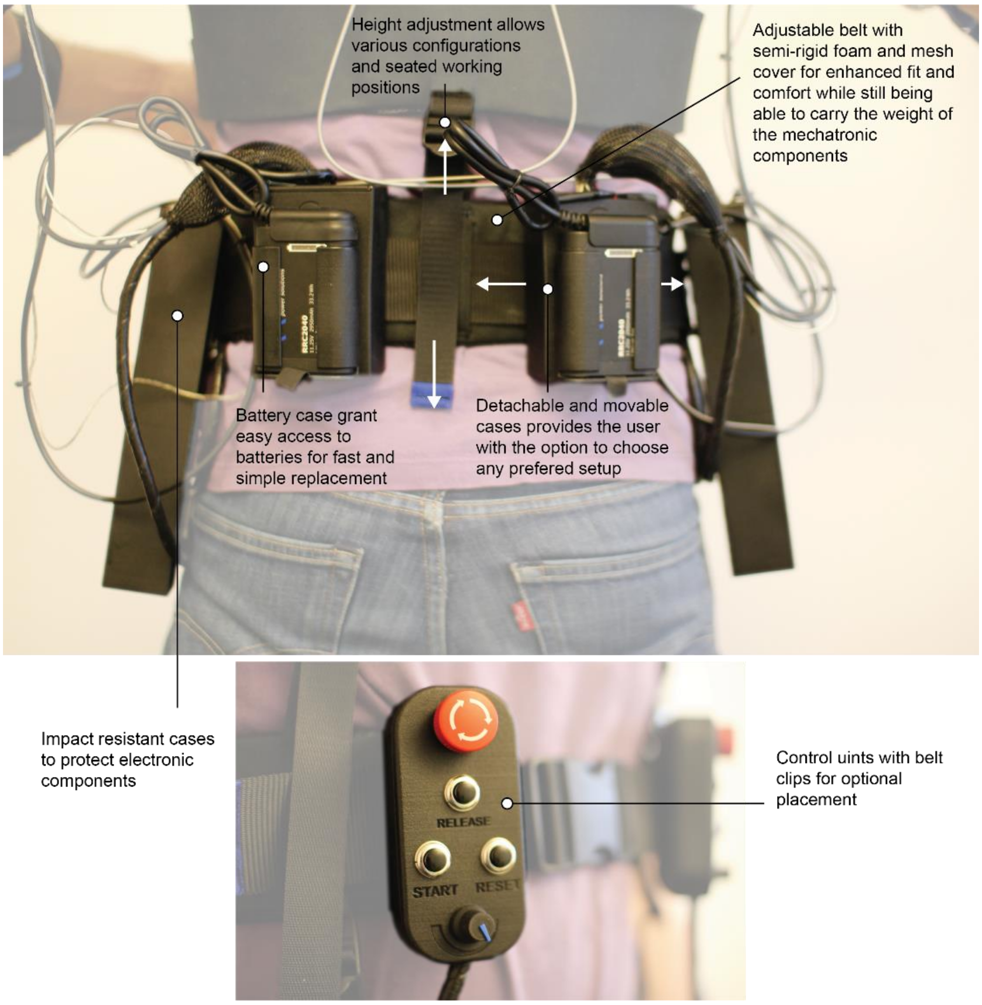


Figure 12.8 Detailed view of the mechatronic cases and belt of the final prototype

The belt was sewed together using foam and mesh on the inside to enhance comfort. The outside with belt loops was created using stiff fabric to provide the force transmission capability. Finally, the three adjustable straps were attached to the stiff fabric to provide a connection between the backplate and belt with mechatronics.

The mechatronic cases were designed using 3D CAD and manufactured using SLS of a nylon polymer. They were padded on the inside to provide a tight fit and damping capability in case of impact between the mechatronics and the surrounding environment.

12.7 Elbow brace

The elbow brace act as the arm anchoring point of the line. Thus, it is vital to provide the force transmission between the line and the arm of the user. It also has the function of holding the IMU sensor that measures the angle of the arm.

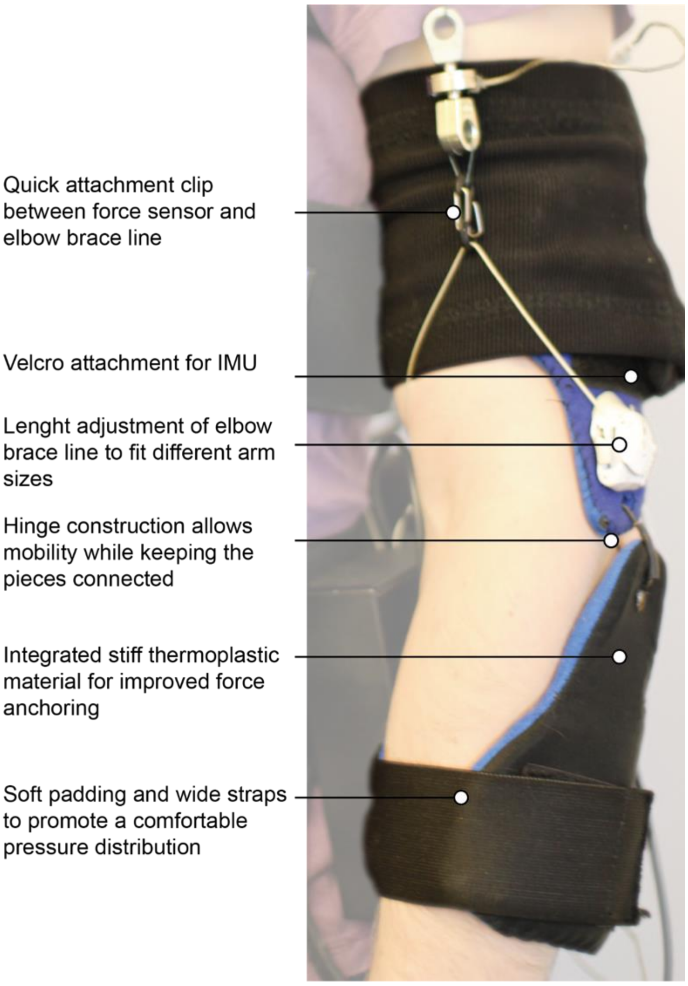


Figure 12.9 Detailed view of an elbow brace used in the final prototype

The elbow braces were developed by employees at the company preceding the thesis. Beside minor modifications, the elbow braces were not further developed and will therefore not be given any further description.

12.8 System during operation

The system during operation with one and both arms at the same time.

Figure 12.10 Final prototype operating one arm

Figure 12.11 Final prototype operating both arms

Figure 12.12 Left: Use able to sit while using system, right: the vest allows rotation of back

12.9 Discussion and conclusion

12.9.1 **Backplate**

The final resulting backplate was built using stiff glass fiber reinforced thermoplastics that was cut to a suitable shaped, guided by user test inputs. One thing to discuss is the necessity of this stiff material. As seen in the report, the main idea was to provide a rigid foundation to anchor forces in the system. But this stiff material also could be a source of discomfort since it doesn’t readily flex if it comes in restraining contact with the user. Instead, if using a more flexible material it might be perceived as more adaptable, soft and organic which since the start of the project has been a company interest. Also, manufacturability could be lower for the chosen composite material design compared to a simpler method, like injection molding. Which at a prototype stage could have been simulated by using a homogeneous polymer instead of the anisotropic composite material structure.

12.9.2 **Straps**

The final straps had the advantage of being close to a standard backpack strap layout, where inspiration also was taken, and had the advantage of being intuitive to the user while giving many possibilities of adjustment to increase comfort. But looking at the results of the user test of the final prototype, questions could arise about the necessity of all straps. Even though the test persons were too small for the vest, causing loose straps and fit, it still performed in a functional way. Resulting in high grading of both mobility, comfort and relief. This could mean that the prototype could be simplified by decreasing the number of straps or maybe changing to a more simplistic buckle setup. For example, where multiple straps are locked in the same buckle.

Other aspects of the straps are their material and width. Only a limited amount of non-flexible polymer straps was tested. They proved satisfying results but it could be more optimal to use flexible straps to obtain a more flexible user experience, especially if the backplate itself is rigid. The width of the straps plays an important role in pressure distribution at its contact with the user which also could affect the perceived comfort and thus be a target for further analysis.

