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Hand ergonomics in early phases of Production Development

Investigation of risks with early phase ergonomics evaluations

Master's thesis in Production Engineering

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Gothenburg, Sweden 2018

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Chalmers Reproservice
Göteborg, Sweden 2018

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Abstract

Volvo Cars want to offer and maintain a safe work environment that meets or exceeds current standards and legislations globally. Despite this ambition, Volvo Cars have noticed an increased frequency of hand injuries among operators in their final assembly plants and that the production development organization might lack tools to predict these types of problems prior to start of production. The purpose of the study is to investigate if there are risks involved with how Volvo Cars work with predictive assessment of hand ergonomics in early phases of production development. The purpose is also to find possible explanations to the recent increase of hand injuries. The aim of the study is to present recommendations that possibly could decrease these risks and the scope is limited to an automotive manufacturing context. In the present study, an abductive approach has been applied by combining theoretical frameworks and empirical data. The theoretical framework was combined with injury statistics and used as a basis for data gathering through interviews, document analysis and shop floor observations. The main finding was that half of all injuries in the studied assembly plant involved hand-related musculoskeletal disorders due to high pressure forces and that the product- and production development organization could not predict these injuries. Recommendations on how to improve the ergonomics evaluations at Volvo Cars are to educate and share competence of ergonomics in all development phases and make investments in a pilot study that investigates how to simulate pressure forces. Lastly, they should consider new emerging technology such as smart gloves that can provide objective assessments of hand ergonomics.

Keywords: Ergonomics, Predictive assessment, Hands, MSD

Acknowledgments

This Master's Thesis was carried out as a final project within the Master's Programme Production Engineering at Chalmers University of Technology, Gothenburg, and has been conducted in collaboration with Volvo Car Corporation, Torslanda, during the spring semester of 2018.

We want to thank everyone who, to a greater or smaller extent, contributed to the completion of this thesis project. The authors want to give a special thanks to Volvo Car Corporation and our company supervisor Dan Lämkull for giving us the opportunity to write this Master's Thesis. Dan has been very helpful and good at communicating information to us. He was also very responsive to questions. We also want to give a special thanks to our examiner at Chalmers, Cecilia Berlin, for fruitful discussions during our supervision meetings and for continuous support throughout the project. The authors would further like to give a special thanks to all the interviewees at VCC that allowed us to take part of valuable information, that constituted the largest part of our data collection. In addition, we would like to thank Sandra Mattsson, Researcher at the division of Production Systems, IMS, for helping us with the proofreading of the report. Last but not least, we would like to thank family and friends for all the support, and Lisa Jodensvi, Victor Andersson, Jonathan Hasselström and Daniel Eriksson in particular.

Anna Collinder
Gothenburg, May 2018

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Gothenburg, May 2018

Glossary

Abbreviations

ANOVA:	Analysis of variance
CMA:	Compact Modular Architecture
DHM:	Digital Human Manufacturing
DfA:	Design for Assembly
DfM:	Design for Manufacturing
HTO:	Human-Technology-Organisation
IoT:	Internet of Things
MSDs:	Musculoskeletal Disorders
P&Q:	Product and Quality
RAV:	Risk Assessment Volvo
RI:	Robust Index
R&D:	Research and Development
SCM:	Swiss Cheese Model
SDA-M:	System Decision Alternative – Manufacturing
SPA:	Scalable Platform Architecture
TIA:	Teknikföretagens Informationssystem om Arbetsmiljö
VCC:	Volvo Car Corporation
VCS:	Volvo Cars Standard
VCT:	Volvo Cars Torslanda

Definitions

Hand Ergonomics:	Ergonomics that include Hands, Fingers and Wrists
Work unit:	A cluster of several workstations
Operator:	Here; an assembly worker at the shop floor
Production Leader:	A manager of one or several work units
Blue Collar:	Labour workers e.g. machine operators and assemblers
White Collar:	Clerks, legislators and professionals
Ergonomic evaluations:	Processes and screening tools that are based on ergonomic principles, ergonomics simulations, early builds etc.

Table of Contents

1. Introduction

This chapter presents the introduction to the present study. It includes a background followed by the purpose of the study, a company description, its research questions and delimitations. Lastly an outline of the thesis is given.

