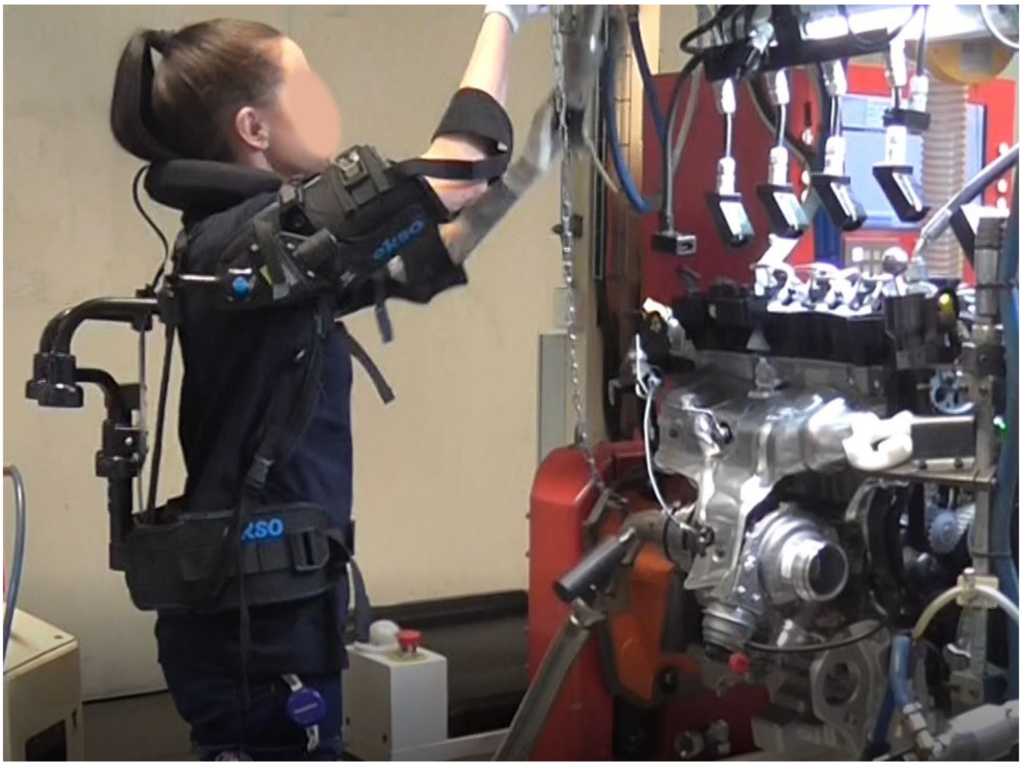

Investigating the application, benefits and challenges of an exoskeleton system in the final assembly of automotive production

Master's thesis in Production Engineering

OSKAR TUNEROTH & PREKSHA PRASANNA

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Abstract

When it comes to manual assembly tasks, work related injuries due to poor ergonomics is a major concern in today's automotive industries. To approach this challenge, several automotive industries have started using new technologies such as Exoskeletons to make the assembly task easier. This research study is focused on investigating the application, potential impact and challenges of the exoskeleton technology at the final assembly in the automotive industry. This was made possible by performing subjective and objective data collection of the exoskeleton in a factory and lab setting. Factory tests were performed with a focus on above shoulder work tasks at Volvo Cars and Volvo Trucks in Swedish plants. Lab tests were performed with the same focus at Chalmers University of Technology. The data was captured through interviews, observations and electromyography. Based on the valuable feedback from the participants, the equipment had positive effects on the shoulder and back while working above shoulders but there were negative effects regarding movability and resistance while working at a lower height. Based on lab testing, there was a reduction in muscle effort with the exoskeletons when compared to muscle activity without the exoskeleton. In addition, further recommendation has been made to investigate the technology for a longer time period in order to evaluate long term effects.

Keywords: Exoskeleton, Electromyography, Under-up work, Final assembly, Ergonomics, Production.

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Oskar Tuneroth & Preksha Prasanna, Gothenburg, May 2019

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Abbreviations

WMSD's - Work related musculoskeletal disorders
EU - European Union
EMG - Electromyography
SENIAM - Surface electromyography for the non-invasive assessment of muscles
RMS - Root mean square
IED - Inter electrode distance
MVC - Maximum voluntary contraction
ECG - Electrocardiography
EEG - Electroencephalography
PSL - Production systems laboratory
BSL - Biopac student lab

Glossary

Exoskeleton - Wearable external mechanical structure that supports the user's body while performing a physical task

Musculoskeletal disorders - A common work related ailment that usually affects back, neck, shoulders and upper limb

Under-up work - Performing assembly tasks with hands above the shoulders

Upper limb - Region of the human body known for its mobility and dexterity. It consists of shoulder, arm, forearm and hand.

Muscle - Organs responsible for the movement of human body.

Pectoral girdle - Also known as shoulder girdle is the set of bones which connects to the arm on each side.

Anterior side of body - Front side of the body

Posterior side of body - Back side of the body

Semi structured interviews - An interview with a formalised list of questions prior to the interview, but with the freedom of asking follow up questions, diving deeper into a discussed topic and adjusting the order of the questions asked.

Biomechanical testing- The study of human motion. It is performed to determine abnormalities and identify how body compensates for these irregularities.

Cross talk - It is the EMG signal detected over a non-active muscle and generated by a nearby muscle.

1

Introduction

This chapter describes the background of the study, what problems that will be investigated, the purpose of the study and the research questions that the study aim to answer.

1.1 Background

Even though the level of automation is increasing daily in the automotive industry there is still a high demand of manual assembly tasks in the final assembly plants. Work related injuries lead to health problems and ergonomics plays an important role in this as it benefits the workers and the organisation.

The working population is currently getting older and the labour force participation rates of males aged between 55 to 64 years is increasing due to pension reforms and female participation rates have also been steadily increased over the past 25 years and a healthy workplace is now more crucial than ever before (European commission,2018).

To approach this challenge, leading automotive industries have started using new technologies such as exoskeletons, which are wearable devices to overcome the current limitations of the human body, to decrease the physical loading for the workers and increase their performance (Looze et al, 2016). This new technology has only been adopted by a few of the manufacturing industries, for example the automotive industry, and the usage of the technology is still at an early stage (Wesslén, 2018). This thesis will focus on understanding the benefits, challenges and application of exoskeletons in a final assembly setting with a focus on under-up work tasks, for potential benefits in the future.

1.2 Problem description

With improved work station design and better ergonomics, workers are less likely to develop work related injuries which will eventually reduce health costs. As working above shoulders has been a major concern in manual assembly work tasks at the automotive industries, Volvo Cars Corporation has invested in a new technology to prepare for future improvements. With the three different models of upper limb exoskeleton purchased, Volvo Cars would like them to be studied and evaluated to understand the benefits, challenges, applications and perceived workload in a final assembly setting.

1.3 Purpose

The purpose of this study is to demonstrate and explore the development of exoskeleton technology and how well the exoskeleton technology tackles the ergonomic conditions and high-risk injuries of participating operators. The research study focuses on implementing and evaluating the exoskeleton technology in under-up assembly work tasks by identifying the appropriate stations and appropriate applications of upper limb exoskeletons. With this, each exoskeleton system is evaluated and compared with each other based on different factors and methods which will provide the benefits and challenges of implementing the use of exoskeleton system in the automotive industries.

1.4 Objectives

The objectives for this project are to; benchmark the different exoskeleton systems available in the industry, investigate the application of upper limb exoskeleton focused on above shoulder assembly task and investigate how the upper limb-focused exoskeletons affect the working conditions and well being of the operators in the assembly work. This will be done through observation and collection of subjective feedback on upper limb exoskeletons applied in the real factory setting were under-up work tasks are performed. It will also be done through a biomechanical testing of upper limb exoskeleton in a lab environment to collect objective data on the equipment.

1.5 Research questions

The following research questions were set as a focus for the study to answer.

- What constitutes an appropriate application of upper-limb focused exoskeleton in Volvo Cars final assembly?

- What are the challenges and benefits of upper limb exoskeletons in the final assembly of the automotive industry?

2

Theory

This section includes the theory needed to grasp the methodology, result and conclusion of this report.

2.1 Ageing

The labour force is the heart of a company and the well-being of the labour force is of utter importance. Taking a closer look at the European work forces there are trends that point towards that the workforce is increasing in age and this can contribute to higher costs in terms of sick leave and other age related expenses. Due to pension reforms the expected retirement age in Europe is going to be increased by 2.3 years for men and 2.9 years for women(European Commission, 2018). Due to this the participation rates for labour workforce between 55-64 years old will approximately increase with 11.3 percentage points for men and 14.3 percentage points for females until the year of 2070(European Commission, 2018).

Taking a closer look at the Swedish population the different population groups are projected to change until the year of 2070. Age group 0-14 years is projected to stay at the same level, age group 15-64 years is projected to decrease by 4.9 percentages and age group +65 years is projected to increase by 5.2 percentages(European Commission, 2018).

An increasing age of the labour force will contribute to elevated costs as there are correlations between higher age and physical issues. Hearing problems, backache, muscular pains has been shown to increase with age if you look at the 95 percent confidence interval(Eurofound, 2017). The level of these problems depends on what type of work that has been pursued, but elevated levels point to more physically heavy work tasks. Musculoskeletal issues have a strong correlation to age but psychological issues do not(Eurofound, 2017).

2.2 Injury statistics

According to the Swedish work environment authority 28 percent of the Swedish working force have experienced some work related health issues during their professional career(Arbetsmiljöverket, 2018). Accidents account for a small portion of the total work related health issues and the portion where other work related health issues affect the workforce was more common for women at 30 percent compared to men at only 20 percent of the workforce(Arbetsmiljöverket, 2018).

The most common reason for these issues is a too high workload put on the individual and this accounts for 65 percent of the workers with work related health issues. Another major contributor was strenuous or static working positions(Arbetsmiljöverket, 2018).

The most common work related health issue amongst the workers are fatigue at 80 percent for women and 68 percent for men. Fatigue is followed by general physical pain and issues with neck,shoulder and arm. Worth noting is that less than 8 percent of non-accidental work related health issues are reported to the Försäkringskassan which is the insurance agency of the Swedish state(Arbetsmiljöverket, 2018).

Regarding work related health issues of the neck, shoulders and arm it can be seen that the level of these increase in relation with the age. Issues with the neck, shoulder and arm are 11 percent higher between ages 50-64 years for the age group of 16-29 years old. The issues are also five percent higher for the age group 50-64 years than the age group of 30-49 years old(Arbetsmiljöverket, 2018).

2.3 Working above shoulder

In an assembly line, it is quite difficult to avoid tasks which requires elevated arm postures above shoulder height as flexibility is a necessity to perform in these locations during daily working conditions.

The automotive industry is one amongst several large industries that have reported many incidents of working above shoulders. According to Schneider & Irastorza, 2010, 41.1% of workers in Sweden reported pain in shoulders and neck. In 2003, 68% of all occupational diseases were caused by postures at work. There were several risk factors associated with upper limb disorders and based on national epidemiological survey, working with hands above the shoulder was one of the risk factors (Schneider & Irastorza, 2010).

2.4 Musculoskeletal disorders

Work related musculoskeletal disorders (WMSD's) are muscle, tendon and nerve disorders, characterised by discomfort, impairment, disability or persistent pains in joints, muscles, tendons or other soft tissues developed during the course of work (WSH institute, 2018). There are a lot of manual handling activities that may contribute to these injuries and some of them are awkward positions, static postures, forceful exertions and repetitive movements.

Occupational musculoskeletal disorders of the upper limb occur to the operators due to several repetitive movements and physical efforts of the upper limb. Musculoskeletal disorder is defined as the alteration of the muscle tendon units of the peripheral nerves and the vascular system (Colombini et al., 2002). According to Colombini, 33% of workers have stated that they are involved in jobs requiring repetitive movements of upper limb.

One third population of women and one quarter of men in general working conditions in Sweden reported pain in the upper limb especially neck and shoulders (Violante et al., 2000). The most common upper limb disorder in the Scandinavian countries is neck stiffness and shoulder pain. Tendonitis is also a common disorder which is inflammation of muscle tendon that mainly occurs at the shoulder and elbow region (Violante et al., 2000).

In Europe, 20% of workers reported pain in upper limb while doing repetitive tasks (Schneider & Irastorza, 2010). There are several causes for WMSD's which include physical, ergonomic and psychological factors. About 62% of workers in EU have reported being exposed to repetitive upper limb movements at least during quarter of their working time (Schneider & Irastorza, 2010). According to the survey conducted by working group european strategy on health and safety at work, 32.8% of workers reported muscular pains in Sweden (Schneider & Irastorza, 2010).

2.5 Muscular system of the upper limb

Any activity such as standing, sitting and walking requires the movement of particular skeletal muscles. The several muscles that are associated with shoulder, neck, back and arms are mentioned below with a description of their location and function.

The muscles of the upper limb can be divided into four groups such as the muscles that position the pectoral girdle, muscles that move the arms, forearm and the muscles that move the hands, wrists and fingers (OpenStax College, 2013). The related muscles with respect to manual handling work tasks are the the muscles that move the shoulder and the muscles that move the arm (Theurel et al, 2018).

There are several actions that assist in the movement of shoulders and arm. At the shoulder joint, humerus bone attaches to the scapula and there are many movements that occur at this joint (Muscles that move the arm, 2017). All the primary muscles have several actions such as abduction, adduction, flexion, extension, internal rotation and external rotation (Muscles that move the arm, 2017).

The different movements of the arm are flexion (forward movement of the arm), abduction (lifting an arm sideways), adduction (bringing an arm towards the body), extension (backward movement of the arm), internal rotation (rotate an arm so that elbow faces forward), external rotation (rotate an arm so that elbow faces backward) (Muscles that move the arm, 2017).

2.5.1 Muscles that move the shoulder

The muscles of shoulder that attach to the scapula, humerus and clavicle are pectoralis major, pectoralis minor, deltoid, coracobrachialis and latissimus dorsi (Muscles that move the arm, 2017).

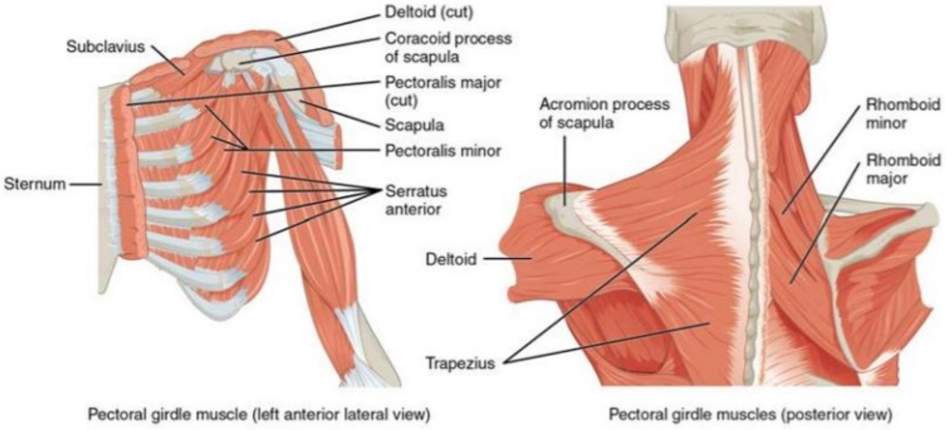

Figure 2.1: Muscles that position the pectoral girdle (OpenStax College, 2013, cc BY 4.0)

The pectoral girdle is a musculoskeletal structure which is located either on the anterior or posterior thorax whose function is to move the arm as shown in figure 2.1. The pectoral girdle consists of the lateral end of the clavicle and scapula with the proximal end of humerus and there are muscles to cover the bones in order to stabilize the shoulder joint (OpenStax College, 2013). Humerus is a long upper arm bone from shoulder to the elbow and both clavicle and scapula are attached to it as shown in figure 2.2. The clavicle, also known as the collarbone lies horizontally on the shoulder girdle and the scapula, also known as the shoulder bone, connects the humerus with the clavicle(OpenStax College, 2013). There are two axial muscles that move the humerus, these are pectoralis major and latissimus dorsi(OpenStax College, 2013).

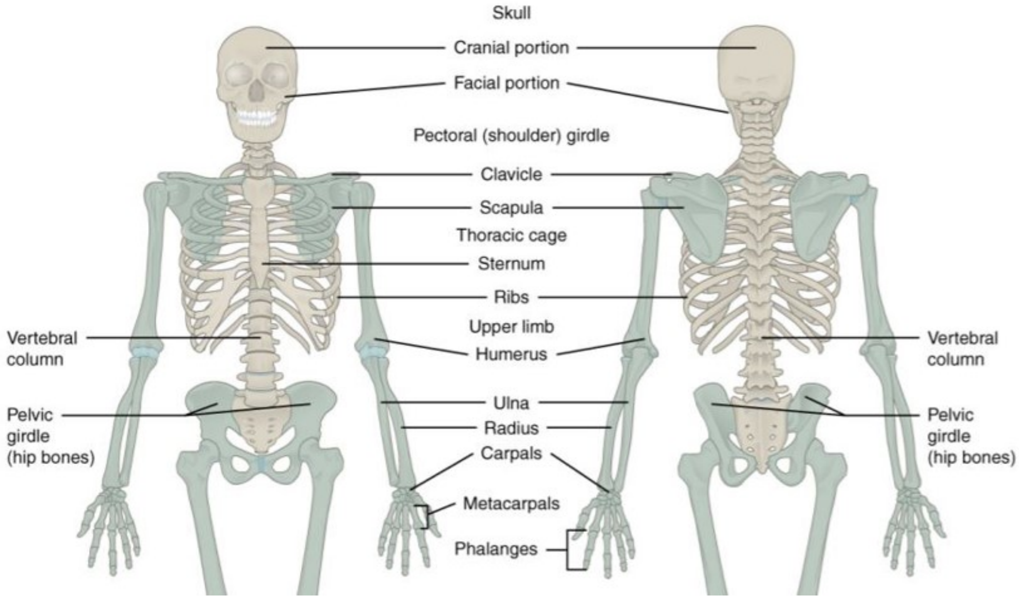

Figure 2.2: Appendicular skeleton of upper limb(OpenStax College, 2013, cc BY 4.0)

Pectoralis major is located on the anterior side of the body and originates from the sternum. This muscle is used for adduction, flexion and medial rotation of the upper arm. It is a large fan shaped muscle which covers the chest that consists of two main regions which are clavicular and sternocostal regions (Upper limb muscles and movements, 2019). The clavicular region originates from the inferior surface of clavicle which attaches to the humerus and sternocostal region originates from the sternum (Upper limb muscles and movements, 2019). Pectoralis minor is a muscle which acts as an accessory muscle of respiration. It is located deep into the pectoralis major and arises from the connecting tissue surrounding a muscle group. It helps in forward reaching and pushing down external shoulder rotation (Muscles that move the arm, 2017).

Latissimus Dorsi is also a large fan shaped muscle (like pectoralis major) which is located at the back of human body. It originates from spinous process of T7-L5 and sacrum, iliac crest (Upper limb muscles and movements). The main function is adduction, extension, internal rotation of the arm and rotation of the trunk as well (Upper limb muscles and movements, 2019).

Another region of muscles to consider for upper limb is the scapular region. This is located on the posterior surface of the thoracic wall (Upper limb muscles and movements, 2019). Scapula helps in the movement of shoulders and neck. Trapezius is a muscle which is located in the scapula region. Trapezius is a large fan shaped muscle found on the back that arises from the spinous processes of C7 through T12 (Upper limb muscles and movements, 2019). The main function is elevation, depression and retraction of the scapula.

Deltoid is a muscle which is in the shape of a triangle and is a thick muscle that facilitates in abduction of the arm. There are 3 sets of fibers in this muscle such as anterior, posterior and and lateral (Upper limb muscles and movements, 2019). The main function of this muscle is abduction, flexion and horizontal adduction. The deltoid muscle moves the humerus superiorly and originate from the superior surface of scapula or the clavicle (OpenStax College, 2013).

Coracobrachialis is a muscle which arises from coracoid process of the scapula (Upper limb muscles and movements, 2019). Adduction and flexion of the arm are its main function.

2.5.2 Muscles that move the arm

The muscles of arm are brachialis, biceps brachii and triceps brachii as shown in figure 2.3(Upper limb muscles and movements, 2019).

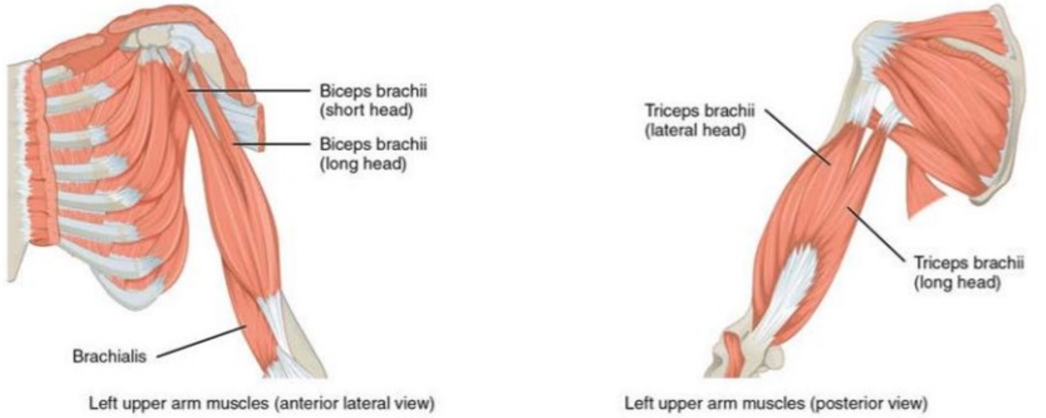

Figure 2.3: Muscles that move the arm(OpenStax College, 2013, cc BY 4.0)

The main function of Brachialis is flexion of the forearm at the elbow joint and it arises from lower part of the anterior surface of humerus (Upper limb muscles and movements, 2019).