12.9.3 **Line exit back**

As seen in the results, the position of the LEB proved to have effect on the perceived comfort during operation. Thus, resulting in it being positioned not straight behind the neck but further out towards the shoulders. Since this result is subjective and could be argued if the effects of LEB position is fully understood. The heuristic approach gained a result that proved well during user tests but it could be that the same results would have been achieved in other ways. Maybe where the LEB was positioned straight behind the neck, which would have given a more compact overall design.

Another aspect of the LEB is its design that it is separated from the backplate. An optional way of designing it could be by simply integrating it with the backplate so that the two separate parts become one. Even though this might restrain the possibilities of separate material selection for the two details, it would have given a simpler design.

Also, the twisted design of the LEB was used to minimize frictional losses in the line by giving a straight exit from the Bowden cable. This frictional loss due to the twisted design wasn’t investigated or measured in detail and should therefore not be taken for granted. But as shown in chapter 11.2-11.3, the position of the LEB clearly affected the frictional loss which also could mean that there exists a relationship between the angle that the line exits the LEB in relation to the position of the TIP, which was manipulated by giving the LEB a twisted design.

12.9.4 **Shoulder part**

The main problem of this thesis proved to be the design of the shoulder part. Even though a functional design was accomplished there are more work to be done in understanding and optimizing its behavior. One way of gaining this would be by isolating the part and applying a more theoretical method. For example, by building a 3D model of it and perform finite element simulations of its performance during operation. Building such a model requires some initial understanding of the forces acting between the line and tower, the interaction between the human shoulder and the shoulder part as well as proper material models etc. But it would have the advantage of excluding simulation of the complex shoulder anatomy itself.

The sliding rail of the shoulder part was a design that was more or less set from the start and kept since then, as it proved to be not a critical problem. But it's worth mentioning whether this solution is an optimal one or if it could be replaced.

The duck beak design provided possibility of changing the shoulder part itself as well as adjusting the angle of the shoulder part. Both of which proved to be useful when fitting the prototype to a person. But an idea could be to combine these features into a more user friendly adjustment since the solution was hard to adjust by the user herself while wearing the prototype, which was more or less necessary while fitting it to the user’s individual anatomy. As can be read previously in the report, the reason for using the duck beak with Velcro was that it provided a joint capability that was hoped to be perceived as soft and organic by the user. Maybe it’s possible to still get this user experience while using mechanical joints made of stiff components that probably wouldn’t be perceived as soft and organic themselves.

12.9.5 Mechatronics and belt

The mechatronics and belt were integrated with the rest of the vest and its components in a functional way which proved the concept to be feasible. But as seen in the results, it was perceived as bulky which isn’t in line with the expressed customer needs. One obvious reason for this was that the components themselves, such as the actuators, were large and therefore required cases of the same magnitude. Since this thesis project did not cover any development of the mechatronic components themselves, focus was put on solving the problem of carrying them in a mobile system no matter their size. The result of this was the solution which placed the large actuators at the side of the hips, which in combination with the adjustable height of the belt gave a functional prototype. It should be mentioned that if the mechatronic components weren’t as large, the design would probably have been different. For example, it might have been possible to integrate the mechatronic components at the back plate instead of having an external belt carrying its components. Thus, achieving a more compact design.

As seen in the prototypes, Bowden cables were used for force transmission between the actuators and the LEBs. This solution was already implemented in previous prototypes and was to some extent functional. But it should be addressed that frictional loss due to this solution could be of substantial magnitude. Even though this loss wasn’t tested during this thesis project, an earlier thesis project at the company showed that losses in a similar system could be above 60 % between the actuator and the insertion point at the arm [1]. Thus, it could be of interest to analyze alternative solutions for this force transmission. For example, a pulley construction with low frictions wheels to guide the line.

Another thing that can be seen in the user tests of the final prototype is that the force sensor has a tendency to interfere with the shoulder part and its tower when the arm is elevated to higher positions. This is for obvious reasons not desirable but could be fixed by exchanging the force sensor to one that isn’t positioned as an extension of the line itself or a sensor that is smaller than the one used in the final prototype.

12.9.6 Elbow brace

The elbow braces were not developed during this thesis but was integrated as part of the prototypes. As seen in the user comments during user tests, they were perceived as bulky and not to practical. The bulkiness could probably be resolved by applying thinner materials and making the overall design of it more compact. But within the scope of this thesis, one of the most interesting points would be to integrate the elbow braces with the rest of the vest.

Also, the routing of cables to the IMU sensors, attached directly to the elbow braces, could be improved since they are protruding and could be at risk of getting stuck to something.

13 User tests of final prototype

13.1 Results

Both test users experienced that the vest was loose on them. Additionally, because of the length of their upper arm, the force sensor got in contact with the tower when they raised their arm over approximately 100 degrees, as seen figure 13.2. Even though this was not intended, they could perform enough of the motions to successfully test the prototype.

13.1.1 **Grading**

The test was carried out as specified in chapter 3.3. Results from the tests can be seen in figure 13.1 below.

Table 13.1 User tests grading of final prototype

User tests	***Test user 3***	***Test user 4***
Mobility	8	8
Comfort	9	9
Relief	7	8
Total points	24	25

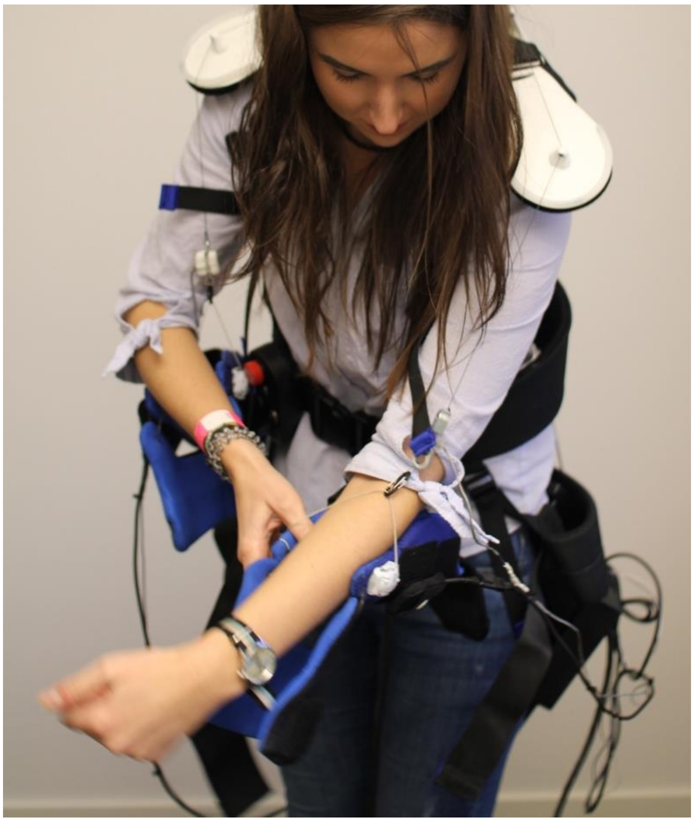


Figure 13.1 Test person 3 donning and doffing the final prototype

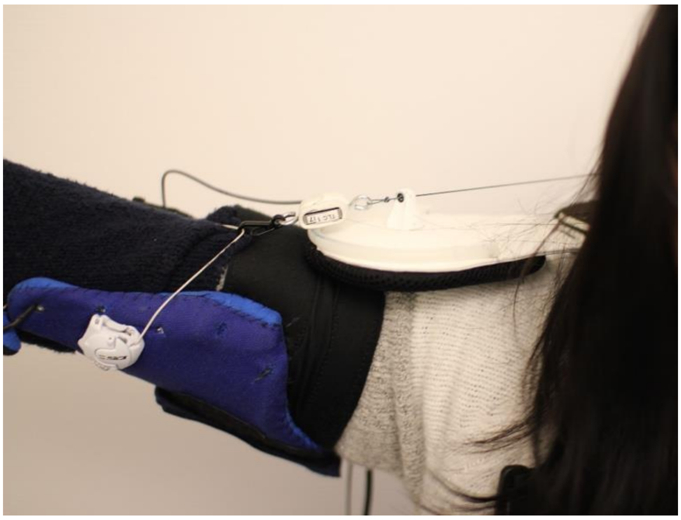


Figure 13.2 Test person 4 during user test

13.1.2 **User comments**

The user comments are a selected few and are the ones which point out improvement potential. They are condensed and paraphrased.