1.1 Background

Volvo Cars want to offer and maintain a safe work environment that meets or exceeds current standards and legislations globally. The ambition includes preventing injuries but also to consider the physical and psychosocial aspects in all parts of the organization from product design to production processes. However, despite this ambition Volvo Cars have noticed an increased frequency of hand injuries among operators in their final assembly plants, where manual operations are highly frequent. In final assembly, hands are indispensable due to their ability of conducting precision work (Berlin and Adams, 2017).

In addition, Klingstam (2016) state that Volvo Cars have identified that the production development organization might lack tools to predict these types of problems prior to start of production. Especially virtual tools have become increasingly important for the manufacturing engineering department since they no longer work in direct physical contact with the factories (ibid.).

Volvo Cars initiated the present study in order to investigate possible explanations/theories of the recent increase of injuries in hands in final assembly at Volvo Cars Torslanda (VCT). They want to identify methods on how to work more preventatively with hand ergonomics in early phases of product and production development.

Bellgran and Säfsten (2009) describe how production development traditionally has been initiated after the finalization of the product development phase, sometimes referred to as *over-the-wall-engineering.* In other words, the design of the production system was fully constrained by the design of the product. In contrast, Bellgran and Säfsten (2010) state that it now is common to work in parallel or concurrently and with methods such as Design for Manufacturing (DfM) and Design for Assembly (DfA). With less constraints from the product design, there are more solutions to choose from when designing the production system, which in turn makes it easier to achieve good solutions. It is also related to lower total costs (ibid.).

In addition of integrating production development into product development, Koren (2010) state that the manufacturing industry is moving towards what generally is referred to as Industry 4.0. Internet of Things (IoT) is assumed to be what initiated this fourth paradigm of manufacturing (following the steam, the electricity and the electronics) (ibid.). Industry 4.0 is also predicted to involve what is referred to as Operator 4.0; a number of new ways to support the operators working in manual assembly, both physically and cognitively, using aids such as Exoskeletons and Virtual/Augmented Reality (Romero *et al.*, 2016).

Volvo Cars process of working cross-functionally and partly in parallel with product and production development is called Volvo Product Development System (VPDS), see Sub-chapter 1.3 below. Further, Volvo Cars aim at reducing the development lead time while becoming even more present globally, which puts increased focus on reducing late changes, on frontloading the development process and on virtual development (Klingstam, 2016).

1.2 Purpose

The purpose of the present study is to investigate if there are risks involved with how Volvo Cars work with predictive assessment of hand ergonomics in early phases of production development. The purpose is also to find possible explanations to the recent increase of injuries in hands among operators in final assembly. The aim of the study is further to present recommendations that possibly could decrease the risk of designing assembly tasks where hand ergonomics are compromised, before start of production.

1.3 Company description

Volvo Car Corporation (VCC) is a car company owned by Zhejiang Geely Holding (Geely Holding) of China. The first car was manufactured in 1927 in Gothenburg, Sweden, and since then additional factories have been built in Belgium, China and the United States. In 2017, about 572 000 cars were sold and 34 000 people were employed at VCC (Volvo Car Corporation, 2018).

The manufacturing plant in Torslanda (Gothenburg, Sweden) is the studied facility in the present study. The plant is divided into three factories; TA-factory (sheet metal forming and body design), TB-factory (paint) and TC-factory (final assembly). The engines are manufactured in Zhangjiakou (China) or in Skövde (Sweden) and then sent to the TC-factory for marriage with the car body (Klingstam, 2016).

The present study focuses on the final assembly in the TC-factory because it primarily involves manual tasks. In the TC-factory, the powertrain as well as all interior and exterior components are attached to the car body within a takt time of 60 seconds. Interior components are for instance seats, instrument panels, cables and panels. Exterior components are for instance tires, doors and windows. A typical five-door car has four doors for the driver and the passengers, an engine bay where the engine is placed and a luggage lid (the fifth door), see Figure 1. The three pillars are referred to as A-, B- and C-pillars and under the doors are the sill mouldings.