Biceps brachii is a muscle that has a short and long head that arises from the scapula and forms the anterior compartment of the arm (Upper limb muscles and movements, 2019). The main function is flexion of the forearm and also supinator of the forearm

Triceps Brachii forms the posterior compartment of the arm and has three heads which are long, lateral and medial (Upper limb muscles and movements, 2019). The function of this is extension of the forearm and elbow joint.

2.6 Anthropometry

Anthropometry is the science of systematically studying the measurements and dimensions on the human body and its skeleton. The body is being measured and the data is presented relative to the individual's ethnicity, sex, age and identity. The goal of anthropometry research is to chart the different characteristics we humans have in measurement of different body parts, weights and statures and then use this information in studies or dimensioning of products or tasks(Smith, 2018).

Measurements in the table below have been acquired from *www.antropometri.se*, which includes an anthropometric database and anthropometric calculator, based on a study by Hanson et al. (2009). The table 2.1 below includes the values of the average, top(95th %-ile) and bottom(5 %-ile) anthropometric measurements for the Swedish population both male and female. The measurements shown below is in millimeters and has been selected amongst other anthropometric values of the human body in Scandinavian setting.

	Male			Female		
Measurement(mm)	Top(95th %-ile)	Average	Bottom(5th %-ile)	Top(95th %-ile)	Average	Bottom(5th %-ile)
Stature(Body height)	1907	1791	1676	1785	1673	1562
Shoulder height	1562	1454	1345	1462	1358	1254
Chest breadth(standing)	403	347	290	342	302	262
Thorax depth	338	211	84	325	231	137
Hip Height(Iliac spine height)	1089	1001	914	1081	933	848
Hip breadth(standing)	407	362	317	411	371	331
Body weight(kg)	100,2	77,5	54,8	82,8	64,8	46,7

Table 2.1: Anthropometric values of the Swedish population

2.7 Previous investigations of exoskeletons

The exoskeleton sector continues to evolve in the medical, industrial, military and commercial sectors. There are two types of exoskeletons, active and passive, where active exoskeletons consist of actuators such as electric motors, hydraulic actuators and pneumatic muscles, which helps in supporting human joints (de Looze, 2016). Whereas a passive exoskeleton works on the basis of springs or dampers that can be required to support a posture or a motion (de Looze, 2016). Exoskeletons can also be classified based on human body parts and movements such as upper body exoskeletons, lower body exoskeletons and full body exoskeletons which provide support for both upper and lower extremities (de Looze, 2016). Moreover, there are single joint exoskeletons as well which can be either used for the knee or elbow (de Looze, 2016).

A number of exoskeletons have also been designed for military purposes where exoskeletons act as rescue devices mainly used for protection (Zoss, 2006 & Yang, 2008). The exoskeleton system was first introduced for rehabilitation applications (Lo, 2012 & Abdoli, 2006). The key advantage of using exoskeletons in industrial sector is to decrease the number of work related injuries, thereby reducing healthcare costs and employee turnover (de Looze, 2016).

Spada(2017) about different types of passive exoskeleton available in the industry. Several effects of physical loading and dynamic lifting of these passive exoskeletons are mentioned in a few research studies which resulted in positive effects on the back muscle activity [Graham, 2009 & Ulrey, 2012 & Whitfield, 2015). These passive exoskeletons are not widely used in automotive industries due to discomfort levels (de Looze, 2016). There has been high interest in large scale implementation of exoskeletons in industries (de Looze, 2016).

Several key technologies in exoskeleton systems are discussed in (Yang, 2008) which includes biomechanical design, system structure modelling, cooperation and function allocation between man and exoskeleton, control strategy and system safety evaluation(Yang, 2008). With ongoing research studies, the exoskeleton technology is going to play a significant role in the development of man- machine system (Yang, 2008).

2.8 Exoskeletons

An exoskeleton is a wearable, external mechanical structure which is intended to increase the user's physical performance(Wesslén, 2018). According to Marinov (2015), there are 3 main advantages of using exoskeletons in physical working industries. They contribute to a reduction in work related injuries, less investment in medical fees and reduction in sick leave. Exoskeletons can be designed to aid different types of body parts and one type focuses on the upper limb which is shoulders, arms and elbow and back. There are different types of exoskeletons such as powered, passive, pseudo passive and hybrid exoskeletons which are used for various purposes(Marinov, 2015). Passive exoskeletons do not have any external power source but instead use springs and dampers for the human's motion and posture (Wesslén, 2018).

In the following sections, three different models of exoskeleton will be described which has been bought by Volvo Cars for this study

2.8.1 Paexo

The Paexo is an exoskeleton produced by Ottobock which is a German leading brand in the orthopedic technology sector. The exoskeleton is passive and focused on upper-limb support in overhead assembly tasks. The construction is lightweight, just below two kilograms, and consist mostly of plastics, metal and fabrics, see figure 2.4(Ottobock 2018).

Figure 2.4: The Paexo exoskeleton

The design consists of straps for the hip, shoulders, arms, chest and the elevating mechanism is situated in two boxes on the back. The mechanism is performed by a mechanical cable pull technology(Ottobock 2018), see figure 2.5. The arms are elevated by two arm cuffs that are placed around each arm, see figure 2.5, and the aiding power of the spring loaded boxes can be adjusted to suit the user by tightening or loosening the tension from the spring loaded box in the shoulder joint, see figure 2.6. All of the straps, the height and positioning of the spring loaded boxes can be adjusted to the user for a comfortable fit.

Figure 2.5: Cable pull technology and arm cuff of the Paexo exoskeleton

The exoskeleton includes a carrying bag which aids in transportation of the equipment and also provides space for instruction manuals and tools for adjusting the exoskeleton to the user, see figure 2.6.

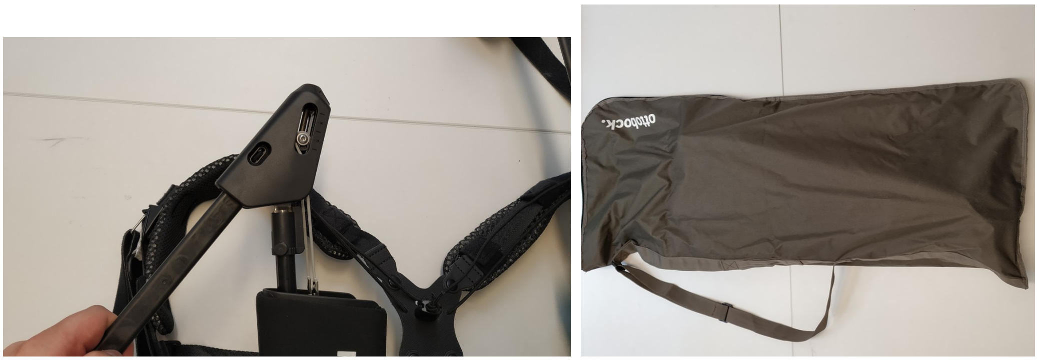

Figure 2.6: Shoulder joint and carrying bag for the Paexo exoskeleton

2.8.2 EksoVest

The EksoVest is an exoskeleton produced by Ekso Bionics which is an American company in the exoskeleton market. The EksoVest is a passive exoskeleton focused on the upper limb. The construction of the equipment is mainly built out of metal, fabric and composite material and weighs 4,3 kilograms, see figure 2.7(Ekso Bionics 2018).

Figure 2.7: The EksoVest exoskeleton

The EksoVest consists of straps made out of fabric for the shoulders, hip and chest. It has two back-plates on the upper and lower back made out of a composite material for a rigid support and adjustability between the two back-plates, see figure 2.8.

The elevating mechanisms are fastened with arm cuffs with two fastening points, held by straps and fastened by magnets. The different parts are connected together by metal rods going from the back-plates to the arm cuffs, see figure 2.8.

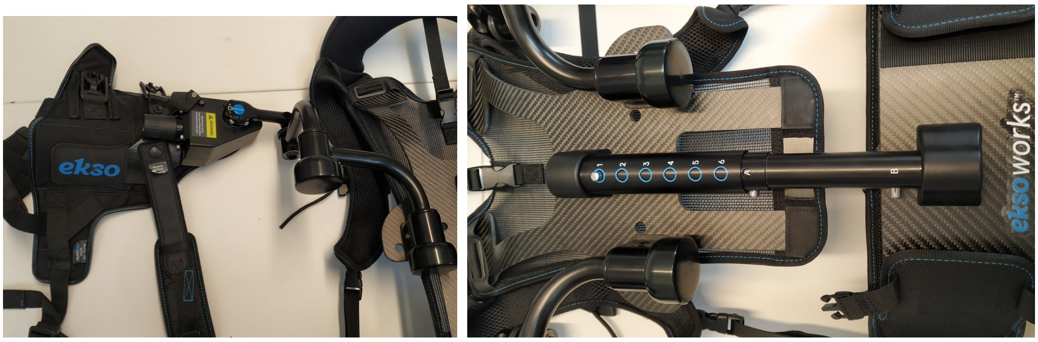

Figure 2.8: Arm cuff and back adjustment on the EksoVest exoskeleton

The equipment can be fitted to the user through adjustment of the straps, exchanging of arm cuffs and belt from small to extra-large size, see figure 2.9. The elevating mechanism is driven by two springs, one on each arm cuff, and these come in 4 different strengths from 2,2 to 6,8 kg of lifting force per arm, see figure 2.9(Ekso Bionics 2018). The elevating mechanism is activated after wearing the exoskeleton by turning a knob on the arm cuffs.

Figure 2.9: Springs and accessories for the EksoVest exoskeleton

The EksoVest includes a carrying case for easier and safer transporting, see figure 2.10, and an accessory bag to store all the different exchangeable parts for the exoskeleton, see figure 2.10.

Figure 2.10: Carrying and accessory bag for the EksoVest exoskeleton

2.8.3 Mate

The Mate is an exoskeleton by the company Comau which is an Italian company in the industrial automation market. The exoskeleton is passive, upper-limb focused and weighs 4,1 kilograms, see figure 2.11(Comau 2018).

Figure 2.11: The Mate exoskeleton

The Mate consist of straps made out of fabric for the shoulders, hip and arms. It has a back-plate made out of metal and two spring loaded boxes on each side of the arms. The straps can be adjusted to the user and the hip belt has a pulling system to tighten the belt even further to suit the user, see figure 2.12. The movability of the arms and shoulders can be adjusted by straps in the back, see figure 2.12. The height of the exoskeleton can also be adjusted in five steps in the back to suit the user, see figure 2.12.

Figure 2.12: Belt, back and shoulder adjustments on the Mate exoskeleton

The elevating mechanism power setting can be changed to suit the user at seven different assistance levels and the torque generator box can be fastened in the end position for easier dressing and undressing, see figure 2.13(Comau 2018). The torque generator is then released by a knob on top of the box, see figure 2.13. The arm is fastened via a Velcro loop that slides vertically on the inside of the torque generator box.

Figure 2.13: Torque generator box and arm cuff of the Mate exoskeleton

The Mate exoskeleton does not include any sort of carrying bag for transporting and the only accessory included is an extension of the hip belt.

2.9 Electromyography

A method that often is used for biomechanical testing is EMG (Electromyography). Electromyography (EMG) refers to the collective electric signal from muscles, which is controlled by the nervous system and produced during muscle contraction (Chowdhury et al., 2013). These signals are formed by physiological variations in the muscle fibre membranes. Unfiltered and unprocessed signals are called as raw EMG signals. This raw EMG is based on many factors and the average baseline should not exceed 3-5 microvolts (Biopac systems, 2019). This is a very important factor while measuring EMG. There are different applications of surface EMG signal. It can be used for an indication of muscle activation, for estimating muscle tension and also for estimating fatigue processes occurring within a muscle (Wehner, 2012).

There are two types of EMG, Surface EMG and intramuscular EMG (Chowdhury et al., 2013). Surface EMG is one type where flat electrodes are attached to the skin surface on the particular muscle which has to be tested (Chowdhury et al., 2013). Intramuscular is another type where needles are inserted through the skin into the muscle of interest.

According to (Wehner, 2012) there are several factors to consider while recording an EMG signal. These factors affect the EMG signal as well as the force produced by the muscles. EMG signal is greatly affected by electrode configuration which means the shape, material, inter-electrode distance and location of electrodes. Intrinsic factors are physiological, anatomical and biomechanical characteristics of muscle such as blood flow to the muscles, tissue type, fiber type, diameter and depth of the active muscle fibers (Wehner, 2012). Other electromechanical properties of the electrodes such as the tendency to record cross talk from other muscles. Deterministic factors such as number of active motor units, fiber interaction and firing rate and also orientation of detection surfaces with respect to muscle fibers are considered as well (Wehner, 2012). All these conditions can greatly vary from person to person.

For a better quality of EMG signal, it is important to make sure of proper skin preparation and better electrode placements. Removing the hair is a requirement in order to improve the adhesion of the electrodes. EMG is used for various research studies in the field of medical research, rehabilitation, ergonomics and sports science.

According to (Hermens et al, 1999), there are a few recommendations before starting SEMG. SENIAM (Surface electromyography for the non-invasive assessment of muscles) is a project group in biomedical health and research program of the European Union. The size of the electrode should not exceed 10mm in the direction of muscle fiber and the electrodes should always be placed on the midline of the muscle belly. It is suggested to use RMS (Root mean square) value to measure the amplitude as it reflects the level of physiological activities in the motor unit during contraction and to always check for crosstalk (Fukuda et al, 2010). Electrode configuration is one of the factors that includes the shape, size, area and inter-electrode distance (IED). The preferred electrode configuration is with a bandwidth of 20-500 Hz. IED should be 20mm which determines the number of motor units being detected. The placement and position of the electrodes is an important factor to consider to minimize the crosstalk and also minimize the risk of electrical contact between the electrodes. The skin at the desired muscle should be shaved and cleaned with alcohol prior to the attachment of the electrodes.

In order to make force predictions or make comparison between test subjects, EMG signals must be normalized to some applied force (Wehner, 2012). The amplitude (microvolt) data is strongly influenced by electrode sites, subjects and other muscle fibres. To overcome this situation, the microvolt scaled parameters should be normalized to a reference value. It involves rescaling data from microvolts to a percentage of reference value which is obtained during standardised conditions (Rota, 2013). This is usually done by normalising to maximum voluntary contraction (MVC) (Wehner, 2012). EMG normalisation method helps in increasing the reliability of EMG data and also provides information on levels of muscle activation (Rota, 2013).

2.9.1 Equipment used for measuring EMG

The MP system (MP 36, MP 35 or MP 45) as shown in figure 2.14 is a computer based acquisition system which takes incoming signals and converts them into digital signals that can be processed with the computer (Biopac systems, 2019). It acts as a data viewing device and with this system, graphical and numerical representations of data can be produced as well. There are several components within the MP system that perform several functions such as the control of data acquisition process, performing real time calculations, performing other mathematical functions and handle file management commands (Biopac systems, 2019).

Figure 2.14: MP data acquisition unit

An electrode lead set is a general purpose electrode cable that is used for most of the applications that requires the use of electrodes. One end of the cable has a connector type (9 PIN) which connects to the MP 36 unit and the other splits into 3 cables. The electrode lead set (2 meter cable) with this MP acquisition unit consists of three pinch leads which are designed to snap directly onto the surface electrodes as shown in the figure 2.15. One end of the cable has a connector type (9 PIN) which connects to the MP 36 unit.

Figure 2.15: SS2L Electrode lead set

As seen in figure 2.15, there are different colors to each pinch lead such as white (-), red (+) and a reference electrode (black). Each pinch lead is 1 meter long. These cables are connected to surface electrodes which are placed on the surface of the skin.

Surface electrodes are simple instruments that are attached to skin surface to pick up electrical signals in the body as shown in the figure 2.16. It is mainly used in applications such as ECG (Electrocardiography), EMG (Electromyography) and EEG (Electroencephalography) to study the electrical activities of heart, skeletal muscles and neurons of the brain (Biopac systems, 2019). These peel and stick disposable electrodes are pre-gelled for a better signal transmission.

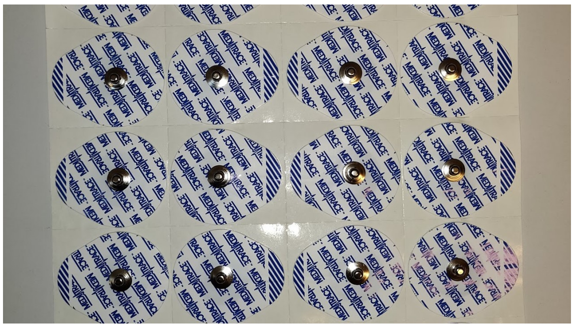

Figure 2.16: Surface electrodes

The equipment also includes abrasive pads (2.5 cm x 5 cm) and isotonic recording electrode gel which is used to remove non-conductive skin cells and is rubbed lightly across the skin before applying the electrode as shown in the figure 2.17. The electrode paste as shown in figure 2.17 is used for skin conductance recording is specially formulated with 0.5% saline to create an isotonic electrode paste.

Figure 2.17: Abrasive pads and electrode paste

2.10 Questionnaire design

Questionnaires include questions relating to topics such as facts, opinions, attitudes, beliefs and perceptions on the use of equipment (Rowley, 2014). Questionnaires are used to conduct a variety of different kinds of research and the most important ones are listed below.

The first kind is profiling and descriptive research where the purpose is to generate a profile of the characteristics of the sample (Rowley, 2014). Second kind is predictive and analytical research where the the purpose is to understand relationship between different variables (Rowley, 2014). Third kind is developing and testing measurement scales where the purpose is to generate a set of statements to measure a complex variable such as service quality (Rowley, 2014).

While framing the questions for any study, the most important factor to consider is the type of question (Rowley, 2014). There are two types of question such as open ended and closed ended questions. Close ended questions are a series of statements the participants are asked to indicate how they agree or disagree and also scale questions which includes different number of options (Rowley, 2014). Open ended question is a type where participants provide a short comment on the question within 3 to 4 sentences (Rowley, 2014). Closed questions are pre-coded, this helps in less time for processing the answer and eventually the task of the operator will not be disturbed in this study.

Designing the questionnaire in such a way that participants find it as easy as possible to respond to the answers so that they can understand the question plays an important role (Rowley, 2014). Rowley (2014) suggests that the questions need to be as short as possible, to not include two questions in one, to not use double negatives and to not lead to any implicit assumptions. The sensitive questions, which the participants do not wish to answer can be included at the end of the questionnaire to encourage them to complete other questions first (Rowley, 2014).

Having a short introduction at the beginning of the questionnaire which contains the title of the study, purpose of the study, contact details of the researchers and thanking the participants for completing the questionnaire improves the quality of response from participants as well (Rowley, 2014). A pilot study could be conducted with colleagues to check if the flow of questions, patterns, variation and respondent interest makes sense and also to eliminate the possible problems from the preliminary pilot study (Rowley, 2014).

The order of the questions plays an important role in designing a good questionnaire. Order could be started from the most general topics and then more into the specific ones (Brace, 2008). The participant will ease into the subject when started with the most general topics at the first (Brace, 2008). Sensitive questions is a type where the participants finds it difficult to answer should be written at the last (Brace, 2008).

Multiple choice questions are one type where the participants would not have to say anything in their own words (Brace, 2008). A “don’t know” response should be included in some of the questions in order to make it easier to answer as the respondent would not know the answer to it or would be not be sure of answering the question (Brace, 2008). Layout of the questions with either horizontal listing or vertical listing is important to decide where vertical listing consumes more space and horizontal looks congested and less attractive to answer (Brace, 2008).

2.11 Design of experiment

This section includes theory that supports methodology regarding design and execution of experiments.

2.11.1 Qualitative data collection

Qualitative data collection is the way of collecting data through qualitative collection methods. The data collected can take many forms from pictures, videos, recorded speech to printed text. The data can provide more context to what is being measured or investigated and it provides a solution to capture thoughts and feelings(Denscombe 2010). Subjective data collection is most often collected as qualitative data due to the fact that context and detailing is most often needed to understand the thoughts and feelings from individuals.

2.11.2 Quantitative data collection

Quantitative data is not as descriptive as the qualitative data and most often comes in the form of numbers. There is not much of context to the data and this can be suitable for large data collections(Denscombe 2010). Quantitative data can be collected through surveys and interviews but these answers will only be polar answers or pure facts, for example age or sex.

2.11.3 Semi-structured interview

To collect subjective data there are a lot of different methods that can be used. One of these methods is to perform a semi-structured interview to collect the subjective data. Interviewing is done to capture subjective responses from the interview participant and the interview can be structured in different ways. An unstructured interview where questions are not predefined can be valuable in the sense of capturing and adapting to specific situation, non repeatable. This leaves a lot of the quality of the interview up to the interviewer, what to ask and how(Firmin, 2012).

A structured interview on the other hand leaves little room for the interviewer to alter the questions and order of the questions as they are predetermined. This makes the interview easy to replicate and perform multiple times and aids in summarizing results from many different interviews. The drawback of using structured interviews is that it leaves no room for interesting thoughts from the participant or a chance for the interviewer to dive deeper into topics that could be interesting for the cause of the study(Firmin, 2012).

The semi-structured interview is a sort of mix of these two. The interviewer will have some sort of predetermined questions, but can change the order of these, change the questions slightly, dive deeper into a topic and ask follow up questions. This makes this method good for summarizing the answers from multiple interviews and at the same time provides the freedom to collect highly valuable answers and feedback from the participators(Newton 2010).