- The vest had a loose fit even though the adjustments were tightened as much as possible
- The chest and waist buckles were hard to tighten when they were closed
- The shoulder pad was too long so the force sensor hit the tower at lifts over shoulder height
- The equipment felt heavy at first, but once the mechatronics belt was tightened around the waist it felt better
- The humerus got pushed into the body when the arm was lifted
- It was not intuitive where the armpit strap should be fastened when putting the vest on
- Relief was experiences at all elevation angles, also above the horizontal plane

13.2 Discussion and conclusion

The tests confirmed that a third party could put on the vest, adjust it to their body without too much assistance and turn it on without further instructions.

The vest was made for a larger body type than both tests subjects. Therefore, it had a looser fit then intended for. The medium size of the shoulder parts, which were the ones available for the tests, were longer than desired. This lead to the force sensor getting in contact with the tower when the arms were lifted over shoulder height. This can be overcome by using the smaller shoulder parts and a more compact force sensor. Regardless of the oversize, it proved that the vest could anchor the forces to the torso even if it did not have a tight fit. This was a valuable insight and showed that the overall construction was robust in anchoring the forces in the system even under non-optimal circumstances.

Regarding the grading, it was positive test results but they cannot be compared to the results from the first tests since it is different prototypes and different test users. The most valuable results are the comments which can be taken into consideration for potential future development. Also, the users expressed a feeling of relief not just at an angle between 0-90 degrees but also at higher arm elevations. This was satisfying results since it corresponded to interpreted user needs of the project.

Additional tests should be performed and they should include the users which the product is intended for while they do actual tasks in their profession. Then, the real value of the prototype can be better understood.

14 Discussion

Since discussions of the prototypes and user tests have already been covered under the corresponding chapters, this discussion has more of a general character. First, the purpose of the system and its effect is discussed. Secondly, the potential to use the system beyond what is defined in indented user is discussed. Thirdly, a discussion about the applied materials and methods a given. Finally, a discussion about the fulfillment of user needs and function analysis is given.

The objective of the thesis was to build a prototype to assist lifting the arms. The user tests of the final prototype confirm that the objective was completed. However, the background for the system was to reduce the risk of work related injuries in the shoulder and neck region. This purpose - to preventing injuries - was outside of the scope of the thesis, but is very relevant for potential further development of the system. This means that currently, the long-term effects of using this system is unknown. Clearly, the hope for a system of this kind is that it has positive effects for the users. However, the effects of this system could also be negative. For example, by reducing the muscle force needed to perform a movement, the muscles and joints might become weaker because they are not activated enough. Furthermore, other parts of the body can be effected and imbalances introduced which in turn can lead to injuries. Again, whether the effects are positive or negative, they are unknown until the long-term effects of using a system of this kind is studied.

The intended user for the system is an individual with normal strength. However, as long as the user can lift their arms by themselves, they could have reduced strength and still operate the system, as of the final prototype. This would greatly expand the user group which the system is relevant for. For example, the system could be used for post-stroke rehabilitation purposes similar what is proposed by Galiana et al [7]. It could also be used as a power-assist tool for elderly, as the initially intent of system [1-4]. If the system should be used as a medical assistive device, there would most likely be changes of the design but the concept could remain the same.

The materials and methods used were a consequence of the given time and resources of the project. The access to building materials and prototype production facilities made it fast and easy to build and test prototypes in full scale. This made the iterative development methodology to take a turn towards a heuristic and practical approach instead of a more theoretical one.

The benefits of this methodology were that it gave possibility to build, test and evaluate different concepts in a short time. This was especially valuable at the initial proof-of-concept state where the functionality of a certain concept was not obvious. At the same time, this heuristic approach reserved less time for theoretical analysis which could have the strength of giving a more in depth understanding of a concepts or prototypes behavior.

The decision to go for the more practical approach was made at the beginning of the project where initial studies of state of the art technology and biomechanical theory was performed. As mentioned in those chapters of this report, due to the complexity of the shoulder complex it is difficult to create a biomechanical model that provides accurate and useful information. Especially when not only forces, pressured etc. are considered, but also subjective experiences such as comfort when those forces are transferred to the human body. This knowledge, combined with given limitations of time was the reason for the heuristic approach.

The material part of this report included not only physical building materials but also the different test users of this report. Unfortunately, the test users were quite a homogeneous group of young healthy people and are friends or relatives of the authors. Preferably, the test users would only be from the defined risk group and not have a personal relationship to the people who introduced the test. Having a personal relationship with people leading the test could make the test user biased in either a positive or negative way. Regardless, the user tests which were performed by other individuals than the authors, were considered to give valuable input on the prototypes.

The user needs and functional analysis are by the authors considered mostly fulfilled through the final prototype. But their fulfillments can be argued, mainly because the specified needs and functions were of subjective and non-measurable character. Even so, a short discussion is given but limited to cover the ones considered not fulfilled.

Three user needs were not met; Product can be cleaned to meet hospital standards; The line should be covered; Increase the speed of the actuator. They were not fulfilled for the same reason, lack of development time. Despite this, they first two are very important user needs that should be covered by a final product to satisfy potential users in the targeted markets. The last one is equally important to satisfy the intended users that performs more dynamic work tasks.

All functions in the functional analysis were met to some extent. The most debatable ones could be considered as; Allow laying; Minimize weight; Avoid protruding out from body. The first one was not tested but is still important since this kind of usage could be expected in some industries. The second one was to some degree considered by using fiber reinforced composite materials. But as seen in the results of the final user test, the users experienced the prototype as heavy. Avoiding protrusion was also considered throughout the thesis but would have been more satisfied if the LEBs were centered behind the neck instead of being moved out towards the shoulders.

15 Conclusion and future work

The results of this thesis showed that a functional vest prototype, for a wearable soft robotic system to support lifting of the arms, could be developed in a satisfying way. It also shows that the main hardware problem to be dealt with was the design of the shoulder part in order to get a functional prototype.

Focusing on the different parts of the system, conclusion can be made that a rigid composite structure back plate can be used to anchor the forces in the system. Even though it is rigid, high levels of perceived mobility and comfort can be achieved using the proposed shape with additional padding and air ventilating materials. Future work on the back plate could involve in depth analysis of alternative construction materials of the back plate. For example, by building prototypes of different materials and put through user tests to see how well it would be perceived by users. Main focus here should be a slimmer and more lightweight design which of cause has a strong relationship with the chosen construction material. The material stiffness should also be evaluated to see if a more flexible material provides better results.

The proposed straps, or system of straps, can be used to provide a solution of force anchoring and individual adjustment. It could in the same way as the back plate be evaluated using different types of straps. For example, flexible straps as mentioned in the discussion chapter. Additional prototypes using different straps and strap setups could be built to go through user tests. Main focus here should be on simplicity, minimizing the amount of straps the user has to adjust while putting on the vest while still keeping the adjustment process intuitive.

Conclusion can be made that LEBs can be used successfully as an exit point for the line coming from the actuators to the shoulder part. The position of the LEB proved to be important for the performance of the prototype since it affected the force in the line and should therefore be further analyzed. For example, by setting up a controlled test environment where its position is alternated as the force in the line is measured. This would provide a better understanding of how it affects the system performance which is valuable during further product development.

The shoulder parts developed in this thesis can be used to anchor the tower and its forces while still allowing shoulder complex motion of the user. The shoulder part is functional but it is still the part with most potential of improvement. Thus, priority should be put in this part in future work. As mentioned in the discussion, mathematical modeling and simulation could be a tool to gain deeper understanding of this part's behavior. An interesting aspect of the shoulder part could be to analyze its design at the weakened perforated position to find a more optimal shape.

A polymer based sliding rail can be attached to the shoulder part as a low friction contact surface for the line to slide on. This kind of rail can be used to decrease the wear on the shoulder part itself as well as on the line. Future work on the sliding rail could be to find a polymer material of the shoulder part that makes the sliding rail unnecessary, i.e. the friction and wear between the line and the shoulder part is low enough by themselves.

A duck beak designed joint can be used to anchor the forces of the shoulder part while also giving adjustment possibilities for individual fitting. Future work on this component could be to analyze possibilities of a more compact design that is more readily adjustable. For example, by using mechanical joints or stiff materials covered with fabric or foam materials. An argument for using this method instead is that the design could become more compact and predictable.