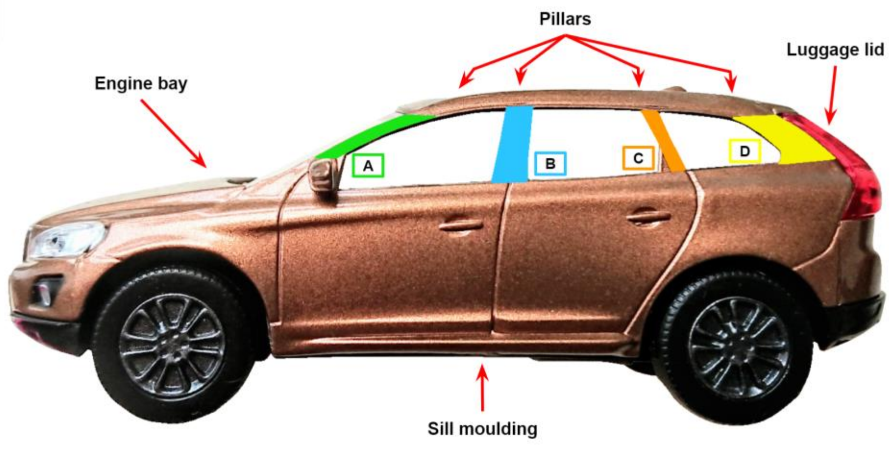

Figure 1 - Overview of the engine area, the A, B, C and D pillars and the sill moulding on car model XC60 from Volvo. Image by A. Collinder

At VCC, the process of working with product and production development is called Volvo Product Development System (VPDS). It is their cross-functional logic to develop vehicles in time with the right quantity. It involves all actions between the point where strategy is frozen to the start of production and is roughly divided into the two phases Concept and Industrialization. Out of the two, the Industrialization phase is the one that mainly includes manufacturing issues. In this phase, the product is digitally evaluated from a manufacturing viewpoint, including evaluation of the manufacturing processes and facilities. All of the above is done to ensure that the product can be produced, at the desired quality level, in the intended manufacturing facility, within the allocated cost and at the required line speed.

In order to launch more car models in a market that demands personalized products (Koren, 2010), Volvo Cars have developed scalable platforms. These platforms only have one dimension fixed and all other dimensions flexible, which has led to that all models currently available on the market are built on either the SPA (Scalable Platform Architecture) or the CMA (Compact Modular Architecture).

1.4 Research questions

Based on the background and purpose stated above, the present study aims at answering three Research Questions (RQ).

RQ1: What ergonomics risks appear to cause MSDs in hands in final assembly at VCT?

This question aims at identifying potential causes to the number of work-related musculoskeletal disorders (MSDs) in hands, that has been reported from the TC-factory in Torslanda. Potential causes in this case are hand-related ergonomic risks that can be identified in injury statistics, in assembly operations and in early phase ergonomics evaluations.

RQ2: What hand-related MSD risks in production are not captured with early phase ergonomics evaluations at VCT?

This question aims at identifying what hand-related MSD risks that are not captured with current early phase ergonomics evaluations at VCT. Courses of actions and technology shortcomings regarding these evaluations are also investigated since they might cause hand-related MSD risks to slip through the development phases and end up in running production.

RQ3: What actions can be taken to correctly assess hand-related MSD risks in the future?

This question aims at identifying what actions or activities that possibly could improve the early phase ergonomic evaluations in the future. Further, it aims at finding recommendations on how to detect risks for hand-related MSDs in order to prevent them from ending up in running production.

1.5 Delimitations

In the present study, the scope is delimited from MSDs that are not related to hands and wrists.
The scope is also delimited from MSDs caused by excessive heat/cold because of its relatively low occurrence in the TC-factory at VCT. However, how heat and cold influence material properties on certain assembly components is important to consider when assessing ergonomics in manual assembly due to its ability of making a component stiff or pliable.

Further, the scope is limited to an automotive manufacturing context meaning that ergonomics evaluations considered for the present study must be suitable for such a context. The focus of the present study is on early phases of production development; hence organizational aspects of the production system are not considered.