2.11.4 Observation

There has been some research conducted globally regarding direct observational methods at globalising industries. According to “Observational Research and Automotive Industry"(2018), observation is observing and noticing of human behavioural patterns, objects and actions in a systematic way to obtain information about a certain event. This provides the researchers to see what actually happens in the real scenario. There are four major types of observations such as structured, unstructured, participant and simple & contrived observation ("Observational Research and Automotive Industry," 2018).

Structured observation is an observation where the researcher engages in a systematic way of observing by setting certain rules and recording it ("Observational Research and Automotive Industry," 2018). THe observer is sure of what to look for and will constraint his observation to only those participants.

In unstructured observation, there is no systematic way of observing in order to record a behaviour ("Observational Research and Automotive Industry," 2018). This approach applies when there is no specific defined problem for it. Participant observation involves engagement of the observer in groups which will provide observations on behaviour and attitude of participants ("Observational Research and Automotive Industry," 2018). When an observer alters the situation to find the effects of interference, that is called as contrived observation.

2.11.5 Objective data collection for lab study

To collect data in the lab study, a systematic observation has to be performed for a particular set of participants for a particular reason. Experiments is one sort of quantitative data collection which involves the manipulation of independent variables by varying degrees of control over other variables (Cleverism, 2017).

To gather data and analyse those results, there are different types of experiments. Laboratory experiments are one such type where the investigator has the control over independent variables where manipulation of variables can be performed (Cleverism, 2017). This type is a typical data collection method in a confined and controlled laboratory environment. Field experiments are another type where the investigator will not have full control over the variables. Natural experiments are another type where there is no control over the independent variable (Cleverism, 2017).

2.11.6 Participant sampling

According to Maxwell (2013) there are three different ways of sampling participants, probability sampling, convenience sampling and purposeful selection. Probability sampling is based on random sampling from all of the available participants. Convenience sampling is based on using the accessible participants and is often used when the choice of participants are slim or very limited by other factors(Maxwell 2013).

Purposeful selection is based on choosing the participants that can provide relevant results to the aim that is pursued. Maxwell (2013) mentions 5 different goals for pursuing purposeful selection. The first goal is to choose participants that will reflect and represent the actual setting of a study. Random sampling will do this but only when applied on a large sample and therefore a smaller sample can end up not representing the actual setting(Maxwell 2013).

The second goal is to represent the whole range of variation amongst the participants, this range of variation will differ but one example can be that an age variation is covered amongst the participants(Maxwell 2013).

The third goal is to test some extreme condition and therefore choose participants to accommodate the study. For example there might be a study on problems that affect taller participants and therefore taller persons are chosen for the study(Maxwell 2013).

The fourth goal is to compare different types of objects or participants and therefore select participants to fulfill this aim. It can be hard to draw any solid conclusions if the sample volume is too small as variation is present among the participants(Maxwell 2013).

The fifth goal is to select participants that you already have or will create good relationships with and therefore can provide the study with great response and feedback(Maxwell 2013).

3

Methods

This section presents the methods used to generate results to support the purpose of this study.

3.1 Research approach

To evaluate the exoskeletons in this study, triangulation was applied including different methods to create a holistic picture of the technology in an assembly setting. The triangulation included both subjective and objective data gathered through subjective and objective collection method described in the chapter 3.2: *Data collection.* Utilizing triangulation, the gathered data combined with information from the literature study will provide a foundation to properly evaluate the technology.

3.2 Data collection

To be able to evaluate the exoskeleton technologies both subjective and objective data was collected during the study. To collect subjective data, semi-structured interview and observations were conducted during factory testing and to collect objective data, electromyography tests were performed during lab testing.

3.2.1 Subjective data collection

To collect subjective data, semi-structured interviews were performed with the participants. A questionnaire was created as a foundation for the semi-structured interview, see appendix A: *Factory testing questionnaire.* The interviewer used this questionnaire to ask predetermined questions and mark down answers from the person being interviewed. The questionnaire was designed accordingly with chapter 2.10: *Questionnaire design.* As the interview was of semi-structured sort, the interviewer could mark down answers not covered by the questionnaire or ask follow up questions on the predetermined questions.

The interviews were conducted on site with the study participant face to face with the interviewer. The interviews were performed at a relative calm place close to the testing area, but still in a production facility setting right after the performed test.

First the participant was introduced to the interview, what types of questions that would be asked, how long time period the interview usually takes and the participant was encouraged to speak freely about the product that had been tested.

The questions were asked and answered in a calming pace and time for consideration was given to the participant on each question. It is important that the participant is not affected by the interviewer and the interviewer therefore had to be careful while asking follow up questions to not steer the mind of the participant.

The study owners had printed out the questionnaire in paper form before the testing and the answers where noted down by pen. After all questions had been answered to the satisfactory of the interviewer the participant was thanked for partaking in the study and informed about where the resulting study can be viewed later if that interest exists.

The answers were later inserted digitally into the questionnaire form and other comments not covered by the questionnaire were also inserted digitally per individual and summarized.

3.2.2 Observational data collection

During factory testing the participants were filmed to allow for further observation of the participants. The observation type that was used for this study was structured observation where the participants were filmed in a systematic way by setting certain rules(“Observational Research and Automotive Industry,” 2018).

In order to observe the participants and investigate the benefits of exoskeletons on the operators at the assembly plants, the operators were filmed using a video recording device. Prior to the start of the factory testing, planning was made such that 2 cycles with the exoskeleton and 2 cycles without the exoskeleton were filmed in each shift for each participant.

To maximize the test duration with the exoskeleton, the assembly sequence without the exoskeleton was either filmed in the beginning of the test or after the test depending on the stations assigned to the operators. The recording was taken from a position which did not disturb any other operators or the production line and the filming covered only the desired operator working at that particular station.

3.3 Factory testing

This section describes how the subjective data collection were performed. To evaluate the application of the exoskeleton technology, a factory testing in the real life production setting was conducted.

The companies involved in the thesis were contacted and a meeting with suitable individuals were set up to start out the testing planning and performance. The test performers introduced the study to the company contact persons, where the reasons behind the testing were disclosed and what testing structure the test performers had in mind. The contact persons got to ask questions about the thesis and returned with some tips on where tests could be done to suit the needs of the thesis.

After deciding on which department the test should be conducted in the potential participants required some sort of information regarding the study. An “informing the participants” document was written to inform the participants, including the most important information regarding the study, see appendix B: *Informing the participants.*

The stations were visited to meet the potential participants, the line managers and to look at the proposed stations where tests could be performed. During the visit of the different stations, information were gathered and observations were made to decide on stations suitable for performing the test on.

After visiting the companies, the line managers and the workers, a participant list was sent to the line manager to list different workers that would like to partake in the study. The participant list included the participant’s name, gender, assembly experience, height, weight and which stations that they knew how to perform the assembly tasks on. Different participant lists were created for the different companies as different assembly stations had to be considered. The mentioned data was collected to make sure that the participant group was large enough and aided the work of setting up the test prior to the actual trial date.

When the participant list was returned an outline planning of the tests were made. Including where to test, who will perform the test, with which of the three exoskeletons and the preliminary settings for the exoskeleton relative to the participant.

The integrity of the participants is important both for the thesis itself and the companies that the participants are working for. Therefore participation consents and photo permits were produced to inform the participants about how the material gathered from the study would be used and to formally ask for their consent to participate in the study and to be filmed during. The documents regarding participation consent can be found in appendix C: *Participation consent* and the documents for photo/film permit can be found in the appendix D: *Photo permit.*

The execution of the tests were done on site, supervised by the study owners. The tests were preferably performed according to the previous testing plan, but the study also had to respect that there was a real life production and had to consider some flexibility in the planning to avoid problems in the production.

One test cycle started out with introducing the participant to the test, confirming participation consent and photo consent. For observational purposes the participants were video recorded doing two cycles of an assembly sequence while wearing the exoskeleton and two while not wearing the exoskeleton. To maximize the test duration with the exoskeleton, the assembly sequence without the exoskeleton was either filmed in the beginning of the test or after the test.

The participants were dressed with the pre-adjusted exoskeleton and final adjustments were made to make sure that exoskeleton suited the user. The participants performed their normal tasks using the exoskeleton for a time period of 1-1.5 hours depending on available slots for semi-structured interviews, length of the working period between breaks and if tests were performed in parallel. The participants were undressed of the exoskeleton and released from their task to perform the semi-structured interview.

After performing the test, subjective data collection through a semi-structured interview was conducted according to chapter 3.2.1: *Subjective data collection* and finally the participant were thanked for partaking in the study.

Due to the unknown nature of how the equipment would affect the workers possibility to perform their tasks, the participants always had the option to abort the test if their ability to perform the intended tasks were affected too much or if it was too discomforting. If the tests were aborted, a lower limit of 30 minutes of testing were set to decide if the participant were eligible to partake in a semi-structured interview.

3.4 Lab testing

This section describes the method for the EMG lab study. The lab experiments were carried out at the PSL (Production systems laboratory) at Chalmers University of Technology. The EMG equipment (BIOPAC systems) was provided by Chalmers and the exoskeletons was provided by Volvo Cars Corporation.

The EMG equipment was studied and learnt with the aid of biopac system solutions (Biopac Systems, 2019). A BSL hardware guide, a biopac student lab pro manual and biopac student lab lessons were used to learn and use the equipment. Prior to the start of lab testing, the complete laboratory manual (biopac student lab lessons) was studied which consisted of tutorials and the instructions to setup the equipment. The software that was used to record and analyse the EMG data was BSL Pro software which was taught with the aid of biopac student lab pro manual. If any desired application was not addressed in any of the manuals, the Biopac systems website was referred.

The objective of this biomechanical study was to investigate at to what degree does the different exoskeletons reduce the muscle effort in the study task. The resources required for the experiment were EMG equipment, a test rig to perform a study task, the exoskeletons and the test subjects.

The setup of the lab study is shown in the figure 3.1 below. In order to perform overhead work tasks, the study required a mimic of a station or a task. As shown in figure 3.1, a test rig was provided by Volvo Trucks, which consisted of an assembly of a wheel well guard which is used to protect the wheels and vehicle body from harmful elements.

Figure 3.1: Setup of the lab study and the overhead work apparatus

The overhead work apparatus consisted of a wheel well guard at the top which was attached to four upright adjustable rods as shown in figure 3.1. The apparatus had a wooden board as a foundation to provide stability. In order to make sure that all test subjects were positioned similarly, the vertical dimensions of the rig was set to a certain height of 194 cm. The test rig consisted of 3 yellow marked bolts on the inside of the wheel well guard. The yellow marked bolts, provided a place where nuts could be screwed to perform an assembly task as shown in the figure 3.2.

Figure 3.2: Yellow marked bolts

3.4.1 Description of the task

Prior to the start of the test, each test subject was instructed about the task to be performed. Due to different factors such as anthropometry, electrode sites, muscle mass and underlying skin fat associated with each subject, the equipment had to be calibrated depending on that data. In order to calibrate / normalize to MVC of the equipment for each subject, participants were asked to gradually exert to their maximum effort by holding a cordless drill on the dominant arm and lifting the arms up straight which is called as upward flexion of arm (180 degrees) and gradually decrease the arm to return back to the original position. They were asked to perform this 3 times in order to take average and avoid faulty errors.

To collect and record data of the test subjects with and without exoskeletons, the following tasks were performed. Each subject was allowed to practice the task before the actual experiment started.

Each participant was asked to pick 3 nuts in one hand and fix them on all the 3 yellow marked bolts. The next step was to pick the cordless drill in the dominant arm and tighten all 3 nuts (task 1). Prior to the start of the next task, the participants were asked to return to the original position and then unscrew the bolts from all the 3 positions (task 2). The approximate time taken to perform each cycle was 70-80 seconds.

The same procedure was carried out for four cycles; one cycle without the exoskeleton, one cycle with the Paexo, one cycle with the Mate and one cycle with the EksoVest. The sequence of these cycles were shuffled for each participant. This avoids bias towards a single type of exoskeleton and the sequencing is shown in the table 3.1 below. The first cycle is always performed without the exoskeleton but the other 3 cycles were shuffled among other exoskeletons. From the table 3.1, “A” represents first which means that type of exoskeleton should be tested first, “B” represents second and “C” represents third.

Test subject	Sex	Measurement(percentile)	Paexo(A)	Mate(B)	EksoVest(C)
Test subject 1	Female	22nd	A	B	C
Test subject 2	Male	12th	B	C	A
Test subject 3	Female	43rd	C	A	B
Test subject 4	Male	67th	A	C	B
Test subject 5	Female	76th	B	A	C
Test subject 6	Male	95th	C	B	A

Table 3.1: Sequencing of exoskeletons

To avoid muscular fatigue, repetitions were separated with 60 seconds of rest between each cycle. In the meantime, the participants were dressed up with different exoskeletons.

Depending on the anthropometric data of the test subjects, the exoskeletons were setup prior to the start of experiments. The subjects underwent a short trial run with all the exoskeletons to check if they fit well to the body and if it was possible to attach all six electrodes to both the muscles without any restrictions.

In order to involve whole range of variation in the study with different heights and widths, the recruitment of test subjects was based on both purposeful selection and convenience sampling (Maxwell, 2013). Purposeful selection was performed by selecting specific male and female test subjects of different anthropometric data with a slight convenience sampling by limiting the selection to only Chalmers students. According to Maxwell (2013), the fifth goal of purposeful selection is to select participants with whom there is a good relationship with. As this is a biomechanical study which involves ethical issues that is attachment of electrodes, cleaning and shaving at desired places, the recruitment was limited to students of Chalmers. Moreover, having students as the test subjects would be flexible and they would also get an opportunity to participate in this study.

Prior to the lab testing, the experimental procedures and the demands of the testing were conveyed to the participants through a written document (appendix E: *Informing students*). They were provided information about the purpose of the study, why they were wanted, what they will be provided with, duration of the experiment, testing week, contact information of the test performers along with a picture of a exoskeleton and the EMG equipment. Signatures were also obtained on the consent form before the test (appendix F: *Participation consent*).

To account for range of variation in the study, the participants were favorably sampled from different anthropometric values from the anthropometry table used in chapter 2.6: *Anthropometry.* Convenience sampling might have to be applied as extreme anthropometric values can be hard to fulfill.

The total number of tests desired was 18 with both male and female volunteers fulfilling different percentiles as shown in Table 3.2. 3 participants from top, average and bottom percentiles from each sex for three exoskeletons are desired. Out of 18 desired tests, 6 participants volunteered for the study to fulfill the required tests.

	Male			Female		
Measurements	Top(95th %-ile)	Average	Bottom(5th %-ile)	Top(95th %-ile)	Average	Bottom(5th %-ile)
Desired test Paexo	1	1	1	1	1	1
Desired test EksoVest	1	1	1	1	1	1
Desired test Mate	1	1	1	1	1	1
Total desired test	3	3	3	3	3	3

Table 3.2: Total desired lab tests

After the completion of testing for each test subject, the electrodes and electrode connections were removed and the total time taken for the complete EMG lab testing was around 50 - 60 minutes.

3.5 EMG procedure

Different phases were performed in the EMG procedure and each phase is explained in the following paragraphs.

Phase 1 is preparing the subject prior to start of experiment. Each test subject is provided with suitable clothing and the desired muscles which are anterior deltoid and clavicular portion of the pectoralis major are located. Skin and electrode preparation is performed by shaving at the desired location, lightly abrading the surface of the skin and by applying a gel on it. After locating the two muscles, electrode positions should be determined.

Phase 2 is attaching the electrodes to the desired muscles. For the muscle anterior deltoid, the white dot represents the acromion and the electrodes need to placed at one finger width distal and anterior to the acromion as shown in figure 3.3(Hermens et al, 1999). The cross (x) on the surface muscle indicate the orientation of electrode pair in ratio to the muscle fibre direction. At least one reference electrode per subject needs to positioned. Usually, a nearby area is selected such as joints, wrists and C7 vertebrae of the cervical spine for the reference electrode (Hermens et al, 1999).

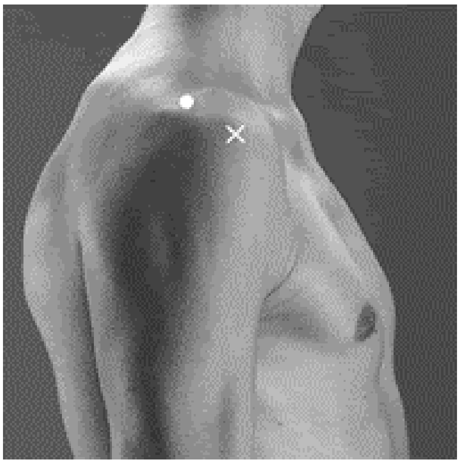

Figure 3.3: Electrode placement for anterior deltoid - Image used with permission from Hermens et al, 1999

For pectoralis major, the clavicular portion of the muscle was tested. This is located on the upper region of the chest that extends from the clavicle (as shown in figure 3.4) to the upper extremity of humerus (upper arm bone) (OpenStax College, 2013). From (Król,H et al, 2007), the surface electrodes measuring 1 cm diameter with spacing of 2 cm were applied on the clavicular portion.

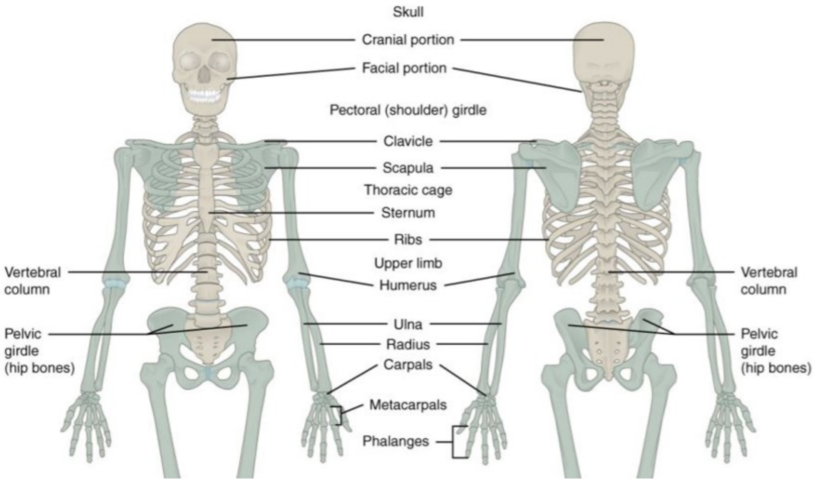

Figure 3.4: Appendicular skeleton of upper limb(OpenStax College, 2013, cc BY 4.0)

The electrode lead sets with the MP acquisition unit consists of three pinch leads which are designed to snap directly onto the surface electrodes. Attach the electrode lead sets to each electrode positions. Each pinch lead is 1 meter long so it is important to tape the wires firmly so that the electrodes do not move out of their position. These electrode connections are plugged into the MP acquisition unit.

In order to setup the hardware unit, plug the electrode lead sets for channel 1 and channel 2 on the MP unit and launch the BSL PRO software on the computer.

Phase 4 is acquiring MVC for normalisation. Before performing the actual tasks, amplitude normalisation is crucial as explained in chapter 2.9: *Electromyography.* MVC normalisation is performed for each investigated muscle of the test subject.

To record/acquire MVC for normalisation, create a new graph on BSL pro software. Setup 2 channels with a preset for EMG (30-500 Hz) and a channel sampling rate of 1.000 kHz. Press start to record/acquire MVC and MVC for the both the muscles is flexion movement of the dominant arm. Repeat the cycle for 3 times and mark the peak waveform when reached maximum MVC. The next step is to note down the maximum peak value and calculate maximum value of the highest peak (mV) by taking the average for all 3 cycles. For example, if maximum value is 1.83 mV, note it down and open a new file. Setup data acquisition channels and perform separate procedures for the both the channels. To rescale the value, maximum EMG in mV (1.83) = MVC (100%) and divide 100/1.83 which gives 54.64. So, 54.64 is the scaling factor for this level of MVC and enter the scaling values and name the units label as %MVC.

The final phase is recording the EMG data for 4 cycles; without the exoskeleton, with Paexo, with Mate and with EksoVest. After amplitude normalisation, the test subjects are asked to perform the assembly task in order to record data for each muscle. For this, 4 separate files are created and the scaling factor of a particular participant is entered in each file. Each cycle takes around 10 minutes with an interval of 2 minutes in between where the test subjects are dressed up with different types of exoskeletons.

4

Results

In this section the results of the study are presented including the subjective factory testing and the objective lab testing. The factory testing section is divided into three parts, stations tested, subjective feedback and observation results. The lab testing section consists of EMG results from each test subject and also the summary of all test subjects.

4.1 Factory testing

The result from the factory testing is presented in this section including the stations tested and the subjective results from the testing.