Conclusions about the possibility of using the mechatronic system with its software have been made by previous master thesis students. But from this thesis, conclusions can be made that this mechatronic system can be made wearable and mobile to meet the customer needs by using the developed belt solution. Future work in this area could be to minimize the size of the mechatronic system so it hopefully can be more tightly integrated with the vest. Maybe even attached directly to the vest itself, making an additional belt redundant. Also, since two main complaints during user tests had to do with the slow performance of the mechatronic system as well as it being restrictive when the user tries to lower the arms, future development could be to improve the speed of it and its control algorithms. The latter should include an algorithm that can distinguish between the arm being elevated or lowered.

Most conclusions about the functionality of the elbow brace has been made by the previous thesis worker who developed it. But from this thesis, conclusion can be made that this kind of elbow brace also can be used in the system developed in this thesis. It can successfully anchor the force from the line to the arm of the user in a comfortable way as well as holding the IMU sensor. Future work could be to integrate the elbow brace more tightly with the vest. For example, by developing a prototype as the one proposed during concept generation in chapter 6.1, this could be done by applying an underlying fabric or textile that would make it possible to put the prototype on just like a jacket. This solution would probably increase the usability of the product since it would simplify donning and doffing. Also, future work on the protruding cables coming from the microcontroller to the IMU could be improved. One of the more optimal solutions could be a wireless connection between the IMU sensor and the microcontroller which would decrease the risk of the cable getting stuck.

Other aspects of future work could be to analyze possibilities to meet hygiene demand like the ones used at hospitals. This would be of importance since many of the potential users of this product work within the healthcare industry.

References

[1] Ekblom, J. (2016). *Development of soft robotics solution*. Linköping University, Institutionen för ekonomisk och industriell utveckling.

[2] Dasht Bozorg, A. (2016). *Mechanical development for a soft robotics solution*. Stockholm: KTH Royal Institute of Technology, Industrial Engineering and Management.

[3] He, S. (2015). *An Arm-Assistive Medical Device using Soft Robotics Technology*. Espo: Aalto University, School of Science.

[4] Papastathis, IA. (2015). *Intention Detection and Arm Kinematic Control in Soft Robotic Medical Assistive Device.* Stockholm: KTH Royal Institute of Technology, Medical Engineering

[5] Eurofound. (2016). *Sixth European Working Conditions Survey – Overview report*. Luxembourg: Publications Office of the European Union.

[6] Kesner, S.B., Jentoft, L., Hammond III, F. L., Howe R. D., & Popovic, M. (2011). *Design Considerations for an Active Soft Orthotic System for Shoulder Rehabilitation.* Cambridge: Harvard University, Harvard School of Engineering and Applied Sciences.

[7] Galiana, I., Hammond III, F. L., Howe, R. D., & Popovic, M. B. (2012). *Wearable soft robotic device for post-stroke shoulder rehabilitation: Identifying misalignments.* Cambridge: Harvard University, Harvard School of Engineering and Applied Sciences.

[8] Natividad, R. F. & Yeow, C. H. (2016). *Development of a Soft Robotic Shoulder Assistive Device for Shoulder Abduction*. Singapore: National University of Singapore, Department of Biomedical Engineering.

[9] Koo, I., Yun, C., Costa, M. V. O., Scognamiglio, J. V. F., Yangali, T. A., Park, D., et al. (2014). *Development of A Meal Assistive Exoskeleton made of Soft Materials for polymyositis patients*. Seoul: Seoul National University, School of Mechanical & Aerospace Engineering/IAMD.

[10] Starkebaum, G. A. *MedlinePlus.* (2015). Retrieved January 6, 2016, from: https://medlineplus.gov/ency/article/000428.htm .

[11] Gopura, R. A. R. C., Bandara, D. S. V., Kiguchi, K., Mann, G. K. I. (2016). *Developments in hardware systems of active upper-limb exoskeleton robots: A review*. Robotics and Autonomous Systems.

[12] Mao, Y. & Agrawal, S. K. (2012). *Design of a cable-driven arm exoskeleton (CAREX) for Neural Rehabilitation.* IEEE Transactions on Robotics.

[13] Knudson, D. (2007). *Fundamentals of Biomechanics*. 2nd ed. New York: Springer Science+Business Media, LLC.

[14] Peat, M & Culham, E. (1993). *Functional Anatomy of the Shoulder Complex*. Journal of Orthopaedic & Sports Physical Therapy.

[15] Kumar, S. (1999). *Biomechanics in Ergonomics*. Edmonton: Taylor & Francis Ltd.

Figures

Figure 2.1	from [4], p 20.
Figure 2.2	Retrieved 6 January, 2017, from http://www.mayfieldclinic.com/pe-anatspine.htm.
Figure 2.4	from [13].

All other figures are created by the authors.

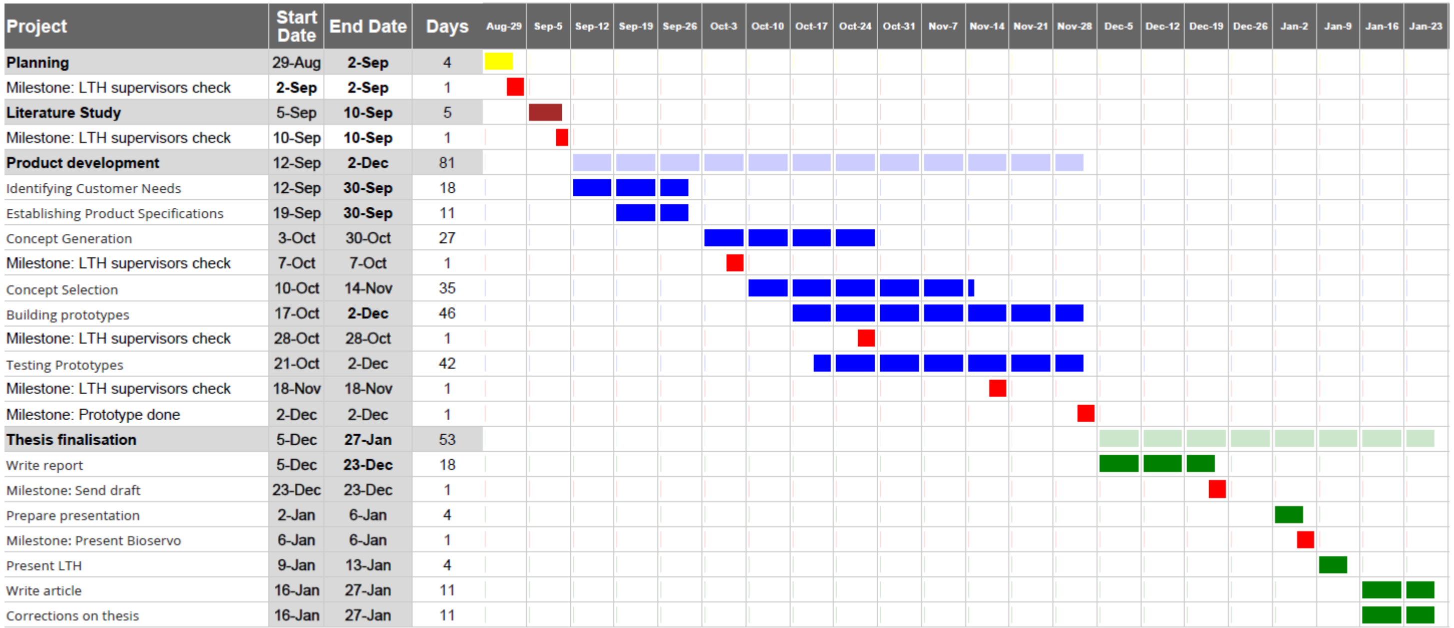
Appendix A Project and time plan

A.1 Work distribution

The vast majority of the time, the authors conducted the work side-by-side at the Bioservo office. The came and left the office at the same time and worked during normal business hours. The work distribution of the individual tasks, both theoretical and practical, was shared equally in as large extent as possible. The reason was not only to have a fair time distribution but also because it was a personal desire of both students to learn as much as possible during the thesis. For example, one of the authors was initially more familiar with prototyping and the other one in FEA simulations. The information and skills needed to perform the tasks were shared among the two, so that both could perform a given task.