4.1.1 Stations tested

The tests were performed at production facilities owned by the Volvo Car Corporation and Volvo Trucks AB. The testing was performed on site with 27 professional Volvo assembly workers and the testing was continuously supervised by the study owners. The test procedure is described under the chapter 3.3: *factory testing.* The study was from the start only planned to be conducted at Volvo Cars facilities, but the opportunity was given to perform tests at Volvo Trucks facilities and this opportunity was gladly taken. Some data of the participants can be seen in table 4.1 below. The heights of the participants were only collected in intervals

Nr	Sex	Age	Height(cm)	Assembly experience(years)
1	Male	41	≈ 180	1-5
2	Male	53	≈ 180	>10
3	Male	57	≈ 180	>10
4	Male	52	≈ 180	>10
5	Male	27	≈ 180	5-10
6	Male	60	≈ 180	>10
7	Male	21	≈ 170	1-5
8	Male	52	≈ 170	>10
9	Male	29	≈ 180	1-5
10	Male	23	≈ 180	1-5
11	Male	25	≈ 170	1-5
12	Male	21	≈ 180	<1
13	Female	22	≈ 160	<1
14	Female	21	≈ 170	1-5
15	Male	23	≈ 190	1-5
16	Male	22	≈ 170	1-5
17	Male	22	≈ 180	<1
18	Female	24	≈ 170	1-5
19	Female	22	≈ 170	1-5
20	Female	34	≈ 160	1-5
21	Female	23	≈ 160	1-5
22	Male	25	≈ 170	5-10
23	Male	32	≈ 170	5-10
24	Male	25	≈ 190	1-5
25	Male	33	≈ 180	5-10
26	Male	33	≈ 180	1-5
27	Male	21	≈ 170	<1

Table 4.1: Factory test participants

4.1.1.1 Tests at Volvo Cars

The tests performed at Volvo Cars were conducted in the Skövde engine plant where Volvo Cars produces car engines for their different car models. The stations tested were the end of line modules one and two where the car engines functionality is tested. 9 individuals were tested at the Skövde engine plant.

The tasks included at these stations were to attach the engine to the testbed and observe the engine during testing to look for leaks and other abnormalities, see figure 4.1. The tasks were performed both above the shoulders and below the shoulders.

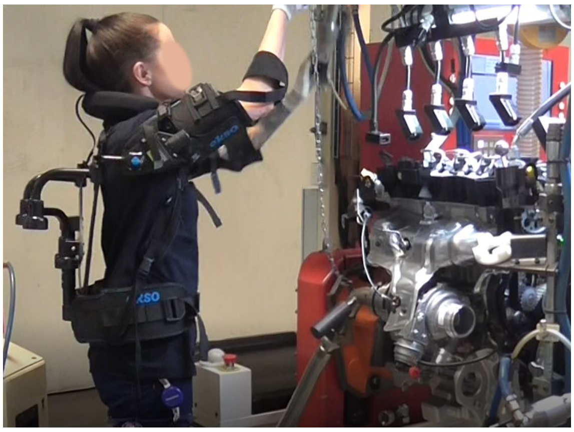

Figure 4.1: Tests performed at Skövde engine plant

4.1.1.2 Tests at Volvo Trucks

Testing at Volvo Trucks were performed at the Tuve truck factory and the tests were performed at two different departments at two different occasions. Both departments were focused on cab assembly. 18 individuals were tested at the Volvo Trucks Tuve plant.

The first tested department focused on assembly of external cab parts, including stations Dampeners, Fix 1, Fix 2, Park-heater and Muffler. The majority of the tasks on the stations were performed above the shoulders or at shoulder height.

At Fix 1 station, the main part that was assembled were heat protection pads underneath the cab and this was mainly performed seated, see figure 4.2. At Fix 2 the steps into the cab were assembled and this was done both standing and sitting. At the Park-heater station the park heater was added to the cab and this was mostly performed in a seated position.

At the Dampeners station, dampeners were attached to the cab and at the Muffler station the muffler was sub-assembled. Both of these stations and their tasks were performed standing up.

Figure 4.2: Tests performed at Tuve department 1

The second department tested focused more on internal cab assembly, including station 6 and station 8. The assembly tasks were performed inside the cab of a truck where different parts were attached inside. At Station 6 the main parts that were assembled were the interior panels for the roof and walls, see figure 4.3, and at Station 8 the main parts that were assembled was the internal cab cabinet and the towing loop for the truck. A majority of the tasks were performed above the shoulders or at shoulder height.

Figure 4.3: Tests performed at Tuve department 2

4.1.2 Subjective feedback on the exoskeletons

The results from the questionnaire answers and supporting comments from the semi-structured interview are shown below. The questions were asked by the interviewer to the participant and noted down by the interviewer.

The participants had the option to abort the testing if the equipment were hindering their performance to an extent that was altering their possibility to perform their work tasks to the companies satisfaction or if it was too discomforting.

Figure 4.4 shows how many of the participants that had to abort the testing prior to the intended test period being over and also includes participants that passed the bar of 30 minutes of testing to be eligible to partake in the interview and only one individual from all the tests did not pass 30 minutes of testing.

All of the aborted tests were due to discomfort in the shoulders and in the arms.

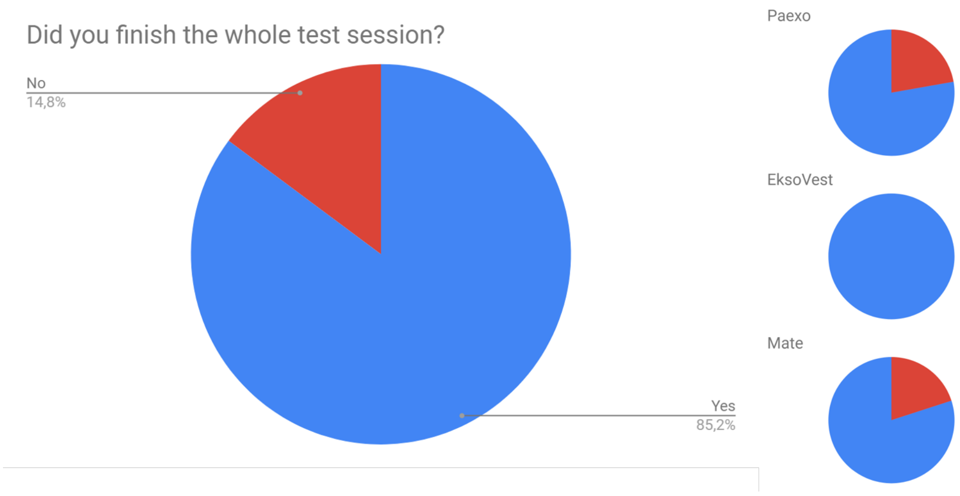

Figure 4.4: Overview of test completion

4.1.2.1 Performance

The participants were asked about how their normal assembly operation was affected while wearing the exoskeleton. As seen in figure 4.5 the workers did not feel like their normal operation was heavily affected by wearing the exoskeleton. None of the participants felt that the exoskeleton was hindering them from performing the task at all and just above 20 percent of the participants thought that they could perform the task, but their usual way of performing the task was affected.

All of the different exoskeleton contributed quite equal to this result but the Mate exoskeleton affects the normal operation more than the Paexo exoskeleton according to the participants.

Multiple comments were made about that it felt unusual to work while performing the tasks, unnatural movements were made and the participants felt constrained.

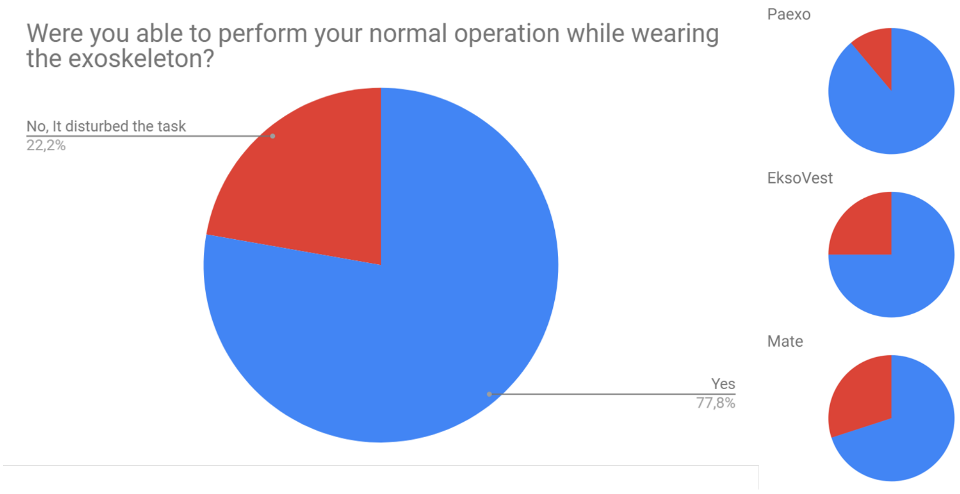

Figure 4.5: Performing normal operation

When asked if their performance of executing the normal tasks was affected while using the exoskeleton just above half of the participants felt that the exoskeleton did not affect their performance as seen in figure 4.6. Around 30 percent of the participants felt that their performance was lowered a little bit by the exoskeleton and a little under 20 percent perceived that their performance was considerably affected in a negative way.

Multiple participants stated that their performance were negatively affected while working on a lower height, but positively affected while working on a higher level. None of the participants commented about that their precision was negatively affected.

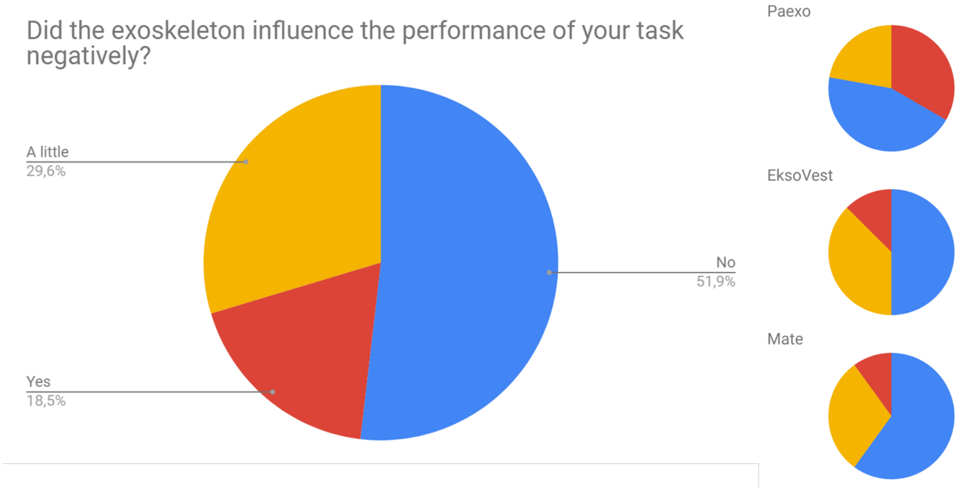

Figure 4.6: Influencing performance negatively

The participants were asked about if they could perform their normal tasks seated while wearing the exoskeleton. Around a third of the participants did not perform any seated tasks. Only a slim portion of the participants could not perform any tasks seated and the rest of the participants were divided between not being affected by the equipment and that it did hinder their movability in some sense, see figure 4.7.

The different exoskeletons are contributing quite equally to this result. The EksoVest had fewer testers performing a seated task and at the same time had the only instance of where the participant could not perform the task seated.

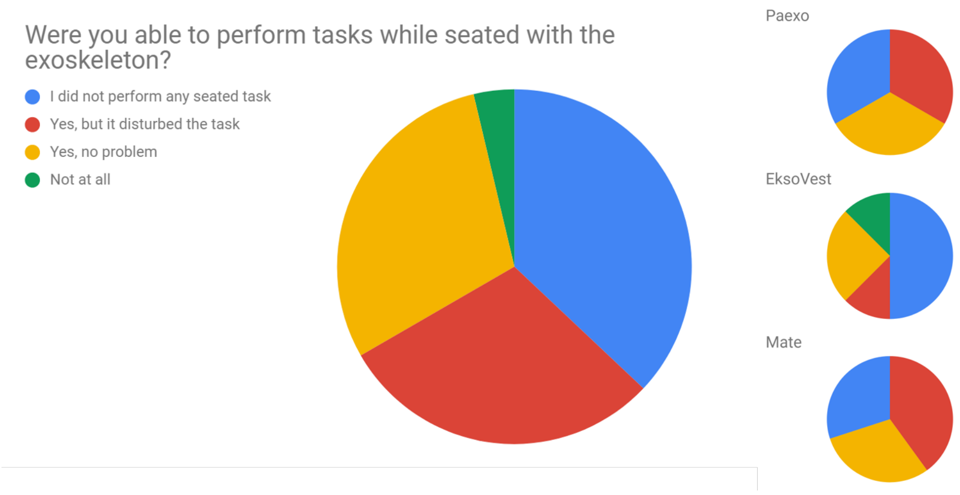

Figure 4.7: Performing seated tasks

4.1.2.2 Movement

The participants were asked if they felt that the exoskeleton restricted their movability and the results were a bit divided on this question. A little under half of the participants felt that the exoskeleton did not restrict their movement as seen in figure 4.8. The other half of the participants were divided between that the exoskeleton did affect their movement substantially or just a little bit.

Between the different exoskeletons it can be seen in figure 4.8 that the participants that used the EksoVest tended to feel less restricted while working compared to the Paexo and Mate exoskeletons.

Multiple comments were made about that the Mate users had an unnatural resting position with arms resting higher up than normal. A recurring theme mentioned was that the participants felt restricted while performing tasks lower, below the shoulders, and hard to bring down the arms.

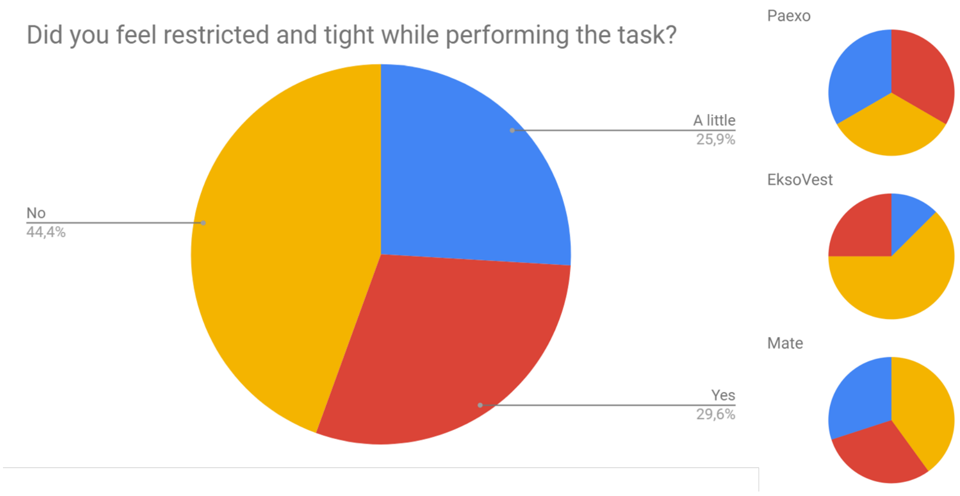

Figure 4.8: Restricting movement

When asked about how heavy the exoskeleton felt to carry while performing the tasks, above half of the participants felt that they had no problem working with the extra weight. Three out of ten workers even thought that the exoskeleton was very light to carry as seen in figure 4.9. Only around 15 percent of the participants felt that the weight of the exoskeleton was affecting their task.

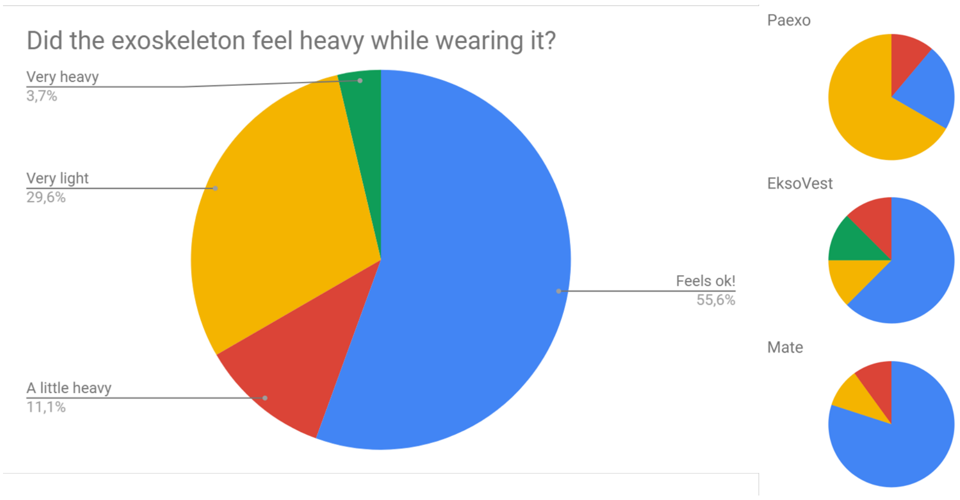

Figure 4.9: Exoskeleton weight

Test participants were asked about issues with their working clothes used beneath the exoskeletons and more than half of the participants had issues with their clothes as seen in figure 4.10.

None of the exoskeleton types are excluded from this problem according the respondents and the most common responses gotten was that the t-shirt rode up on the arms and in the lower back. None of the participants stated that the clothes underneath the exoskeleton got stuck in the equipment, nor did any of the participants' hair got stuck in the equipment.

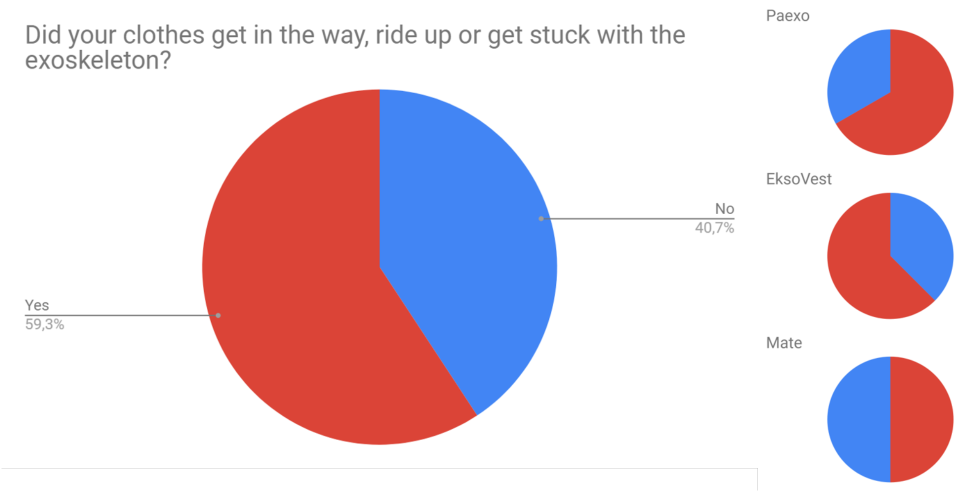

Figure 4.10: Clothes beneath exoskeleton

The interviewer asked the test participants if the exoskeleton was in the way while performing the assembly tasks or while moving around in the assembly area and a majority of the participant did not feel like the exoskeleton came in the way as seen in figure 4.11.

The EksoVest had a higher response rate of being in the way while performing the tasks, followed by the Mate exoskeleton. The Paexo exoskeleton had the lowest rate of complaints regarding being in the way during assembly or moving around in the assembly area.

Many of the participants commented that they bumped into things at the station quite frequently and that they had to think about how they moved as the exoskeleton made them wider.

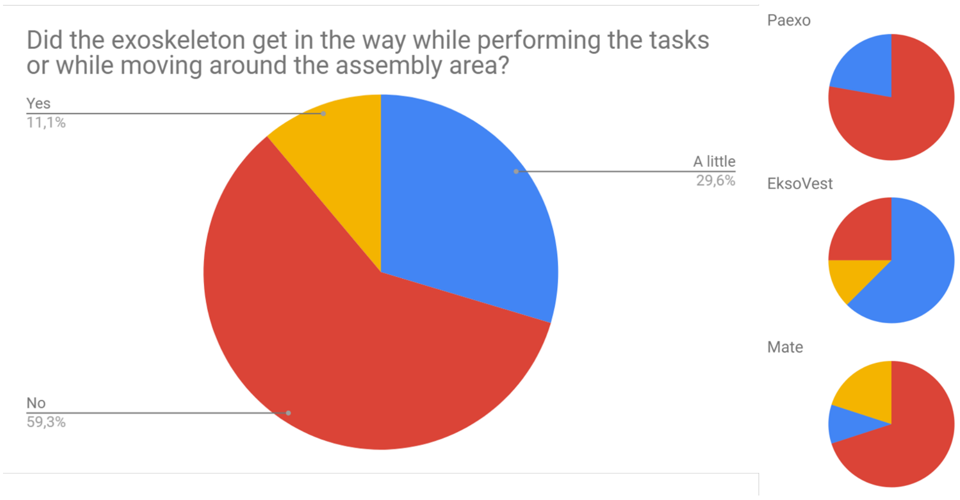

Figure 4.11: Obstructing exoskeletons

The participants were asked about how their ability to bend and reach tools were affected by wearing the exoskeletons. A majority of the participants felt that the equipment did not affect their movability in that sense as seen in figure 4.12.

The different exoskeletons contributed equally to this result.

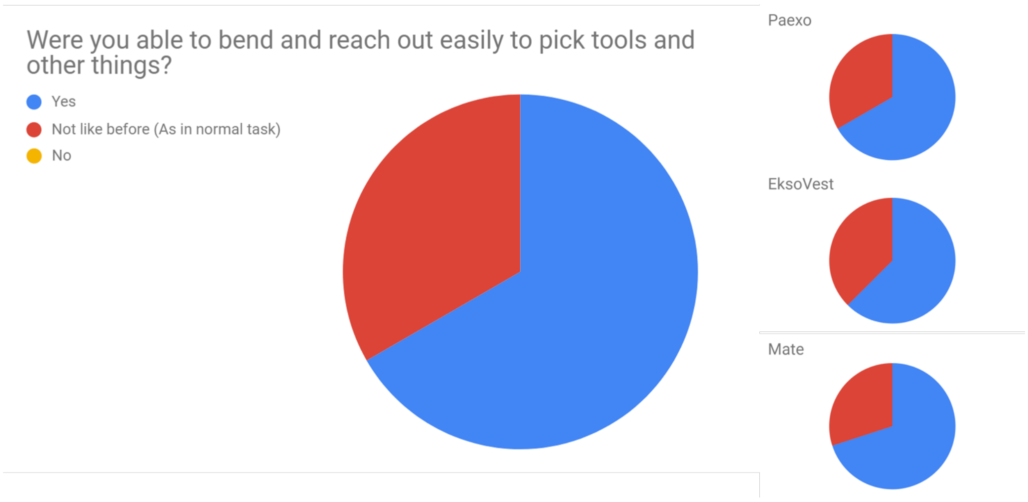

Figure 4.12: Bending and reaching

4.1.2.3 Comfort

The test participants were asked about if they felt any discomforting sensations in the shoulders during testing and above 80 percent of the participator did not feel any discomfort in the shoulders. Below ten percent of the participants felt any substantial discomfort during the testing, see figure 4.13.