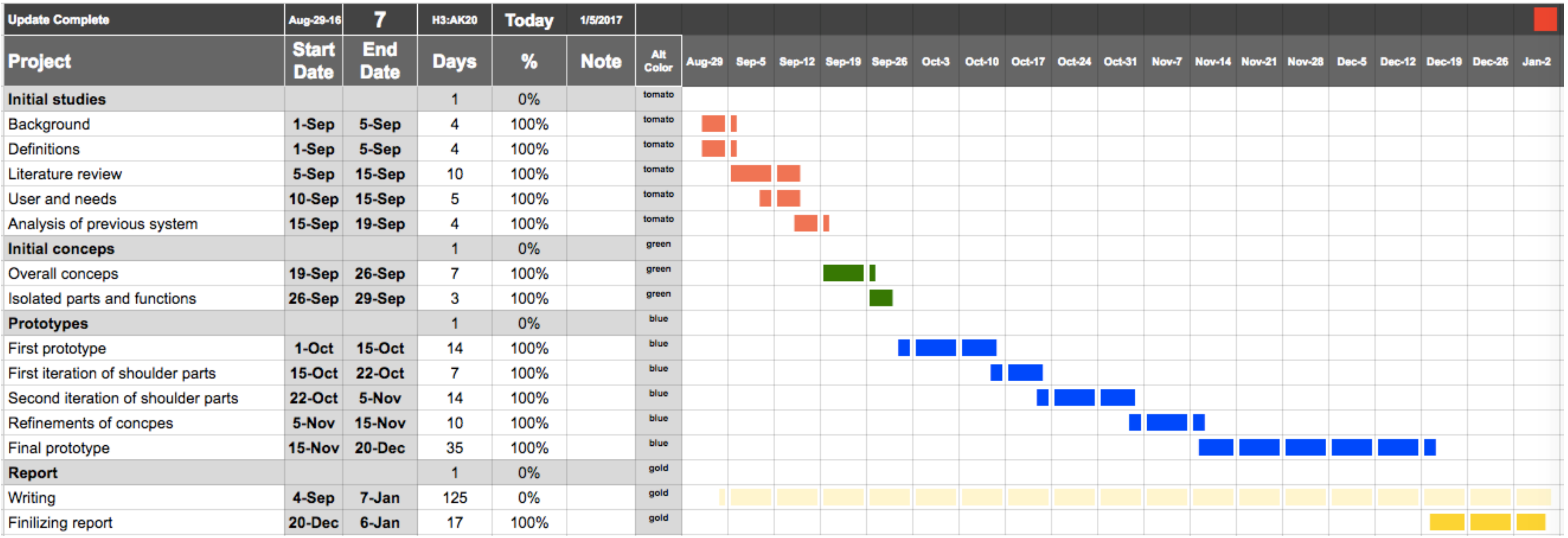
A.2 Project plan and outcome

The initial time plan and the effective one have some differences. The main ones are that the prototyping phase was conducted in iterative way and hence several of these sections were added. Additionally, the prototyping phase lasted three weeks longer than initially planned. However, the initial end date for the prototyping phase was set to allow time for report writing. Effectively, more of the writing was done throughout the thesis and therefore, less allocated time was needed at the end.



Project	Start Date	End Date	Days
Planning	29-Aug	**2-Sep**	4
Milestone: LTH supervisors check	**2-Sep**	**2-Sep**	1
Literature Study	5-Sep	**10-Sep**	5
Milestone: LTH supervisors check	10-Sep	**10-Sep**	1
Product development	12-Sep	**2-Dec**	81
Identifying Customer Needs	12-Sep	**30-Sep**	18
Establishing Product Specifications	19-Sep	**30-Sep**	11
Concept Generation	3-Oct	30-Oct	27
Milestone: LTH supervisors check	7-Oct	7-Oct	1
Concept Selection	10-Oct	14-Nov	35
Building prototypes	17-Oct	**2-Dec**	46
Milestone: LTH supervisors check	28-Oct	28-Oct	1
Testing Prototypes	21-Oct	2-Dec	42
Milestone: LTH supervisors check	18-Nov	18-Nov	1
Milestone: Prototype done	2-Dec	2-Dec	1
Thesis finalisation	5-Dec	**27-Jan**	53
Write report	5-Dec	**23-Dec**	18
Milestone: Send draft	23-Dec	23-Dec	1
Prepare presentation	2-Jan	6-Jan	4
Milestone: Present Bioservo	6-Jan	6-Jan	1
Present LTH	9-Jan	13-Jan	4
Write article	16-Jan	27-Jan	11
Corrections on thesis	16-Jan	27-Jan	11

Figure A.1 Original Gantt schedule of main activities during master thesis



Update Complete	Aug-29-16	7	H3:AK20	Today	1/5/2017	
Project	**Start Date**	**End Date**	**Days**	**%**	**Note**	**Alt Color**
Initial studies			1	0%		tomato
Background	1-Sep	5-Sep	4	100%		tomato
Definitions	1-Sep	5-Sep	4	100%		tomato
Literature review	5-Sep	15-Sep	10	100%		tomato
User and needs	10-Sep	15-Sep	5	100%		tomato
Analysis of previous system	15-Sep	19-Sep	4	100%		tomato
Initial conceps			1	0%		green
Overall conceps	19-Sep	26-Sep	7	100%		green
Isolated parts and functions	26-Sep	29-Sep	3	100%		green
Prototypes			1	0%		blue
First prototype	1-Oct	15-Oct	14	100%		blue
First iteration of shoulder parts	15-Oct	22-Oct	7	100%		blue
Second iteration of shoulder parts	22-Oct	5-Nov	14	100%		blue
Refinements of concpes	5-Nov	15-Nov	10	100%		blue
Final prototype	15-Nov	20-Dec	35	100%		blue
Report			1	0%		gold
Writing	4-Sep	7-Jan	125	0%		gold
Finilizing report	20-Dec	6-Jan	17	100%		gold

Figure A.2 Outcome Gantt schedule of main activities during master thesis

Appendix B Illustrations for state-of-the-art

B.1 Active Soft Orthotic System for Shoulder Rehabilitation

Figure B.1 Active Soft Orthotic System for Shoulder Rehabilitation [5]

B.2 Wearable soft robotic device for post-stroke shoulder rehabilitation

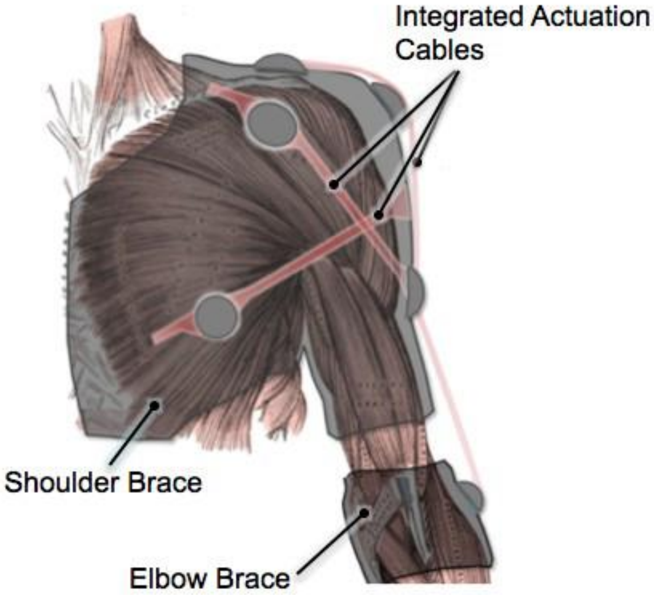


Figure B.2 Wearable soft robotic device for post-stroke shoulder rehabilitation [6]