The EksoVest did not receive any responses regarding shoulder discomfort and the other two exoskeletons had only a few complaints regarding shoulder discomfort.

Multiple participants stated that it was not uncomfortable in the shoulder area but that the exoskeleton provided an unusual sensation while working, not necessarily a negative effect. Many of the participants stated that the lifting aid provided by the exoskeleton did have positive effects on the comfort in the shoulder region.

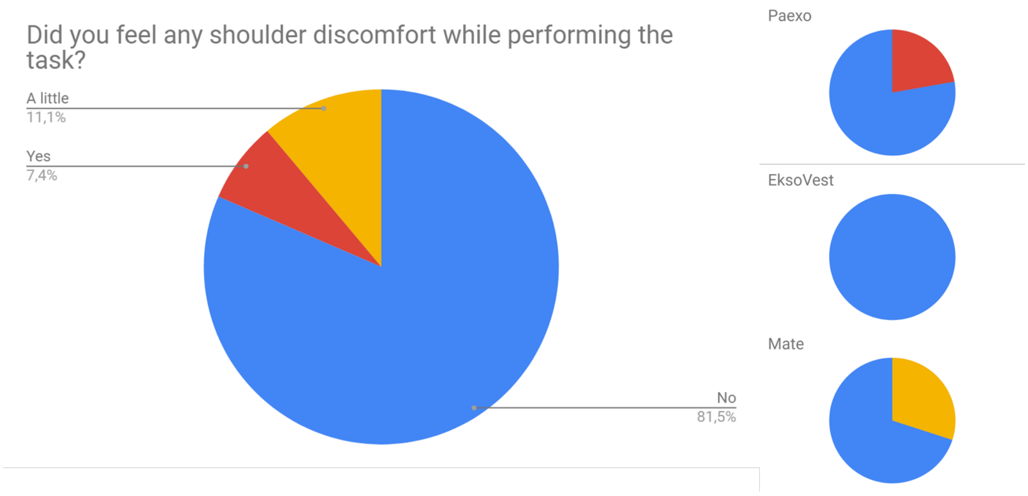

Figure 4.13: Shoulder discomfort

The interviewer asked the participants if they experienced any arm discomfort during the test period and around 60 percent of the participants did not experience any arm discomfort during testing as seen in figure 4.14. About a quarter of the participants experienced some tendencies of discomfort in the arms and around 15 percent of the participants experienced a significant discomfort in the arms.

It can be seen in figure 4.14 that the largest contributor to the discomfort in the arm region was the Paexo exoskeleton with above 75 percent responses complaining about some discomfort in the arms. The Mate had only a few complaints regarding discomfort in the arms and the EksoVest had the least complaints.

Many participants commented about that it was uncomfortable to have straps around the arms while working and that the sliding of the arm straps was uncomfortable.

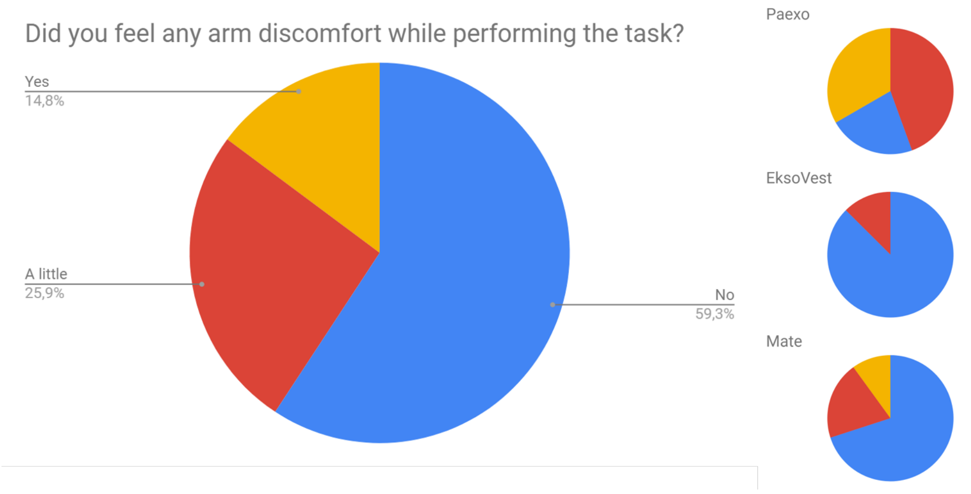

Figure 4.14: Arm discomfort

The workers were asked if they felt any discomfort in the back while performing their assembly tasks dressed in an exoskeleton. Above 90 percent of the respondents did not experience any discomfort in the back while performing the test, see figure 4.15.

The Paexo and Mate exoskeleton had no responses pointing towards any back discomfort during testing and the EksoVest did get a few complaints about discomfort in the back during testing.

Some participants stated that the exoskeleton contributed to a better posture and that this was comforting and relaxing.

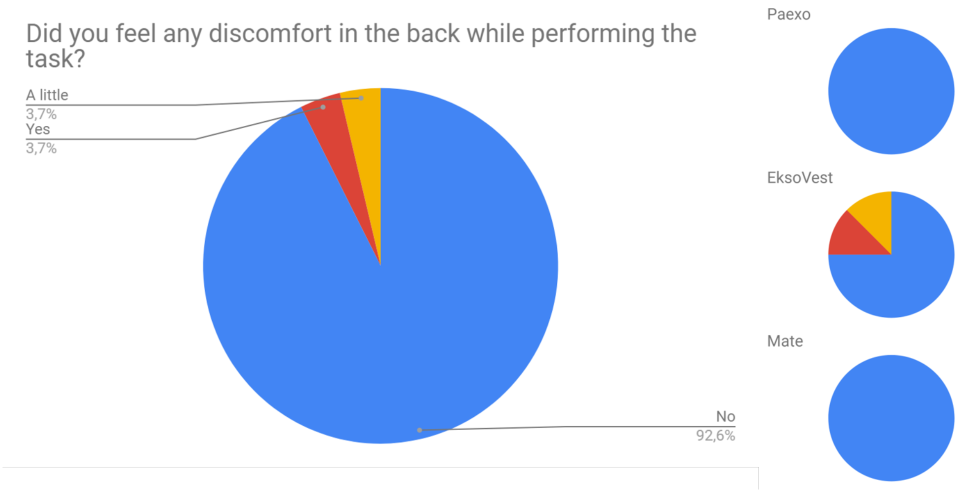

Figure 4.15: Back discomfort

The participants got asked the question regarding if the experienced any neck discomfort, caused by the exoskeleton during testing. Above 95 percent of the collected responses did not elevate any concern with neck discomfort due to the exoskeletons, see figure 4.16.

The EksoVest and Mate exoskeletons did not get any responses indicating neck discomfort and the Paexo exoskeleton only got minor complaints.

Participants who got to test the EksoVest stated that the provided neck pillow was very comfortable while working above the shoulders.

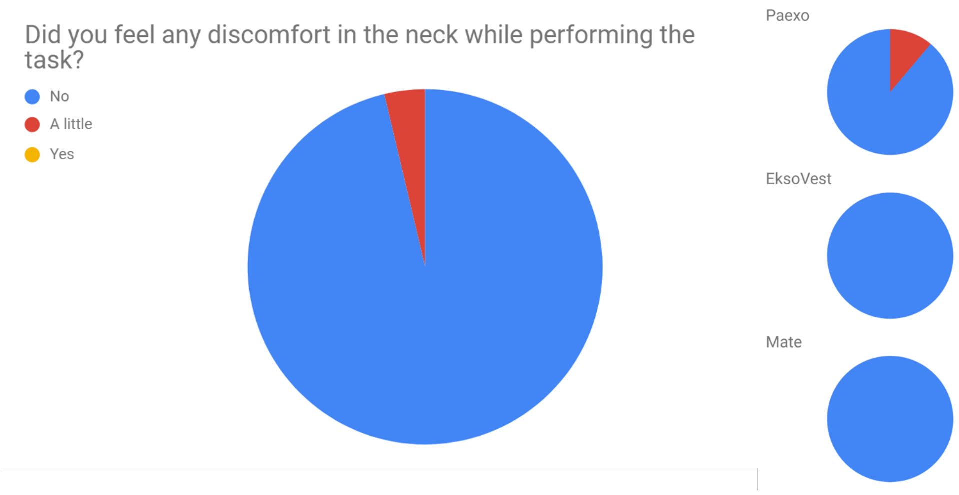

Figure 4.16: Neck discomfort

The interviewer asked the participants a question regarding how they experienced the aiding pressure put on the arms from the exoskeletons and if this pressure was comfortable or not. A majority of the participants perceived the aiding pressure as comfortable as seen in figure 4.17. Approximately a quarter of the respondents felt that the pressure was a little discomforting and only a slim portion of the respondents experienced the pressure as substantially discomforting.

The EksoVest received the lowest rate of complaints about discomforting pressure as seen in figure 4.17 and the Paexo and Mate exoskeletons had a similar response rate with a little below half of the respondents that felt some discomfort from the aiding pressure on the arms.

Multiple participants commented about that it was discomforting to work against the aiding pressure while working below the shoulders. Comments were also made about that the aid was comfortable while working but uncomfortable during rest.

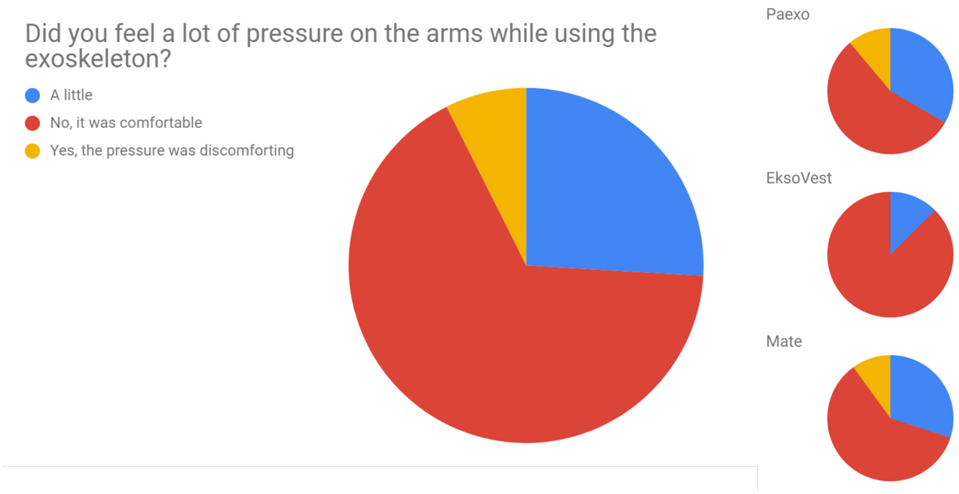

Figure 4.17: Arm support pressure

The participants were asked regarding how they experienced the usage of the exoskeletons amongst their colleagues from a social perspective and if they experienced any awkward sensations socially while wearing the equipment. The collected responses state that around 90 percent of the participant did not experience any social discomforting sensations as seen in figure 4.18.

The different exoskeletons contributed quite equally to the result.

The participants were also asked how they would respond to a colleague using the equipment in their surrounding and a majority of the participants responded that they would not mind it at all or that they would be curious about the technology used.

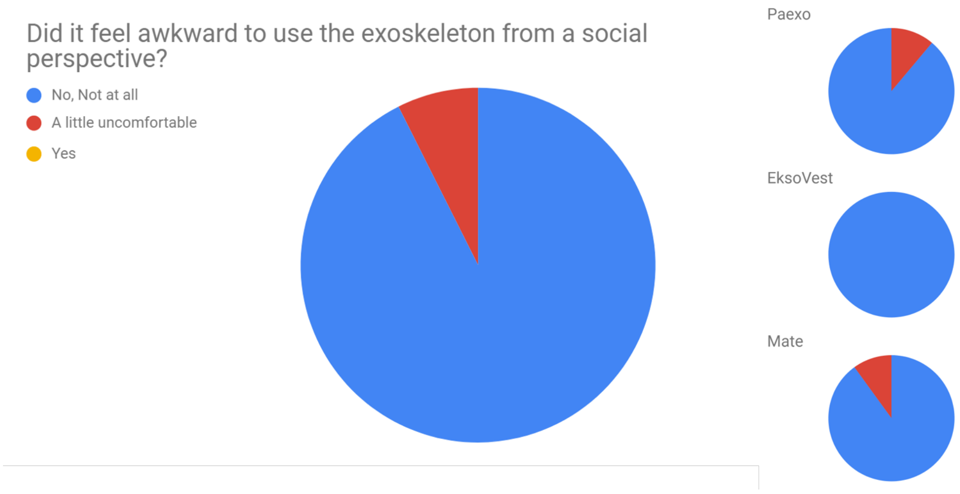

Figure 4.18: Exoskeleton in the social environment

The interviewer asked the participants if they experienced any numbness or tingling in the extremities during testing. Above 75 percent of the participants did not experience any vascular issues during testing caused by the exoskeleton as seen in figure 4.19. The remaining test participants were divided between discomforting numbness and mild numbing in the extremities.

The different exoskeletons did contribute quite equally to this result and the EksoVest was the only exoskeleton that did not cause any substantial numbness during testing.

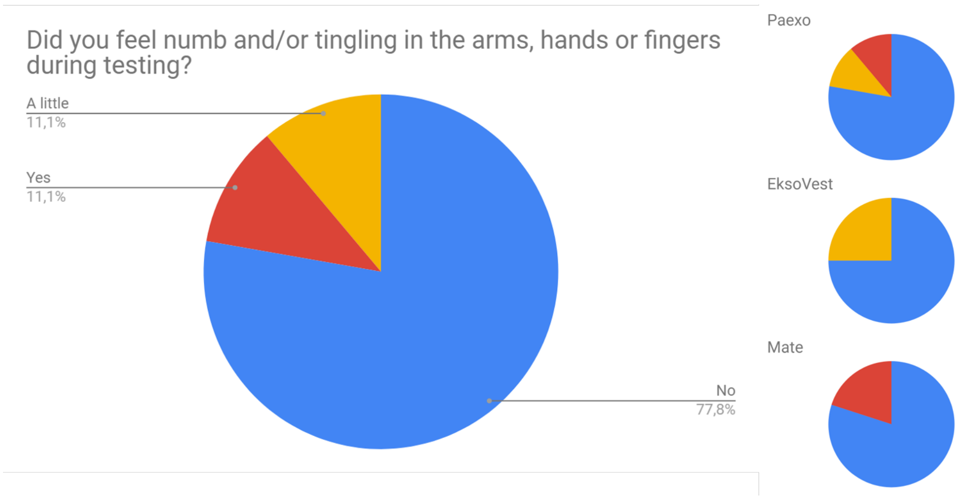

Figure 4.19: Numbness and tingling in extremities

The participants were asked about how they experienced that the arm cuff and arm straps functioned while working. The interviewer asked if they experienced any sliding of the arm support while performing their tasks and above half of the participants did not experience any problem with sliding arm support as seen in figure 4.20. About a quarter of the participants experienced that the arm cuff was slipping and sliding of their arms quite frequently and the rest of the participants had issues with a sliding arm support just a few times during the test period.

Looking at the different types of exoskeleton it seems to be the Paexo exoskeleton that contributes heavily to the problem of sliding arm support with above 75 percent of the participants experiencing this problem, as seen in figure 4.20. The exoskeleton that seems to have the least problem with this slippage is the Mate exoskeleton followed by the EksoVest.

Multiple comments from the participants pointed towards that the sliding of the arm support were one of the major reason for discomfort in the arms.

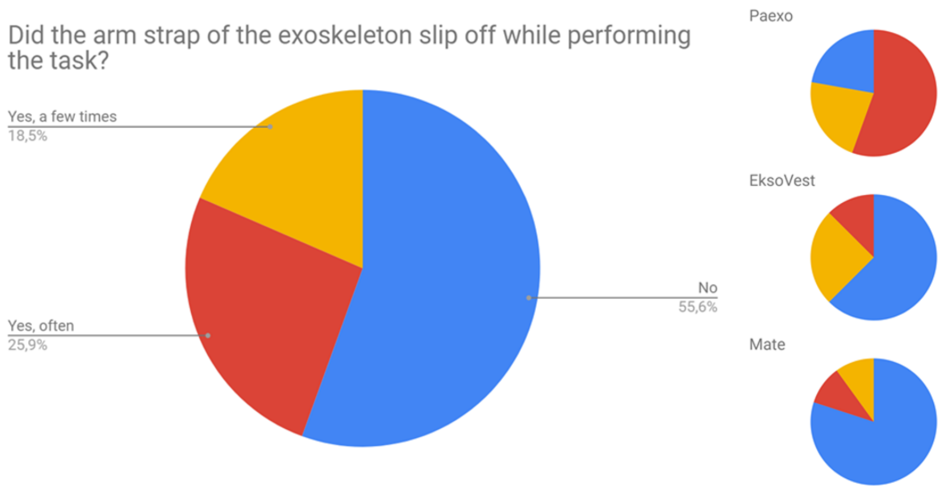

Figure 4.20: Arm support sliding

4.1.2.4 General thoughts on the technology

When asked about how the participant would appreciate using the equipment for a longer time period than the test period performed, around four out of ten persons did not want to use the equipment longer than the performed test period which is seen in figure 4.21. A little under half of the participants had no problems with the idea of using the exoskeleton longer than the test period and around 15 percent of the workers were positive towards using the equipment for a longer time period, but were not convinced that they would agree to wear it every day.

The participants were asked what they would like to change with the equipment to make it more approachable. Multiple comments were made about how the participants wanted the equipment to be more flexible in movement, that the equipment should fit closer to the body and that they would prefer to use it at a station where a high majority of the assembly tasks are performed above the shoulders.

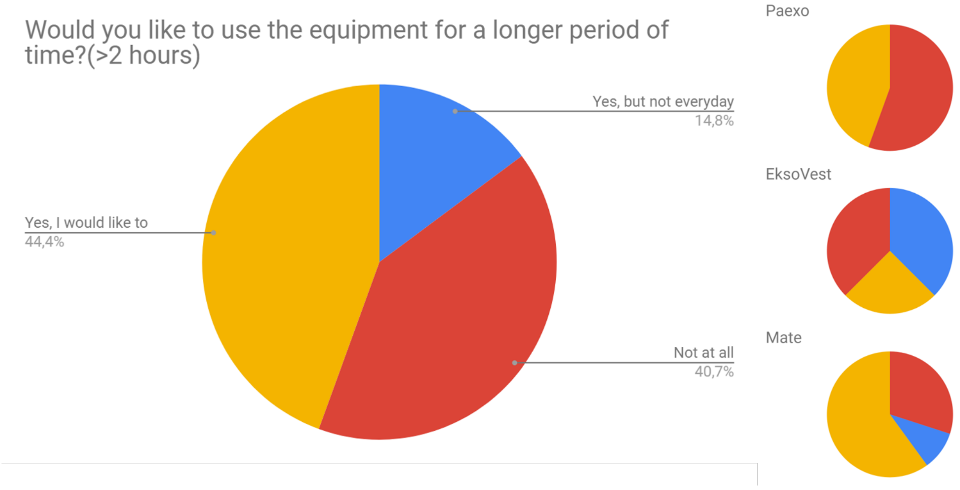

Figure 4.21: Using exoskeleton for a longer time period

The interviewer asked the question if the test participants would prefer to use the exoskeleton to perform the tested assembly sequence. It is worth noting that the answers were solely based on the participants' experience from the test which had a duration between one to two hours long. The responses can be seen in figure 4.22 and around half of the test persons did not prefer to use the equipment in the tested assembly task. Around 40 percent of the participants did prefer to use the exoskeleton to perform the tasks and ten percent were neither convinced nor dissatisfied with the technology.

Multiple comments were made regarding the positive effect that the equipment had on shoulders and back while working above shoulders, but many commented that these positive effects did not outweigh the negative effects hindered movability and resistance while working at a lower height.

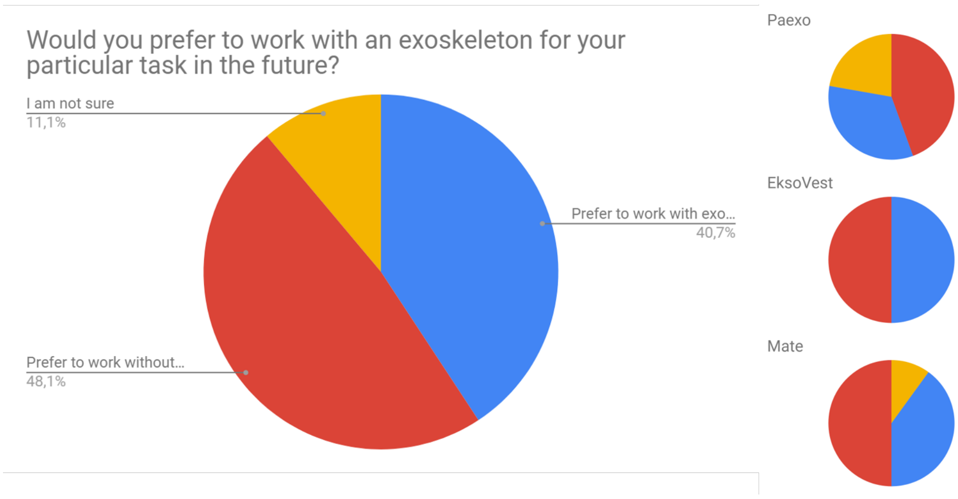

Figure 4.22: Prefer to use the exoskeleton

The participants were asked how likely it would be for them to participate in future tests regarding exoskeleton. The majority of the workers were positive towards the thought of testing the equipment further in the future as seen in figure 4.23.