B.3 Soft Robotic Shoulder Assistive Device for Shoulder Abduction

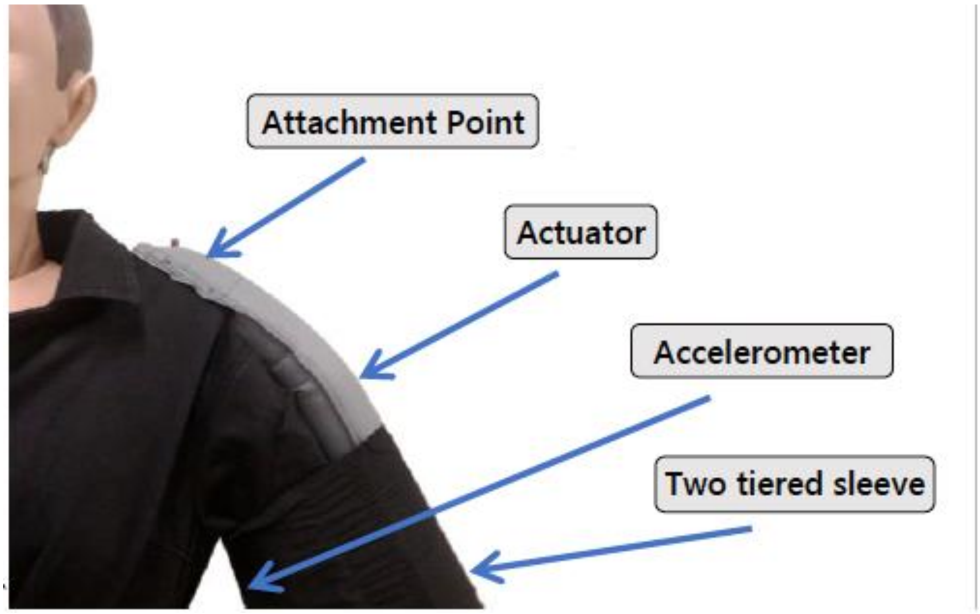


Figure B.3 Soft Robotic Shoulder Assistive Device for Shoulder Abduction [7]

B.4 Meal Assistive Exoskeleton made of Soft Materials for polymyositis patients

Figure B.4 Meal Assistive Exoskeleton made of Soft Materials for polymyositis patients [8]

B.5 Cable-Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation

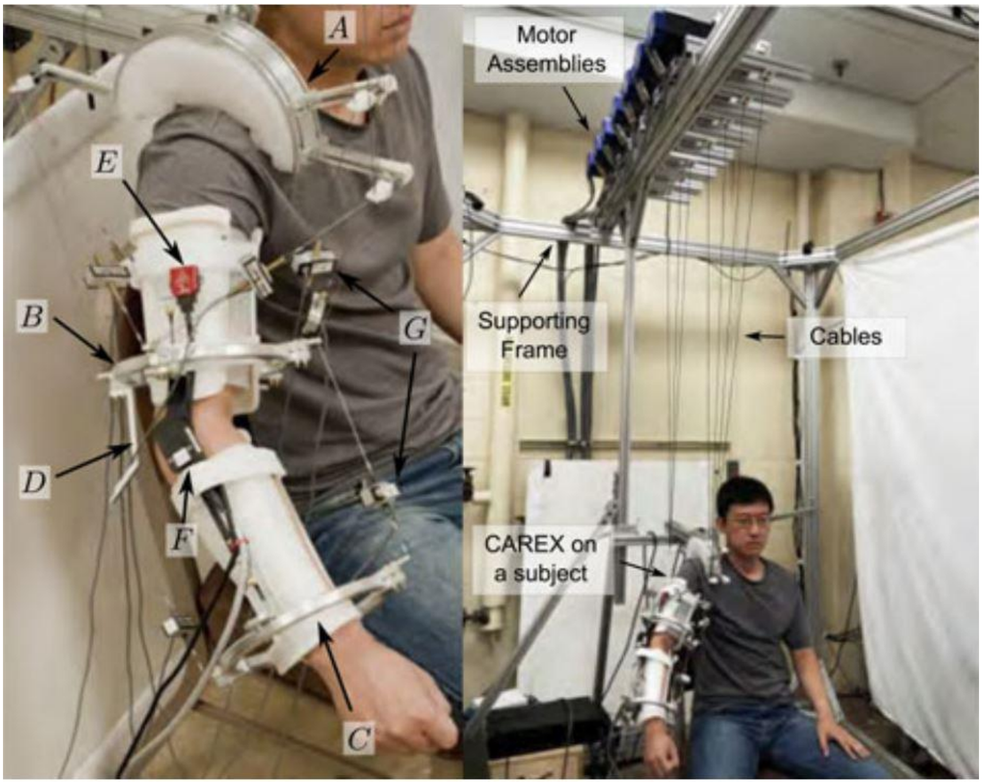


Figure B.5 Cable-Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation [9]

Appendix C Function analysis

C.1 Additional function analysis for product

Table C.1 Function analysis which relate to the product more than prototype

	Function		***Comment***	***Class***	***Type***
Category	***Verb***	***Noun***			
Use	Promote	use	a longer period of time	N	Product
	Last	work-day	of continuous use	D	Product
	Promote	usability		D	Product
	Withstand	use	long-term	D	Product
	Be	modular	sizes	D	Product
Construction	Be	interchangeable	for repairs	D	Product
	Allow	series production		D	Product
	Ease	assembly		D	Product
	Minimize	size		D	Product
	Ease	service		D	Product
	Allow	washing	of fabric	D	Product
	Allow	cleaning	with cleaning agents	D	Product
Durability	Withstand	impact		D	Product
	Withstand	dust		D	Product
	Withstand	water		D	Product
Appearance	Use	design language	of Bioservo	D	Product
	Express	quality		D	Product
	Express	trustworthiness		D	Product
	Express	robustness		D	Product

Appendix D User test of prototypes

D.1 Template of test procedure

Purpose

To obtain end-user input in order to better answer the following questions:

- Does this type of lifting system benefit the user in her work?
    - Why? Why not?
- Are the adjustments sufficient to hold the vest tight to the user's body?
    - If ‘no’: Where does it feel loose?
- Is the system comfortable to wear on the body when unloaded?
- Is the system comfortable to wear on the body when loaded?
    - If ‘no’: where does it feel uncomfortable?
- Which shoulder pad concept is most promising to continue to develop?
    - Why? Why not?

The input will aid in the decision process of the development of the system.

Test session

Introduction

Who we are and motivation to the product.

User

- Work context of the user?
- Potential injuries at the work?
- Measurements of the user?

Purpose of test and user involvement

- Tell person that we are testing the prototypes, not the person.
- Tell person to be honest if something isn’t good. Purpose of test is to improve the prototypes.
- Tell person we will answer as few direct questions as possible. We want the person to act like if we weren’t there when doing the tests, i.e. try to use the prototypes without our help.

Outline of test

- Put on vest followed by “before lift” questionnaire
- Perform motion scheme followed by “after lift” questionnaire

Procedure

1. User puts on the vest and adjust the size. Observe user and take notes, record video, ask “before lift” questions.
2. Perform motion scheme, “after lift” questions and grading using visual analog scale.

D.2 Questionnaire

Before lift

- How do you perceive the possibility to adjust the vest to your body?
- Does the vest feel comfortable to wear?
- How is your movement in the upper body with the vest on?
- Other opinions?

After lift (after each prototype)

- How did the lift of the arm feel?
- Was the feeling different when the arm was in different positions?
- How did you experience the comfort during use?
- How did the mobility of the shoulder feel?
- Other opinions?

Final questions (when all lifting tests are done)

- In which situations would the vest be useful (based on your experience)?
- Other opinions?

D.3 Visual analog scales

Figure D.3 Visual analog scale

D.4 Motion scheme

Observe that beside of written information and figures in this appendix, the user was provided instructional videos of the motion scheme.

During all motions, the user should strive to keep the wrist rotated as in posture 1 in figure D.4 shown below. This is to ensure a more natural working posture of the wrist and so that the test is being performed in the same manner every time.

Figure D.4 Wrist position while performing motion scheme

Static

Hold up both arms with 1-2 kg weight in the hands and perform small muscle activating motions with the hands (for example small circular motions).

1. Upper arm at 90 degrees of flexion, 60 – 90 seconds. Or until some level of muscle fatigue occurs.
2. Upper arm at 135 degrees of flexion, 45 seconds – 60 seconds. Or until some level of muscle fatigue occurs.

Beside this restriction, the test subject can use her natural body posture during work.

The weight and the time will be set to fit the user’s strength but will be kept consistent between the tests.

The test simulates a static working situation for a welder, electrician etc.

Dynamic

Hold 1-2 kg weight in the hands and perform small muscle activating motions with the hands (for example small circular motions).

1. Pure extension 0-170 degrees.
2. Pure adduction 0-170 degrees.
3. In between extension/adduction 0-170 degrees.
4. Circular motion in full range of motion of shoulder in both directions.
5. Free motion of user’s choice.

The test simulates a dynamic working situation for assembly workers, painters, postmen, cleaners, polishers etc.

D.5 User test grades of shoulder part prototypes

All user test grades were done using the visual analog scale.