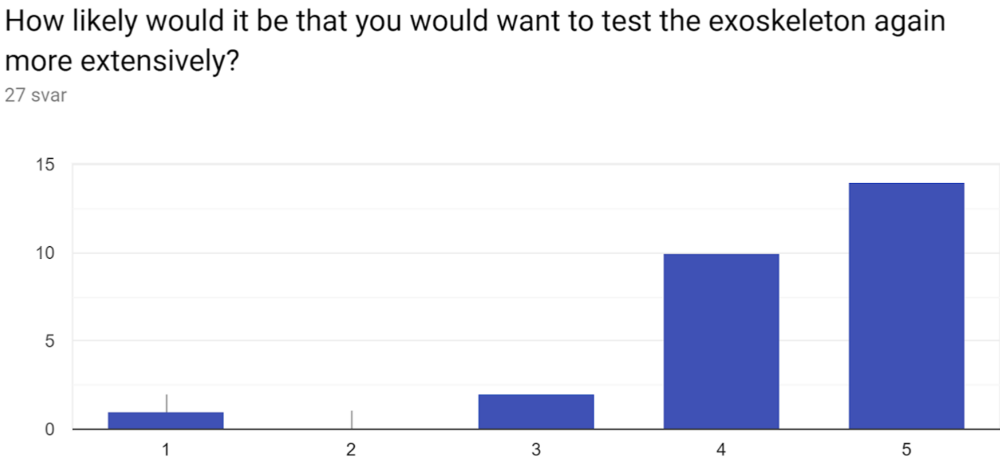

Figure 4.23: Additional testing of exoskeletons

The participants were asked to rate the complete experience of using the exoskeleton during the test in production at a scale from one to five. The responses were mainly positive and the rate 4 got the most responses out of the five options, see figure 4.24.

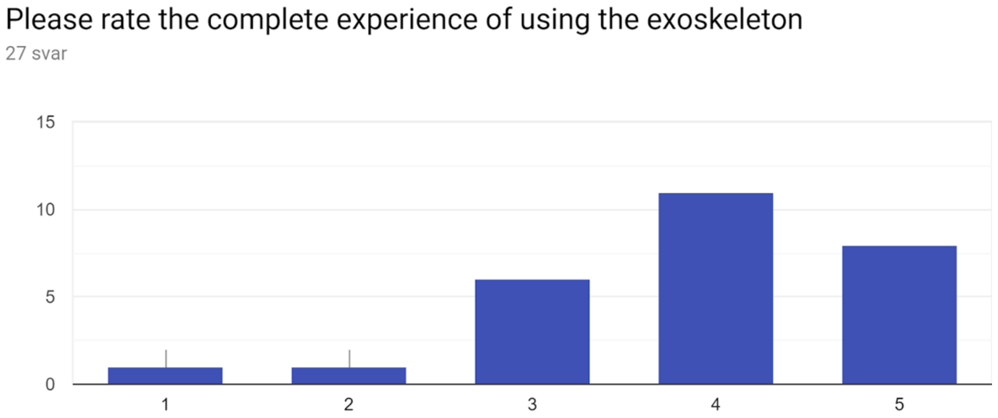

Figure 4.24: Experience of testing the exoskeleton

4.1.3 Observation

This section describes the observational result from the factory testing. It is divided into three subsections which consists of observation of all three assembly departments. The observation was performed using a video camera. In the following section, the task performed by each participant with and without exoskeleton is mentioned along with the comments related to the observation. The participants were compared during the test while working with the exoskeleton and while not wearing the exoskeleton at the beginning and end of the test periods.

4.1.3.1 Volvo Trucks Tuve - Department 1

In this assembly department, 5 stations were tested which were Dampeners, Fix 1, Fix 2, Park-heater and Muffler. A total of 10 participants (age 50+-10, mass 80+-20 kg, height 170+-20 cm, all male) volunteered for this study and all were right handed. These individuals were assessed during the assembly cycle of their work that was repeated during each work shift. Observation was performed for approximately 14 minutes per job task which involved 2 cycles of recording without the exoskeleton and 2 cycles of recording with the exoskeleton. Each cycle was approximately 5-6 minutes.

Observation of participants at Dampeners station
2 participants wearing Eksovest and Mate were tested at this station. The participants worked comfortably when the tasks were above shoulder. No damage to the cab doors were made while working with the exoskeleton.

With the EksoVest, the operator was working as usual, no discomfort shown. The operator seemed limited while rotating the body but heavy objects looked to be easy to lift while performing the task. Around 15 extra seconds was taken to perform the task with the vest.

A change in the body posture was observed when wearing the Mate exoskeleton resulting in positioning of the arms higher than normal while walking and discomfort could be seen in the upper arm where the arm strap was positioned. A better performance was measured with the vest, 20 seconds less were taken to perform the task.

Observation of participants at Fix 2 station
3 participants wearing Eksovest and Paexo were tested at this station. The task performed with and without the exoskeleton took the same amount of time at around 130 seconds. Both the operators showed no discomfort nor any damage to the external parts of the cab. A slight discomfort could be seen while reaching out for the tools.

One of the participant had to abort the test with the Eksovest due to that the vest slammed into the door of the truck too much while working and no subjective feedback was collected from this participants.

Observation of participants at Fix 1 station
2 participants wearing Paexo and Eksovest were tested at this station. The time taken to perform the task with and without exoskeleton was the same, at 120 seconds. The Fix 1 station was one of the stations that included more lower height performed tasks compared to the other stations at department 1 and it could be observed that the station did not suit the use of the exoskeleton due to this. The participant had to work against the exoskeleton a lot while performing these lower height tasks.

The arms cuffs of the Paexo were a distraction to the operator, as it was repeatedly readjusted each cycle of tasks. The Eksovest bumped into the tools several times while performing the tasks. The operator did adjust the worn t-shirt repeatedly, 2-3 times each cycle.

Observation of participants at Park-heater station
1 participant wearing Mate was tested at this station. The time taken to perform the task with and without exoskeleton was the same, at 60 seconds. There was a change in the body posture while seated resulting in the arms held higher than normal.

4.1.3.2 Volvo Trucks Tuve - Department 2

In this assembly plant, two stations were tested which were station 6 and station 8. A total of 10 participants (7 male and 3 female, age 25 +- 5, mass 70+-20 kg, height 170 +-30 cm) volunteered for this study and all were right handed. These individuals worked in the station 6 and station 8 and they were assessed during the assembly cycle of their work that was repeated during each work shift. Observation was performed for approximately 12 minutes per job task which involved 2 cycles of recording without the exoskeleton and 2 cycles recording with the exoskeleton. Each cycle was approximately 4-5 minutes.

Observation of participants at station 6
5 participants, 3 male and 2 female were tested on station 6 where 1 Eksovest, 1 Mate and 3 Paexo were tested by the participants. Few tasks at the station were performed below the shoulder. The average time taken to perform this task was 3 minutes 30 seconds and during the 2 cycles that was observed, participants took at least 30 seconds extra with the exoskeleton.

There was discomfort seen in the movement while turning the cab when wearing EksoVest as it involved bending down and reaching for a tool. Both the female participants experienced discomfort while bending down.

The operator was distracted with velcro straps of Paexo as it was not sticking together properly and the arm cuffs were sliding down as well.

Arms were held high up in the resting position by the operator who was wearing Mate and the waist belt was becoming loose. Also, the torque generator box shifted several times upwards and the vest bumped into the truck several times.

Observation of participants at station 8
5 participants, 4 male and 1 female were tested on station 8 where 3 Eksovest and 2 Mate were tested by the participants.

The Eksovest was bumping into the cab above the windshield several times and no discomfort was seen. Participant was extra careful while working with the exoskeleton. Discomfort for the female operator in the back as it was very heavy to wear. Difficulty while turning the cab as the vest came in the way while bending and reaching out. The operator adjusts the worn t-shirt a few times, once in 2 cycles. Almost the same time was taken to perform the task with and without Eksovest.

While wearing Mate, one of the participants adjusts the waist strap by himself, several times during each cycle and discomfort is seen around the waist. There was a change in the body posture resulting in the arms held higher than normal.

4.1.3.3 Volvo Cars - Skövde engine plant

In this assembly plant, 2 stations were tested which were module 1 and module 2. A total of 9 participants (age 28+-7, mass 60+-20 kg, height 170+-20 cm) volunteered for this study and all were right handed. These individuals were assessed during the assembly cycle of their work at each module that was repeated during each work shift. Observation was performed for approximately 15 minutes per module which involved 2 cycles of recording without the exoskeleton and 2 cycles with the exoskeleton. Each cycle was approximately 10-12 minutes. At both module 1 and module 2, similar job tasks were performed with 9 participants (6 male and 3 female).

2 participants who were wearing Paexo were distracted by the Velcro straps and the arm strap had to be tightened a few times during the cycle. The time taken to complete the task with and without the exoskeleton was the same.

2 participants who were wearing Mate held a different body posture and their hands were held high up while working. One of the participant started sweating after wearing the vest for 30 minutes and the hip belt was sliding down as well.

Eksovest was worn by 2 participants where one of them was a female. The performance of the female participant slowed down after wearing the vest. The participant was lifting up the vest and showed a little discomfort while bending and working. There were some adjustments of the worn t-shirt while performing the task.

4.2 Lab testing

This section describes the results from EMG lab testing for each individual as well as a summary of all individuals.

The total number of test subjects for the lab testing were 6 volunteers with different anthropometric measures (3 male and 3 female, ranging from 12th percentile to 95th percentile, age 25 +- 2, height 170 +-20 cm), see table 4.2. Prior to the start of lab testing, body length of the test subjects was noted down and those measures were converted to percentile based measures using a converter at `http://www.antropometri.se/calc.php`.

Sl.No	Sex	Measurement(Body length)	Measurement(percentile)	Age
1	Female	162 cm	22nd	24
2	Female	166 cm	12th	25
3	Female	172 cm	43rd	24
4	Male	166 cm	67th	24
5	Male	177 cm	76th	26
6	Male	185 cm	95th	27

Table 4.2: Lab test participants

In order to record EMG data and analyse, 2 tasks were performed which involved screwing and unscrewing of nuts on the over head work apparatus. In the following graphs, task 1 refers to screwing of nuts and task 2 refers to unscrewing of nuts. The horizontal coordinate represents the comparison for both task 1 and task 2 without exoskeleton and with Paexo, Mate and Eksovest. The vertical coordinate represents the percentage of maximum voluntary contraction (MVC).

4.2.1 Results of female test subjects

The figure 4.25 below shows the reduction of MVC in % for the muscle anterior deltoid for female with a height of 162 cm (22nd percentile) and dominant arm being right. MVC measured without exoskeleton for task 1 was 56.25% and for task 2 was 79.064%. Muscle activity was significantly reduced for this muscle when the test subject was wearing the exoskeletons. For both the tasks, MVC for Eksovest was the least when compared to other vests.

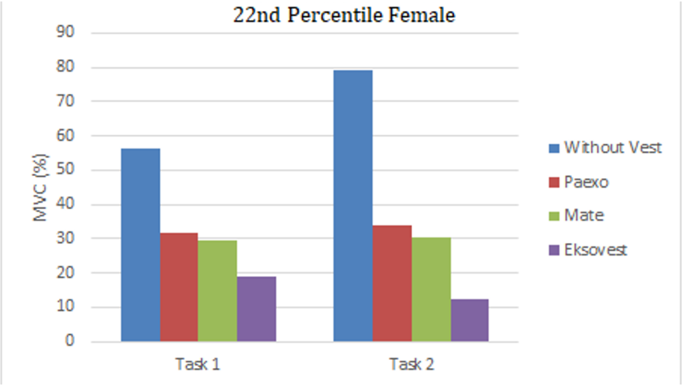

Figure 4.25: Anterior deltoid (22nd Percentile Female)

As seen in figure 4.26, MVC (%) for the muscle pectoralis major reduced to less than 30% without the exoskeleton and there has been significant decrease in the muscle activity with all the 3 exoskeletons.

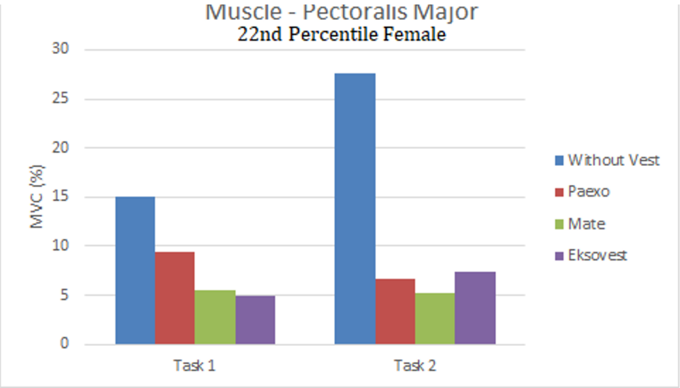

Figure 4.26: Pectoralis Major (22nd Percentile Female)

The figure 4.27 below shows the reduction of MVC in % for the muscle anterior deltoid for female with a height of 166 cm (43rd percentile) and dominant arm being right. The MVC measured without exoskeleton for task 1 was 76.485 % and for task 2 was 77.951 %. The MVC for all three exoskeletons is significantly lower with an average of 22.08 % for both task 1 and task 2. MVC for Eksovest was the least among other vests for this test subject too.

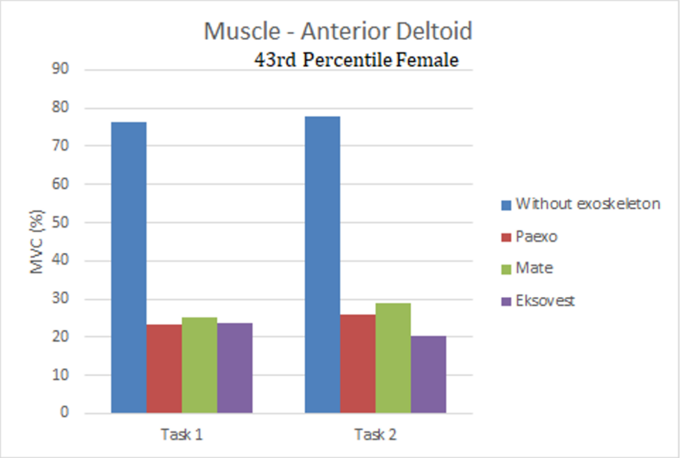

Figure 4.27: Anterior deltoid (43rd Percentile Female)

In figure 4.28, which depicts the muscle activity for pectoralis major, there has been a significant reduction of MVC in task 2 for Paexo. In task 1, MVC without exoskeleton was 11.07% and for both Paexo and Eksovest, it reduced only by 3% approximately.

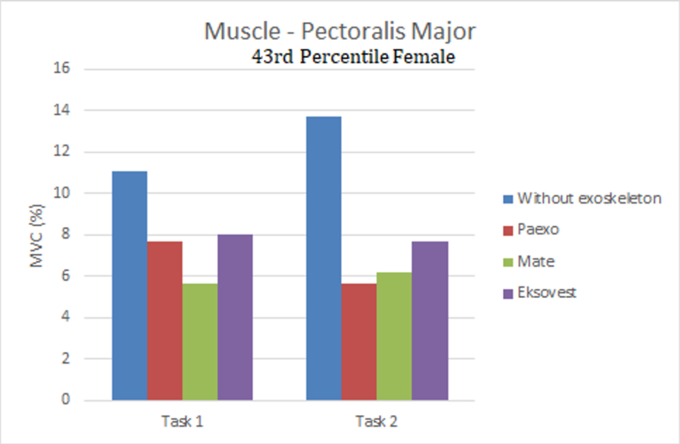

Figure 4.28: Pectoralis Major (43rd Percentile Female)

The figure 4.29 below shows the reduction of MVC in % for the muscle anterior deltoid for female with a height of 172 cm (76th percentile) and dominant arm being right. The MVC measured without exoskeleton for task 1 was 72.366 % and for task 2 was 89.588 %. For both the tasks, Paexo has indicated lesser muscle activity than the other 2 exoskeletons.

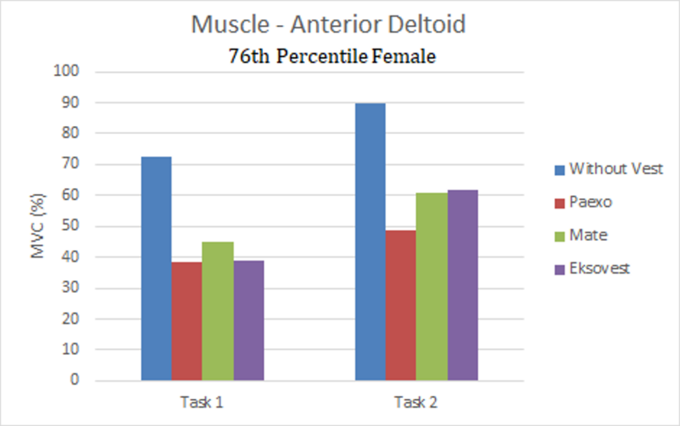

Figure 4.29: Anterior deltoid (76th Percentile Female)

In figure 4.30, the MVC measured without exoskeleton for task 1 was 49.557 % and for task 2 was 76.503 %. It can be seen that for task 2, the muscle activity for both the exoskeletons, Mate and Eksovest was almost equal to the muscle activity without the vest. There has been a reduction of 5% MVC approximately. The MVC for Paexo in both task 1 and task 2 is low (25.26% - average) compared to Mate and Eksovest.

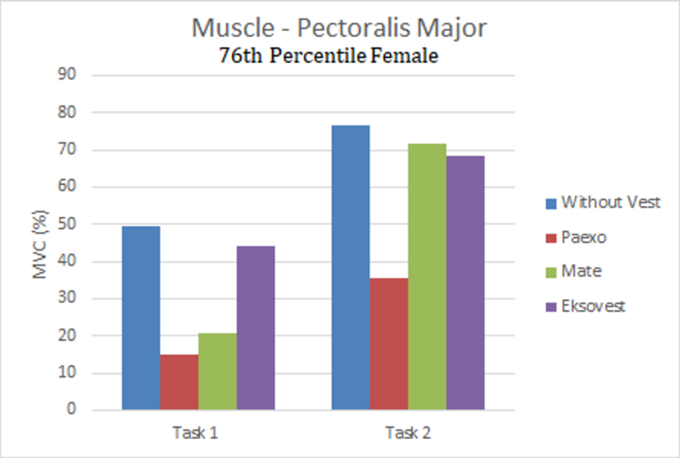

Figure 4.30: Pectoralis Major (76th Percentile Female)

4.2.2 Results of male test subjects

Figure 4.31 below shows the MVC in % for the muscle anterior deltoid for male with a height of 162 cm (12th percentile) and dominant arm being right. The MVC measured without exoskeleton for task 1 was 69.325 % and for task 2 was 80.815 %. For both the tasks, Mate has indicated more muscle activity than other 2 vests when compared to MVC without the exoskeleton.

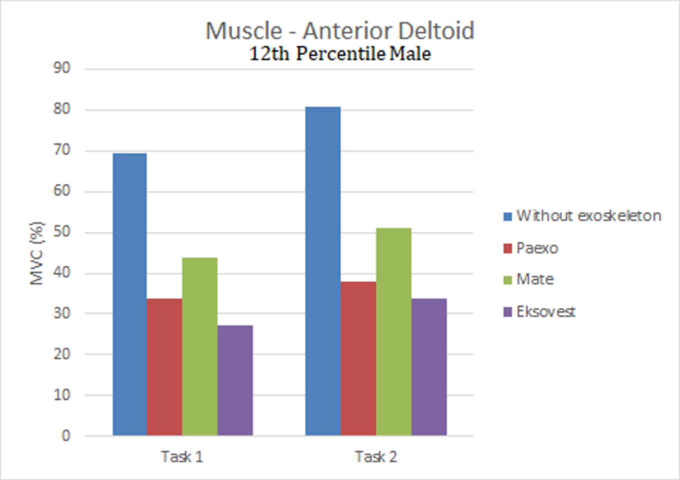

Figure 4.31: Anterior deltoid (12th Percentile Male)

As shown in figure 4.32, the difference between MVC(%) value without exoskeleton and with exoskeletons is huge when compared to other test subjects. In task 2, MVC without vest is 67.221% and with all vest on an average is 14.7%. There has been a reduction of 52.5%.

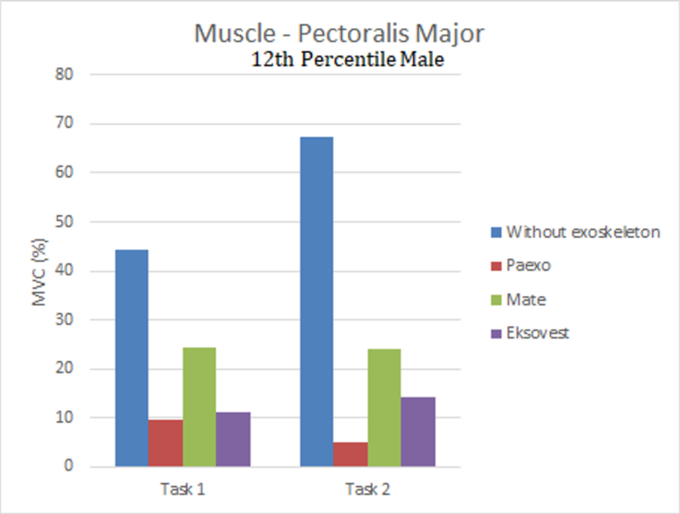

Figure 4.32: Pectoralis Major (12th Percentile Male)

Figure 4.33 below shows the MVC in % for the muscle anterior deltoid for male with a height of 177 cm (67th percentile) and dominant arm being right. The MVC measured without exoskeleton for task 1 was 40.5125 % and for task 2 was 68.0774 %. For both the tasks, Eksovest has indicated lesser muscle activity than the other 2 exoskeletons.

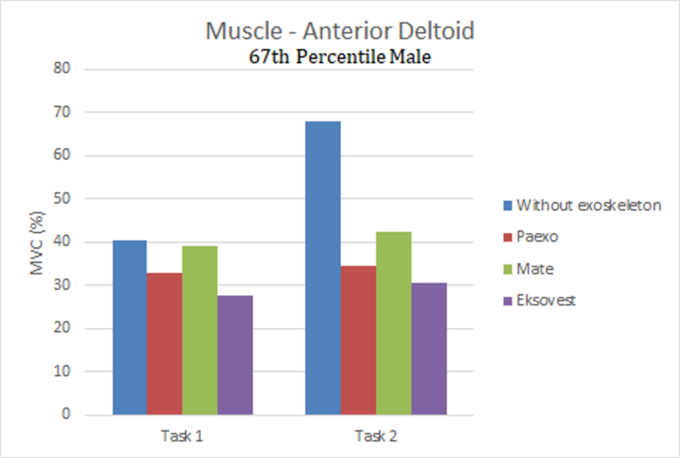

Figure 4.33: Anterior deltoid (67th Percentile Male)

Figure 4.34 shows the MVC values for the muscle pectoralis major, the difference between MVC(%) value without exoskeleton and with exoskeletons is huge here as well. In task 1, MVC without vest is 81.566% and with all vest on an average is 22.8565%. MVC has decreased by 58.7095%.

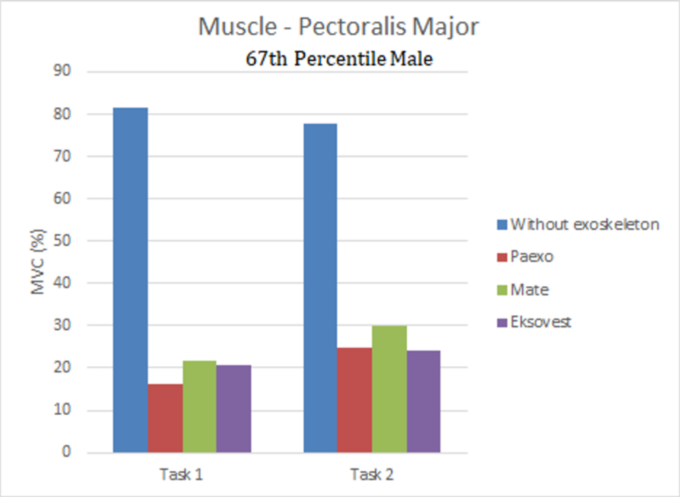

Figure 4.34: Pectoralis Major (67th Percentile Male)

Figure 4.35 below shows the MVC in % for the muscle anterior deltoid for male with a height of 185 cm (95th percentile) and dominant arm being left. The MVC measured without exoskeleton for task 1 was 60.5147 % and for task 2 was 48.4224 %. For both the tasks, Mate has indicated lesser muscle activity than the other 2 exoskeletons.

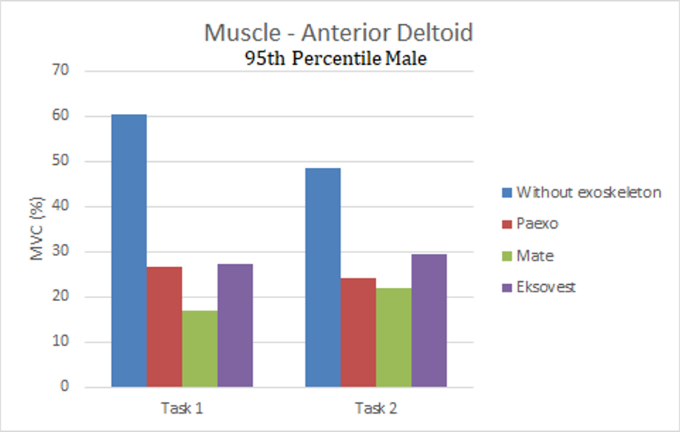

Figure 4.35: Anterior deltoid (95th Percentile Male)

Figure 4.36 shows the muscle activity for the pectoralis major and MVC is significantly less than what was for anterior deltoid. MVC for Paexo is 1% less than for MVC without any exoskeleton for task 1.

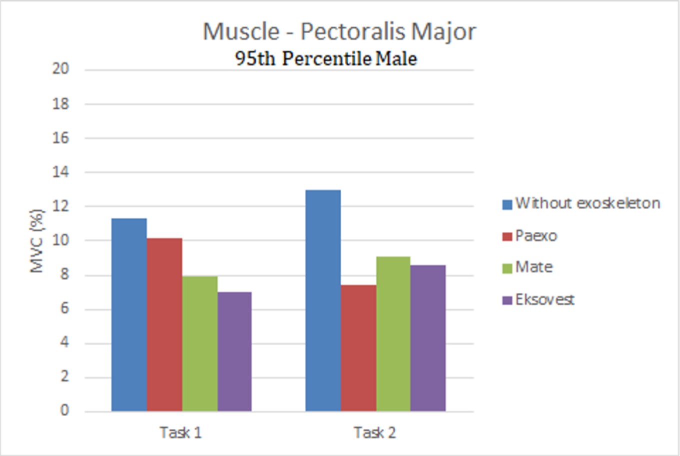

Figure 4.36: Pectoralis Major (95th Percentile Male)

4.2.3 Summary of EMG testing

This subsection describes the summary and comparison of both muscles for each test subject with and without each of the exoskeletons. The horizontal coordinate represents 6 test subjects for both male and female indicating the percentiles based on the body length by comparing values without the exoskeleton and with the exoskeletons. The vertical coordinate represents the percentage of MVC.

Figure 4.37 describes the MVC(%) for anterior deltoid of all 6 subjects without the exoskeleton and with Paexo, Mate and Eksovest. Out of the 6 test subjects, 4 subjects wearing Eksovest have indicated lesser muscle activity when compared with Mate and Paexo. Whereas, four test subjects wearing Mate have indicated more muscle activity when compared to Paexo and Eksovest for the same muscle. Paexo indicated different muscle activity for each test subject.

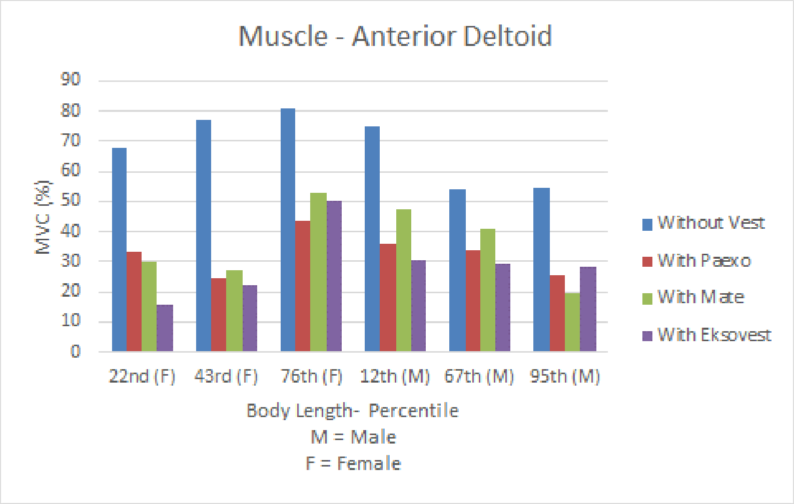

Figure 4.37: Anterior Deltoid (All 6 test subjects)

Figure 4.38 represents the MVC(%) with and without exoskeleton for pectoralis major. When compared to Mate and Eksovest, Paexo has indicated lesser MVC for this muscle out of the 6 test subjects.

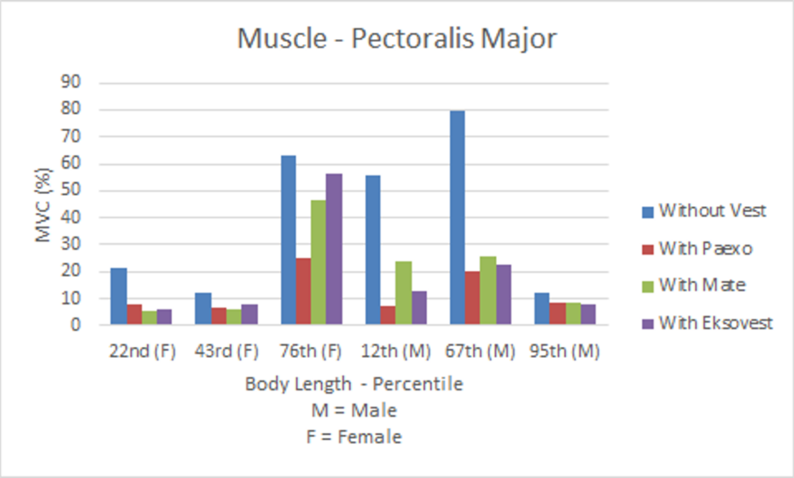

Figure 4.38: Pectoralis Major (All 6 test subjects)

5

Discussion

The exoskeleton technology is an interesting topic but the exploration of the applications of the technology in real life production is limited at the time. From this study no concrete verdict could be stated regarding if the technology can be successfully implemented in real life production.

5.1 Investigation of exoskeleton technology on final assembly work

Factory testing was a big part of this project and contributed with a lot of valuable feedback from the workers who actually perform the value adding work. The test locations at Volvo Cars and Volvo Trucks were chosen to provide input on the equipment from the automotive industry and final assembly tasks and the locations provided both of these elements. The specific stations at these departments were chosen due to their nature of involving a lot of tasks performed above the shoulders and this was interesting for the purpose of this project.

Testing in factory setting comes with a lot of challenges that can be hard to foresee. This is an everyday workplace for these individuals who participated in the testing and therefore a great respect to their working times and other needs needed to be respected during testing. Another thing that needs great respect is that this is an ongoing production and that output of vehicles can not be altered due to the testing. Both of these problems were tackled with planning of the tests and a solid communication between the test performers and the leading staff. The production output were not altered due to the tests and every participant's personal needs were respected to the full extent during the testing.

To properly evaluate the technology in a Swedish factory you would want to collect feedback from all of the workers actually working there and that would presumably be affected by a potential implementation of the technology. The project had to limit the participation size though due to resources and time constraints as it would be impossible to test every worker at a department. The participants were also volunteers and this was important that the participants wanted to participate in the test by free will. To properly evaluate the technology with these limiting factors there was instead a wish of testing different ages, sex and anthropometric values to cover feedback from the whole range of the workers at a Swedish factory. A goal of purposeful selection to accommodate for a range of variation was set up, but this was quickly acknowledged to be impossible to fulfill.

The workers at the testing sites were mainly male workers with quite similar anthropometric values. Convenience sampling had to be applied instead to be able to perform any tests. As of this not the whole range of variation could be tested in the factory tests but the actual workers that represents those stations performed the tests. There is a large percentage of male workers in the automotive assembly and these test represent the reality in this case.

While designing the questionnaire for semi structured interviews, several factors such as the availability of operators during the shift, duration of the shift and rotation of operators for a particular station in the shift were considered. Due to this, combination of both open and close ended questions were used. For instance, multiple choice questions were included in the study as the participants would not have to say anything in their own words and there would not be more time invested in answering the question. Moreover, operators were available for interview only for a specific time period. Having a questionnaire designed avoided any disturbance to the production line and saved time as well.

Along with the semi structured interviews, participants were video captured during factory testing as observation provides a broader picture of behavioural patterns. Moreover, the experience of each participant could be understood easily and better conclusions could be drawn on them. 2 cycles of the assembly task was captured with and without exoskeleton for each participant. This provided enough time to observe and video capture other planned participants during that particular shift. The observation on each participant was made from various positions in order to not have any disturbance to the pace of the production line nor to any operators.

The collected feedback from the testing is a valuable resource when evaluating the exoskeletons, but due to the subjective nature of this test drawing any solid conclusions from this has to be done very carefully. There are many factors that can alter the mind of the test participant and these can alter the way that they responded to the equipment.

Looking at the performance of assembly tasks during the testing, the participants had divided thoughts surrounding how their normal way of working was affected. There was not an unanimous perception that the equipment affected the way of working negatively, some of the participants felt that the equipment helped and some did not. In this kind of environment it is important that the tools used can be used by all of the workers performing the tasks and this can be hard if some of the participants did not feel that they could deliver good results while using the equipment.

This can be due to that exoskeleton simply hinders the operators movability and therefore negatively affects their way of working and tempo. It can also be due to the relatively short test period and that the participants did not get to use the equipment long enough to get used to it. It was seen in the observation that some of the stations did take longer time to perform using the exoskeleton and this will have to be considered by the company if the potential benefits of using the equipment outweighs the lowered performance.

Regarding movement while working with the exoskeleton there were no unanimous thoughts here either. A majority of the participants did not feel that their movement was affected by the exoskeleton but there were still some participants that felt that their movement was substantially affected and that the equipment got in the way while working. If the tool is supposed to be for everyone working at the department then this is a problem.

The comfort of the workers are of highest importance if this wearable equipment is supposed to be used daily. Most of the participants did not experience any discomfort while using the equipment in the back, neck and shoulders. A minority of the participants did experience discomfort in the arms due to that the exoskeleton were fastened around the arms and the Paexo model caused more discomfort than the others regarding this issue. Participants often mentioned that it felt unusual to wear the exoskeleton and one reason that the arm had the most discomfort could be due to the unusual sensation. Having something tied around the waist and over the shoulders could be a more familiar sensation while wearing a rucksack for example than having something tied around the arms.

The aid that the participants got from the vest were not discomforting according to the subjective responses and only minor vascular issues, like numbing extremities, were mentioned by the participants. In general the exoskeletons seems to be quite comfortable to wear and the cases where the participant did experience discomfort could be counteracted by adjusting the exoskeleton further to their body.

The exoskeletons were preset to the participants during the tests based on some of their anthropometric values. Minor adjustments were performed if the participant experienced any discomfort or if the exoskeleton did not fit perfect in the start of the test. If the test period were to be longer, even further minor adjustments could be made to fit the participant perfectly and therefore theoretically counter experienced discomfort.

Overall the participants were not convinced that the technology would aid them in their work tasks as around half of the participants did not prefer to work with the exoskeleton based on this test. At the same time most of the participants rated the technology and test in general quite high. This can be due to that they did not want to be rude towards the test owners, even though the participants were encouraged to speak freely about the technology and the test.

An often mentioned positive effect from the exoskeletons was the aid that the participants got while working above the shoulders and at the same time a common negative effect was the resistance that the equipment had while working at a lower height. All of the stations had some tasks performed at a lower height and this can be a contribution to that the technology was not preferred on the tested stations. A station where only above shoulder tasks are performed are not common in the automotive industry due to the ergonomic issues that comes with it. According to the subjective responses a station where only above shoulder height tasks were performed was preferred while using the equipment.

There are other ergonomic problems that occur while performing a lot of above shoulder height tasks that are not countered by decreasing the muscle activity of flexion focused muscles. Having the arms in an unnatural position for a longer time period can affect nerves and ligaments in the shoulders and tasks at a higher height requires some neck tilt to be able to see where the task is performed. These effects could not be tested during this project due to resource and time limits.

5.2 Biomechanical assessment of exoskeletons

Biomechanical testing was performed to collect objective data of the exoskeletons which provided the study with better comparisons of each exoskeleton and also with and without the exoskeletons. There were several reasons for performing the lab testing at a different setting instead of the actual production line. The time and resources needed to perform a biomechanical assessment for operators with the exoskeletons would be limited in a factory setting. Moreover, the preparation phase takes time and space as the EMG equipment provided by Chalmers was wired. Also there will be less flexibility to move around and perform normal assembly tasks with the equipment on. Considering these issues, the lab testing was performed by mimicking an under-up work station at Chalmers.

Before performing this EMG testing, understanding the movements and muscular system of upper limb was crucial. As the study was based on above shoulder work tasks, upper limb muscles were of interest here. Considering the movements, functions and origin of the muscles and other limitations of the study, two muscles were tested and measured (Anterior deltoid and clavicular portion of pectoralis major). There were several limitations for selecting and measuring only specific muscle of the upper limb.

First, the straps of exoskeletons would come in the way. When the testing is performed with the exoskeletons, the electrodes cannot be attached on all muscles as they might damage the electrode which will lead to unclear EMG signals. Pictures were taken while wearing the exoskeleton before performing the test in order to see where the disturbances are associated with the exoskeleton. Due to this, most of the muscles were opted out for the testing.

Secondly, when it comes to the muscle pectoralis major there are three parts which are clavicularis, sternocostalis and abdominalis. Except clavicularis, the other two parts are located on the chest and this could cause discomfort for the female volunteers. The clavicular portion is located on the upper region of the chest starting from the collar bone to the humerus (upper arm bone). The placement of electrodes for clavicularis is towards that region. Hence, clavicular part of pectoralis major was measured as there won't be any discomfort for female participants with regards to the body. Moreover, clavicular portion was focused more on flexion of the arm compared to other lower parts.

Third is a limitation of the EMG equipment at is a wired MP36 4 channel data acquisition unit. There is a need of getting contact with the muscle which is very hard if the muscles are small. Some muscles are not accessible to attach the electrodes and perform the shoulder up work tasks. While attaching the electrodes to these muscles, the wires might come in the way or get tangled which results in interrupted EMG signals. Also, there is a possibility of other muscles affecting the readings as well.

From the overall EMG results, the muscle activity lowered for both the muscles with all three exoskeletons. When it comes to comparing the exoskeletons with each other, a proper conclusion cannot be drawn as the muscles and vests have responded differently for different anthropometric measures.Moreover, the functionality of these vests are similar to each other. For stronger conclusions, more number of subjects should be tested for a longer duration.

5.3 Benefits and challenges of different exoskeleton technology

Advantages of the exoskeleton technology that could be seen from the testing was positive effects during work above shoulders. Participants felt that they got a support and could relax more during these tasks. The posture of the exoskeleton users was affected in a positive way by straightening the back and providing support for the upper body. Reduced muscle activity of flexion focused muscles could be seen from the performed EMG study and this could theoretically contribute to an extended work period before fatigue of these muscles.

Disadvantages of the exoskeleton technology that could be seen from the testing was that not all of the participants appreciated the technology in a real life production setting. The exoskeleton is an external wearable equipment and has tendencies to get in the way while working. The equipment is not suitable while working below the shoulders as it is restricting the movement of the operators. The exoskeleton did also contribute to lowering the performance of the operators as some tasks did take longer time than normal to perform. The equipment can not be used by everyone for medical reasons as having a pacemaker, having previous injuries in the shoulders and back.

The Paexo exoskeleton is light and fits close to the body which makes it easier to work with. It can be adjusted properly to the operator and is easy to put on by yourself. The Paexo also includes a carrying bag which makes transporting of the exoskeleton easy.

At the same time the Paexo had the most problems with attaching the arm support to the arms causing slippage and discomfort amongst the users. The Velcro straps that are attached around the arms also tended to wear out causing the arm straps to get loose.

The EksoVest was seen to be comfortable for the user and could be properly adjusted to the operator and no tools were needed to adjust the equipment. It have a robust design which withstood wear great during testing. The equipment was easy to put on yourself and the product includes a carrying bag and accessory bag for easy transport.

The EksoVest is at the same time heavier than the Paexo and sticks out from the body more, causing problems to the movement of the user. It also takes a long time to adjust the equipment which can cause problems if the equipment is supposed to be shared.

The Mate exoskeleton could be adjusted relatively quickly compared to the other exoskeletons but the equipment had fewer adjustment options. It fit close to the body and had a robust design minimizing wear on the exoskeleton during testing.

Like the EksoVest, the Mate is heavier which can hinder the movement of the user and the exoskeleton is really hard to put on yourself. It could be seen from the observation that the Mate exoskeleton did contribute to an unusual resting position for the arms, resulting in that the arms were held higher during rest. The Mate does not include any transporting bag which is a disadvantage while transporting the equipment.

Implementing the exoskeleton in real life production comes with a lot of challenges. The practicality of using the equipment is hindered by that the exoskeleton has to be adjusted for the individual operator. This makes it hard to share the equipment for practical reasons between different operators and having an exemplar of the equipment for each workers comes with a lot of costs. The practicality of putting on the equipment between stations suited and not suited for the equipment will add time to an already time limited process.

Even though you solve this problem by implementing some sort of size standards of these exoskeletons, with only minor adjustments to make the equipment fit the operator, the issue of hygiene is present. This is an equipment that is worn close to the body and is exposed to body fluids during the usage of it. Sharing this type of equipment is not optimal in the long term and operators should not be exposed to other individuals body fluids. The exoskeleton equipment should therefore be seen as a personal equipment.

Wear on the equipment was present after the short tests and this will lead to a lot of maintenance cost for the equipment if it were to used for a longer time period and at a greater scale. These costs have to be considered compared to the benefits that the exoskeleton provides the operators.