D.5.1 Test user 1

D.5.1.1 Soft attachment

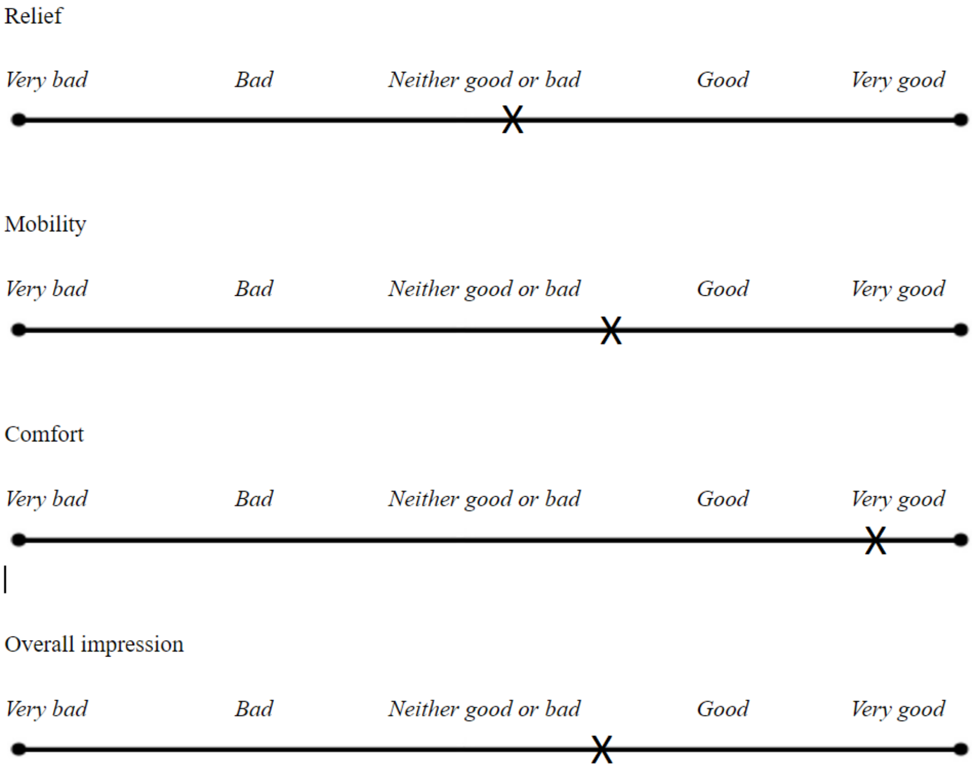


Figure D.5.1.1 Test user 1 grading of the Soft attachment prototype

D.5.1.2 Polymer plate

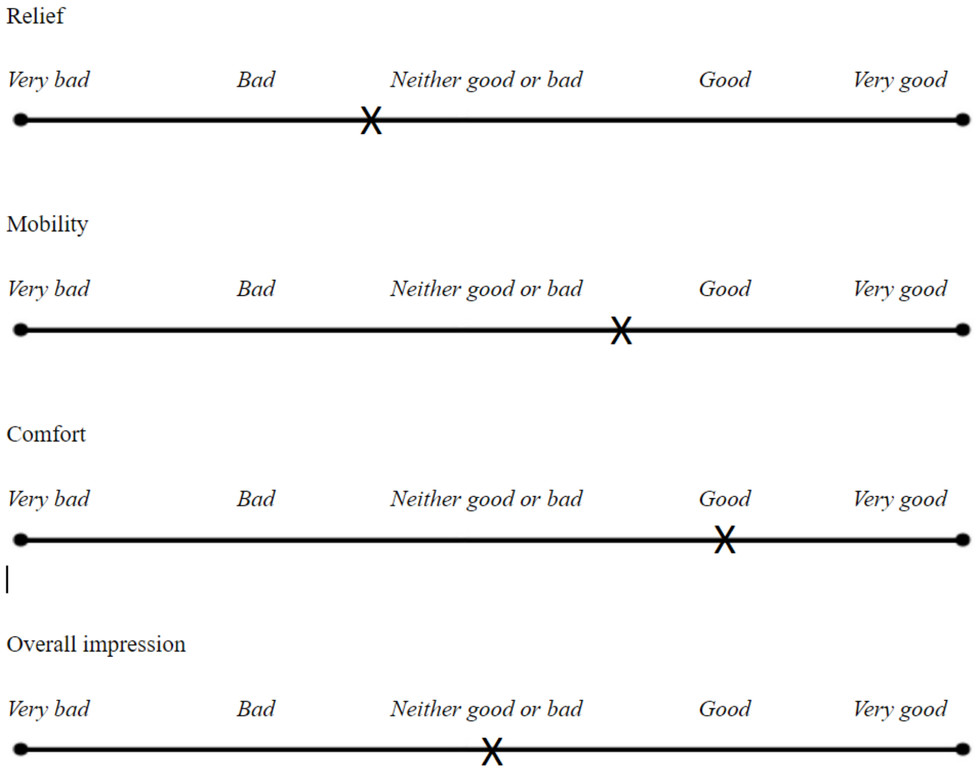


Figure D.5.1.2 Test user 1 grading of the Polymer plate prototype

D.5.1.3 Rigid link

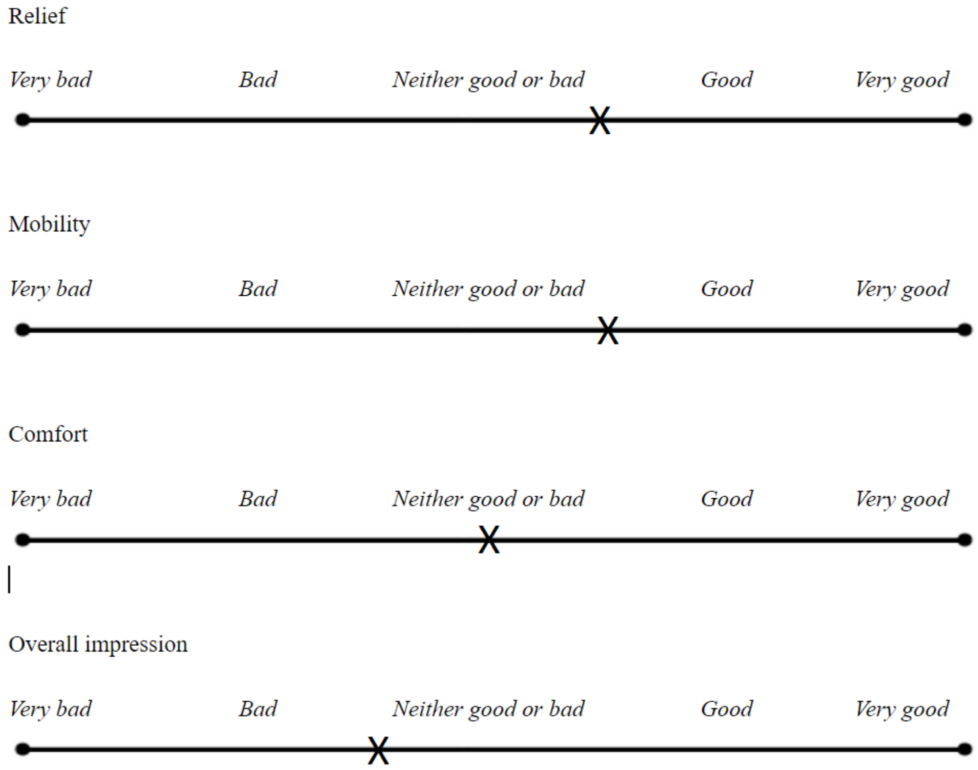
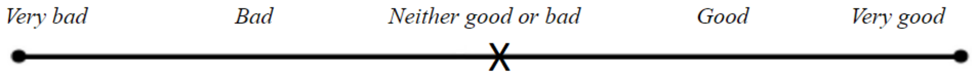


Figure D.5.1.3 Test user 1 grading of the Rigid link prototype

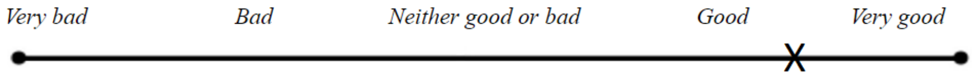
D.5.2 Test user 2

D.5.2.1 Soft attachment

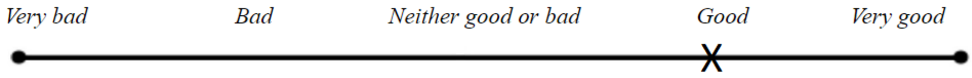
Relief



Mobility



Comfort



Overall impression

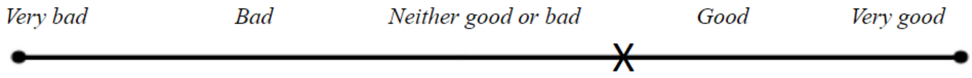


Figure D.5.2.1 Test user 2 grading of Soft attachment prototype

D.5.2.2 Polymer plate

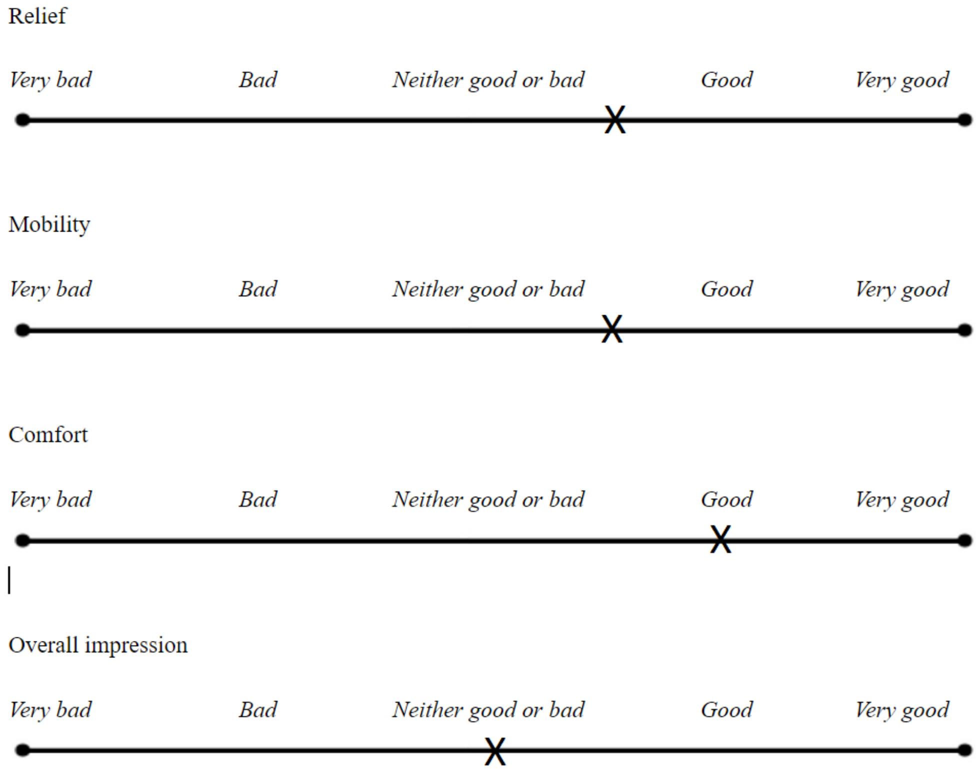


Figure D.5.2.2 Test user 2 grading of the Polymer plate prototype

D.5.2.3 Rigid link

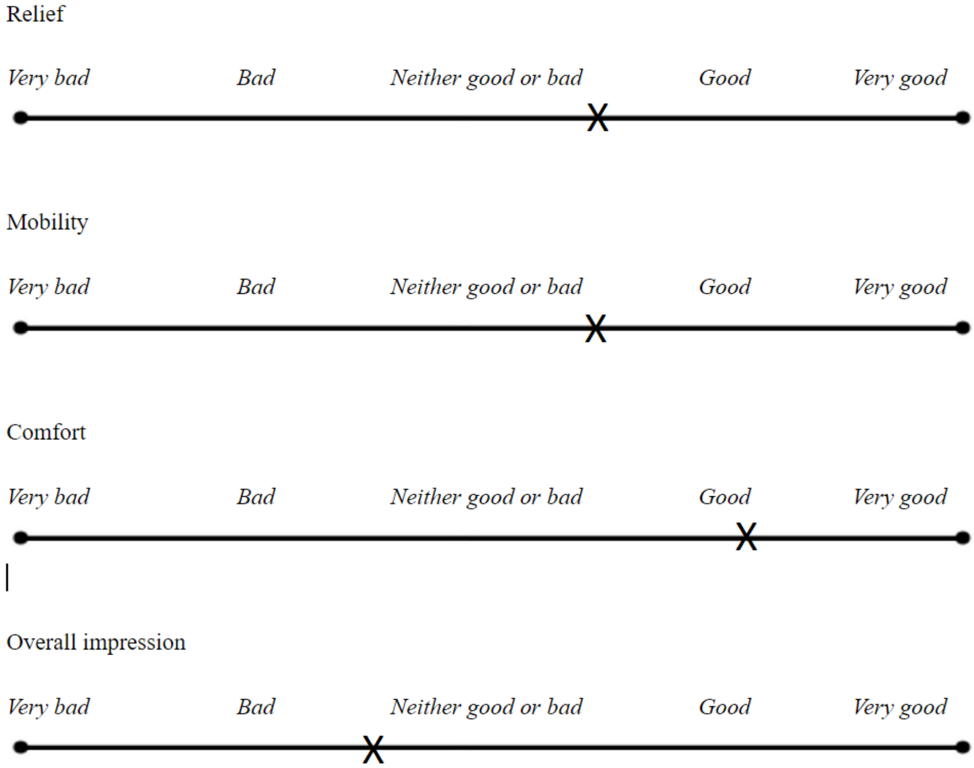


Figure D.5.2.3 Test user 2 grading of the Rigid link prototype

D.6 User test grades of final prototype

D.6.1 Test user 3

Figure D.6.1 Test user 3 grading of the final prototype

D.6.2 Test user 4

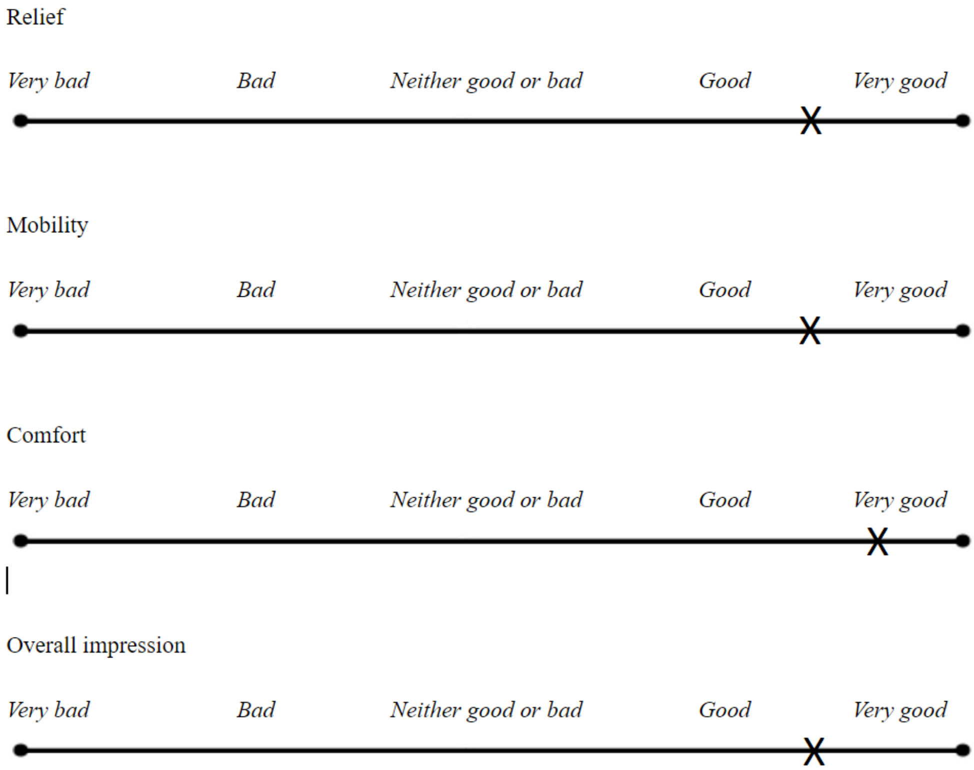


Figure D.6.2 Test user 4 grading of the final prototype