5.4 Ethics of the study and the testing

Ethics is a topic that is important to discuss and reflect upon while examining new technology that potentially could affect humans way of working. The exoskeleton is a tool that is supposed to improve the working conditions for operators and lower the impact that the performed tasks have on the body of the workers.

This study elevates a lot of challenges that has to be overcome to be able to implement the technology in question and also approach the possibility of no implementation at all. The testing in this study has been limited by resources and time availability and extensive testing has not been able to perform. The tests performed and their relative results has hinted towards some positive effects of the technology, but at the same time many negative effects and challenges has been noted.

There is a need of a more long term approached testing to be able to fully grasp what benefits and complications that the technology can contribute to. In the current state these effects are quite unknown and complications with elevated arms and lowered muscle activity could potentially be a big problem in the long term. This study only focuses on short term effects in its current form. It is important that the automotive industries completely understands this. This is very important from an ethical perspective to fully understand to not cause any long term damage, based on the examined short term effects.

From the start of this study the focus has been on to improve the ergonomic situation of above shoulder working tasks. Some positive effects could be seen from the testing which indeed could potentially improve these working conditions. The questions is what these results could lead to in the future. The Volvo Cars Corporation has been very clear with that potential positive effects only will be used to improve the working conditions for the operators in the final assembly. But could these positive effects be seen as a potential to elevate the workload of the operators to gain more output in the production? Could these results be used by other companies in their search for technologies to elevate their production output?

This thought has crossed the test owners minds multiple times and there are not any easy answers to these questions. Investigating new technology is always important to avoid negative effects that could arise from an implementation of the technology. As future production engineers there has been a passion linked to this investigation to aid operators well being in their daily work tasks. The work force is the heart of the company and without their wellbeing no company will succeed in its task to further evolve itself. This is understood by the test owners and therefore the belief has been towards that these positive effects will not be exploited by educated engineers in the future.

A subjective data collection was performed during this study, involving testing in a real factory with real assembly workers. There can arise ethical issues when real people are involved in a test if the test could lead to complications for the participant. The test owners were really strict with that the persons that were to partake in the test did this by their free will. Measures were taken to assure this by really informing the participants about what the testing would include and that it was completely okay to not partake in the study. Before starting the testing a consent was signed by the participants to assure of this.

As there are not much of long term studies performed on the exoskeleton technology there was a question if even a short amount of testing could be hurtful for the operators testing. It was considered and concluded that these equipments are made for this purpose and it had been stated by the producers that the products did reduce the stress on the body and no negative effects were mentioned. As the equipment was passive as well they were seen as quite harmless. It was concluded that possible short term effects would not be devastating for the operators and that the equipment was safe for the testing purpose.

6

Conclusion

This chapter describes the conclusive remarks of the thesis study along with future recommendations.

As exoskeletons are a relatively new technology in the automotive industry, the application of these exoskeletons is slim at the moment. Moreover, there is potential in the technology but long term effects are quite unexplored regarding the upper limb focused exoskeletons due to specific safety standards and significant technical challenges.

What constitutes an appropriate application of upper-limb focused exoskeletons in Volvo Cars final assembly?
A practical implementation of the technology in the automotive assembly plants comes with a lot of challenges, for example sharing the equipment and dressing/undressing the operators between stations. For appropriate application of upper limb exoskeleton in the final assembly, identification of appropriate station of shoulder up assembly work, a thorough study on upper limb focused exoskeletons, practical tests of exoskeletons prior to the implementation and the safety standards of the operators should be considered.

What are the challenges and benefits of upper limb exoskeletons in the final assembly of the automotive industry?
There was both positive and negative feedback from the 27 assembly operators who volunteered to participate in the factory testing. It could be seen that the equipment got good response regarding the aid that it provided during tasks performed above shoulders. At the same time there were many operators that had issues with the equipment regarding movability, comfort and resistance while working below the shoulders. The posture of the exoskeleton users was affected in a positive way by providing support for the upper body. Moreover, the participants could relax more while performing under-up assembly work.

The objective data from the biomechanical assessment resulted in reduced muscle activity in flexion movement of the focused muscles with the exoskeleton technology. With lowering muscle activity in the upper limb muscles, it does not mean that work related musculoskeletal disorders can be solved. There are several other factors that have negative effects on the body while performing above shoulder assembly work that have to be considered as well.

The limitations of the upper limb exoskeleton in the final assembly was that most of the participating operators did not appreciate the technology for a longer term to be used in real life production as it restricted the movement of operators while working below the shoulders and the equipment came in the way while working.

In order to understand the technology better and to get more conclusive results, a further recommendation would be to investigate the exoskeleton technology for a longer time period to assess and evaluate the long term effects of the use of the technology.

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A

Factory testing questionnaire

QUESTIONNAIRE TO EVALUATE THE BENEFITS OF AN EXOSKELETON SYSTEM IN THE FINAL ASSEMBLY

As a part of master thesis project, two master students of Chalmers University are conducting a research study to investigate how the use of upper limb exoskeletons affect the working conditions (under-up work) of the assembly workers. The study will examine if the equipment reduces the burden on the worker's health while maintaining or increasing the production efficiency in the final assembly plant at Volvo Cars Torslanda and Volvo trucks Tuve. Valuable feedback from the participants is an important part of this study, as the assessment of the equipment should be carried out by those who really have knowledge of what is required to be able to carry out the work in the final assembly. This study will contribute to future development and improvement of working conditions in vehicle production. Please fill out the form.

Investigators:

Oskar Tuneroth, Msc Production Engineering, Chalmers university of technology, email: tunerot@student.chalmers.se

Preksha Prasanna, MSc Production Engineering, Chalmers university of technology, email: preksha@student.chalmers.se

Instructions:

Carefully read the questions and please mark a response for each question. You or your name in any way will not be revealed anywhere and will be kept confidential. Feel free to ask questions to the investigators if you do not understand any question. Return the questionnaire to any of the students.

Name of the participant: ______________________________

Age: ____________

Sex: Male ☐ **Female** ☐

Type of task performed: ______________________________
____
____

Exoskeleton Questionnaire

* Required

General questions and performance of exoskeleton

1. **Name and Task performed**

2. **Which exoskeleton did you use?** *
Mark only one oval.

○ Paexo - by Ottobock

○ EksoVest - by Ekso Bionics

○ Mate - by Comau

3. **For how long time period did you try on the exoskeleton?** *

4. **Did you finish the whole test session** *
Mark only one oval.

○ Yes
○ No

5. **If not, why? Please comment below**

6. **Did the exoskeleton fit you well?** *

Mark only one oval.

○ Yes
○ No
○ Do not know

7. **If no, why did it not it fit you?**

8. **Were you able to perform your normal operation while wearing the exoskeleton?** *

Mark only one oval.

○ Yes
○ No, It disturbed the task
○ Could not perform the task at all!

9. **Did you feel restricted and tight while performing the task?** *

Mark only one oval.

○ Yes
○ A little
○ No

10. **Did the exoskeleton influence the performance of your task?** *

Mark only one oval.

○ Yes
○ A little
○ No
○ Do not know

11. **If yes, please comment on how it influenced the performance of your task.**

12. **Did the exoskeleton get in contact with or touch other things around you such as the body of the vehicle or tools while wearing it?** *

Mark only one oval.

○ Yes
○ No
○ Do not know

13. **If yes, how did the exoskeleton get in contact with other things around you?**

14. **Did other assembly workers get affected by the exoskeleton?** *

Mark only one oval.

○ Yes
○ No
○ Do not know

15. **If yes, how did they get affected?**

16. **Would you like to use the equipment for a longer period of time?(>2 hours)** *

Mark only one oval.

○ Yes, I would like to
○ Yes, but not everyday
○ Not at all

17. **If you answered "not at all", do you have any suggestions on how to change your mind?**

18. **Would you prefer to work with an exoskeleton for your particular task in the future?** *

Mark only one oval.

- ○ Prefer to work with exoskeleton
- ○ Prefer to work without exoskeleton
- ○ I am not sure

19. **How likely would it be that you would want to test the exoskeleton again more extensively?** *

Mark only one oval.

	1	2	3	4	5	
Not likely	○	○	○	○	○	I would like to try it again!

Questions regarding fit and usability

20. **Did the exoskeleton feel heavy while wearing it?** *

Mark only one oval.

- ○ Very heavy
- ○ A little heavy
- ○ Feels ok!
- ○ Very light

21. **Did the exoskeleton fit close to the body in the chest area?** *

Mark only one oval.

- ○ Yes, it fit well
- ○ No, too loose
- ○ No, too tight
- ○ Do not know

22. **Did the exoskeleton fit in the shoulder area?** *

Mark only one oval.

- ○ Yes, it fit well
- ○ No, too loose
- ○ No, too tight
- ○ Do not know

23. **Did the exoskeleton fit in the hip/stomach area?** *

Mark only one oval.

- ○ Yes, it fit well
- ○ No, too loose
- ○ No, too tight
- ○ Do not know

24. **Did your clothes get in the way, ride up or get stuck with the exoskeleton?** *

Mark only one oval.

- ○ Yes
- ○ No
- ○ Yes, but it did not matter
- ○ Do not know

25. **If yes, how?**

____

26. **Did your hair get tangled with the exoskeleton?** *

Mark only one oval.

- ○ Yes
- ○ No
- ○ Do not know

27. **Did the arm strap of the exoskeleton slip off while performing the task?** *

Mark only one oval.

- ○ Yes, often
- ○ Yes, a few times
- ○ No

28. **Did the exoskeleton get in the way while performing the tasks or while moving around the assembly area?** *

Mark only one oval.

- ○ Yes
- ○ A little
- ○ No
- ○ Do not know

29. **If yes, how?**

____

30. **Were you able to perform tasks while seated with the exoskeleton?**

Mark only one oval.

- ○ Yes, no problem
- ○ Yes, but it disturbed the task
- ○ Not at all
- ○ Do not know
- ○ I did not perform any seated task

31. **How would you rate that the exoskeleton fit you?** *
Mark only one oval.

	1	2	3	4	5	
Not at all	○	○	○	○	○	Fit very well

Questions regarding comfort

32. **Were you able to bend and reach out easily to pick tools and other things?** *
Mark only one oval.

○ Yes
○ Not like before (As in normal task)
○ No
○ Do not know

33. **Did you feel shoulder discomfort while performing the task?** *
Mark only one oval.

○ Yes
○ A little
○ No
○ Do not know

34. **Did you feel arm discomfort while performing the task?** *
Mark only one oval.

○ Yes
○ A little
○ No
○ Do not know

35. **Did you feel discomfort in the back while performing the task?** *
Mark only one oval.

○ Yes
○ A little
○ No
○ Do not know

36. **Did you feel discomfort in the neck while performing the task?** *
Mark only one oval.

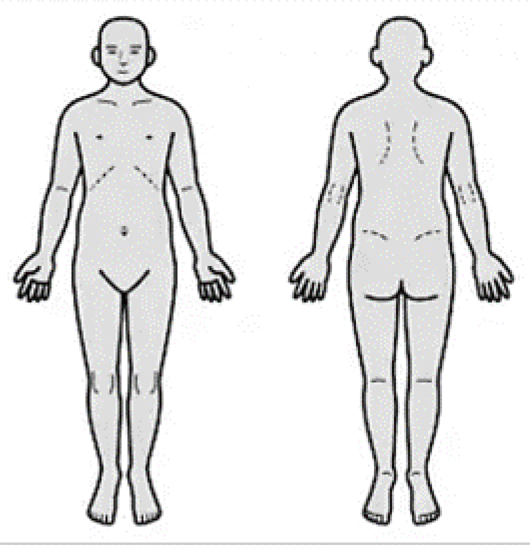
○ Yes
○ A little
○ No
○ Do not know

37. **Did you have discomfort elsewhere on the body?** *

Mark only one oval.

○ No discomfort elsewhere
○ Yes (please describe where and how below)
○ Do not know

38. **If yes, please specify. (You can also mark on the picture where you felt discomfort)**

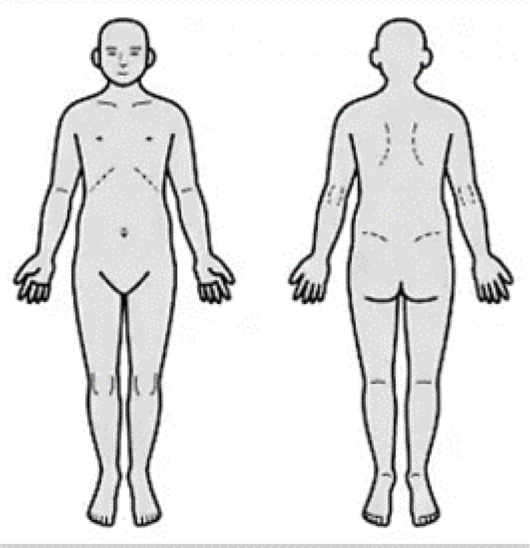


39. **Did you feel numb and/or tingling in the arms, hands or fingers during testing?** *

Mark only one oval.

○ Yes
○ A little
○ No

40. **If yes, where did you feel numb and/or tingling. (You can also mark on the picture where you felt numb)**



41. **Did you feel a lot of pressure on the arms while using the exoskeleton** *

Mark only one oval.

○ No, it was comfortable
○ A little
○ Yes, the pressure was discomforting
○ Do not know

42. **Did it feel awkward to use the exoskeleton from a social perspective?** *

Mark only one oval.

○ Yes, It felt really weird
○ A little uncomfortable
○ No, Not at all
○ Do not know

43. **How would you respond to working with a collegue that is using an exoskeleton?**

44. **Please rate the complete experience of using the exoskeleton** *

Mark only one oval.

	1	2	3	4	5	
Awful	○	○	○	○	○	Excellent

45. **Any extra comments or experiences while using the Exoskeletons. Please write below.** *

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B

Informing the participants

Evaluating the benefits of an exoskeleton system in the final assembly plant

We are master thesis students studying production engineering at Chalmers and we would like to invite you to take part in this research study regarding exoskeletons. Please take some time to read the information which contains why the study is being done and what are the possible benefits of taking part in this study. If you feel like some things are unclear and need more information regarding the study, do not hesitate to contact us.

Purpose of the study:

The purpose of this research study is to investigate how the use of upper limb focused exoskeletons affect the working conditions (under-up work) of the assembly workers. The study will examine if the equipment approves the workers working conditions while maintaining or increasing the production efficiency in the final assembly plant at Volvo Cars Torslanda and Volvo Trucks Tuve.

Why participants have been invited:

Participants of this study will get the opportunity to wear exoskeletons and test the new equipment during the performance of regular operation tasks. In order to investigate the use of exoskeleton in the assembly plants, the participants will be studied while using the equipment and they will be analyzed based on ergonomic issues and comfort level. The number of participants that are planned to test the equipment are at least 18 as there are 3 different exoskeletons and each of them will be worn by 3 different participants (9 participants from Volvo Cars Torslanda and 9 participants from Volvo Trucks Tuve). Participants with different anthropometric measurements are going to be recruited to account for different range of variation.

Do the participants have to take part in the study? :

It is not mandatory to take part in this study. The decision of participating in this study is totally up to you. You will get to sign a consent if you agree to participate in this study. You or your name in any way will not be revealed anywhere and will be kept confidential.

Participation requirements:

Participants with the following traits will not be suitable to partake in the study.

- Previous history of major injuries or operation on shoulder, arms, back or hands.
- With skin diseases, inflammations or constricting scars on their upper limb.
- With any pacemakers or active implants.
- Pregnant women
- Minors
- With severe varicosis in the usability area.

What’s in it for the participants? :
Participants will get the opportunity to try modern technology and leave feedback on the new equipment. The technology is rather new and your feedback will therefore be extremely valuable towards potential implementations in the future at Volvo Cars. This study will add to the continuous development of better working conditions for assembly workers.

Contact information of the investigators:
Preksha Prasanna, MSc Production Engineering, Chalmers university of technology, email: --, phone: --

Oskar Tuneroth, Msc Production Engineering, Chalmers university of technology, email: --, phone: --

C

Participation consent

Consent – Participating in exoskeleton study

You will participate in a study regarding exoskeletons. The purpose of this study is to gather subjective information on how the usage of the exoskeleton is experienced from a professional workers view.

By signing this consent you agree to partaking in this study, which implies;

- The participant will get the opportunity to use equipment which is owned by the Volvo Car Corporation. Use the equipment according to the study owners instructions during testing.

- After the test has been conducted the participant will get to fill in a questionnaire or be involved in a semi structured interview and give to one of the study owners.

- The study owners would like to film the participants during the testing, for academic purpose only. The participants will get to sign a waiver for photo permit if they are okay with this.

- You or your name in any way will not be revealed anywhere and will be kept confidential

- The testing will be conducted at Volvo Trucks Tuve factory, during performance of the ordinary assembly tasks.

You have the right to withdraw your consent at any time. Upon withdrawal of consent, we will stop the study and delete collected data that is linked to your involvement in the study.

Name:____

Date:____

D

Photo permit

Waiver – Usage of photo and/or film

You will participate/have participated in a photo shoot and/or filming organized by Volvo Group. Volvo Group wants to use the photographs and/or films from this occasion (referred to below as “Image Material”) for communication and marketing purposes.

The purpose of this photo shoot and/or filming is

____

____

____

By signing this waiver you agree that Volvo Group may use the Image Material in accordance with the conditions stated below.

- The Image Material will be produced by Volvo Group or by suppliers hired by Volvo Group. Volvo Group retains the right to edit the Image Material.
- Volvo Group will use the Image Material for communication and marketing purposes, for instance in recruitment publications, on Volvo Group’s website, or in annual reports.
- Volvo Group has permission to use the Image Material in both printed and digital formats, including publication on Volvo Group’s website or in other digital channels.
- Volvo Group retains the right to publish your name, and any quote approved by you, in connection with the Image Material.
- Volvo Group has the right to use the Image Material without any limitation in time.
- Volvo Group does not offer any compensation for use of the Image Material.

You have the right to withdraw your consent at any time. Upon withdrawal of consent, we will stop using the Image Material for the production of new communication and marketing material. However, the Image Material that has already been published in printed form prior to withdrawal may still be used.

I hereby approve that Volvo Group may use the photographs and/or films of me as per the above terms and conditions and for the above purposes

Name:____

Date:____

E

Informing students

Volunteers Needed
Can you help?

Investigating the benefits of an exoskeleton system in the final assembly plant

We are master thesis students studying production engineering at Chalmers and we would like to invite you to take part in this thesis study regarding exoskeletons. Please take some time to read the information which contains why the study is being done and why you are needed. If you feel that some things are unclear or need more information regarding the study, do not hesitate to contact us.

Purpose of the study:

The purpose of this master thesis study is to investigate how the use of upper limb focused exoskeletons affect the working conditions (under-up work/shoulder up) of the assembly workers. Exoskeleton is a wearable, external mechanical structure which is intended to increase the user's physical performance. Due to fast paced environment at the final assembly plants, biomechanical testing cannot be performed at the real factory setting in a feasible manner. Instead, we are going to set up a test rig to perform biomechanical testing of upper-limb exoskeleton in a lab environment which leads us to obtain objective data. The method that is used for biomechanical testing is Electromyography (EMG) which measures the muscle response or electrical activity in response to a nerve's stimulation of the muscle. Moreover, qualitative study is conducted at the final assembly plant of Volvo Cars Engine, Skövde and Volvo trucks, Tuve to examine if the equipment approves the worker's working conditions while maintaining or increasing the production efficiency.

Why do we need volunteers:

Volunteers of this study will get the opportunity to wear exoskeletons and be a part of EMG testing. The objective of this study is to compare the electrical activity of pectoralis major (clavicular portion- muscle located on the upper chest) and anterior deltoideus (muscle occupying the upper arm and shoulder. Electromyographic signals (EMG) will be obtained by placing surface electrodes on the required muscles. The skin surface where electrodes will be attached will be cleaned and shaved to obtain better results. You will be given a t-shirt to wear in order to make the testing easier and convenient.

The number of volunteers required for testing are 9 including both female and male. Volunteers with different anthropometric measurements will be required to account for different range of variation.

Lab testing week: April 29th to May 5th (Week 18)
Time required for testing: 1-2 hours

If interested, contact the below investigators for further information.

You will get to sign a consent if you agree to participate in this study. You or your name in any way will not be revealed anywhere and will be kept confidential.

Contact information of the investigators:
Preksha Prasanna, MSc Production Engineering, Chalmers university of technology
Email: preksha@student.chalmers.se, Phone: --

Oskar Tuneroth, Msc Production Engineering, Chalmers university of technology
Email: tunerot@student.chalmers.se, Phone: --

F

Participation consent for lab testing

Consent – Participating in exoskeleton lab study

You will participate in a study regarding exoskeletons. The purpose of this study is to gather objective information on how the usage of the exoskeleton is affecting the activation on the deltoid and pectoralis major muscles.

By signing this consent you agree to partaking in this study, which implies;

- The participant will get the opportunity to use equipment which is owned by the Volvo Car Corporation. Use the equipment according to the study owners instructions during testing.

- Testing will involve attachment of six(6) electrodes and cleaning/shaving of the skin area before application. The test subject will be provided with suitable clothing during the testing.

- EMG recordings of muscle activity will take place during the testing, the data will be used to compare the maximum voluntary contraction (MVC) of the muscles with and without the exoskeletons.

- The testing will be conducted at the PSL at Chalmers, Johanneberg. The participant will get to conduct a short assembly sequence during testing.

You have the right to withdraw your consent at any time. Upon withdrawal of consent, we will stop the study and delete collected data that is linked to your involvement in the study.

Name :____

Date :____