The scope is delimited from providing a full market analysis of solutions that potentially could improve the hand ergonomics at VCC. The recommendations presented in the present study are examples of possible ways of moving forward after the finalization of the study. Additionally, the scope is delimited from implementation of potential improvement proposals.

Lastly, regarding the terminology, the following terms are used synonymously:

- MSDs and Injuries
- MSDs in hands and hand-related MSDs
- Volvo Car Corporation and Volvo Cars
- P&Q and R&D

1.6 Outline of the thesis

The present study begins with a theoretical framework where relevant theory is presented to make the reader familiar with the subject and to support conclusions drawn from the collected data. Further, a methods chapter is presenting the used research approach and how the present study was conducted. The results chapter is divided into three sub-chapters based on each research question. Findings from literature, findings from qualitative data (interviews, documents and shop floor observations) and findings from quantitative data provided by VCC, are hence separated based on which question they answer. Theory and findings are then discussed in the discussion chapter and recommendations for future work are presented. Finally, conclusions from the present study are given.

2. Theoretical framework

This chapter presents the theoretical framework of the present study. It includes theory on ergonomics, hand anatomy, ergonomics evaluation tools and risk prevention models.

2.1 Ergonomics

In the following sub-chapters ergonomics is presented along with an anatomical orientation of the hand and what work conditions it is most suitable for.

2.1.1 Ergonomics definition and purpose

According to the International Ergonomics Association (2018) ergonomics is a term sprung from the Greek words *ergon* meaning work and *nomos* that means natural laws, and together ergonomics can be defined as "the science of work". They also state that another frequently used is term is human factors. It is a wider concept meaning everything that affects humans when they perform any kind of working activity (ibid.). Ergonomics and human factors has been a scientific discipline since the late 1940s and is core to engineering since it underpins and interacts with many other disciplines such as psychology and product design (Chartered Institute of Ergonomics & Human Factors, 2015).

Aspects included in ergonomics

There are numerous aspects included in HFE, such as physical loading on muscles and joints when performing a work task as well as how the work organization is affecting the work satisfaction and efficiency of a worker, to the climate conditions in the actual working area and how e.g. the humidity is an influencing factor (Berlin and Adams, 2017). The focus of ergonomics when designing a workplace is the human, and by taking into account the physical and cognitive capabilities and limitations of humans, unsafe, unhealthy and inefficient work situations can be avoided (Dul and Weerdmeester, 2017).

Purpose of ergonomics

According to Berlin and Adams (2017), in order to obtain and maintain a sustainable production system it can be assumed that it is of high importance that it runs as efficiently as possible and makes economic profit. To continue, they state that the manager of such a system would like all of its subsystems, where the human system is one, to function well together. Humans in production have the advantage of being potential problem-solvers as well as likely bringing flexibility and innovation to the production system. On the downside, as a result of physical work that overloads the human body while working in the production system, humans are prone to develop musculoskeletal disorders (MSDs) (ibid.).

The social and economic value of ergonomics

Dul and Weerdmeester (2017) claim that Ergonomics can both serve social goals of well-being and economic goals of performance. In addition, they state that at a society level, the costs of work-related MSDs can decrease if ergonomics is used to improve working conditions. Berlin and Adams (2017) further state that the ability to perform work is fully dependent on a person's physical health. Nevertheless, they state that it is possible to ignore the body's warning signals of pain and discomfort and still execute the work tasks. Berlin and Adams (2017) sums up the consequences of ignoring the warning signals in the following four statements; First, the discomfort leads to that the body will work slower and with reduced power, precision and quality and it is also more prone to make errors. Secondly, when the limit of what a human body can endure is reached regarding physical loading, the result is employees on sick leave to recover from the physical impairment. Thirdly, this is related to high costs due to the need of recruiting and training a new employee to replace the one on sick leave. And fourthly, until the new employee has reached the same level of skill, competence and working speed the company has made both productivity and quality losses. These costs are wasteful since they are generated by unnecessary physical impairments that could have been avoided (Berlin and Adams, 2017). At company level ergonomics can indirectly contribute to the competitive advantage of company. In terms of productivity and quality the human performance can be increased with ergonomically designed production processes (Dul and Weerdmeester, 2017).

2.1.2 Ergonomics is linked to productivity and quality

According to a study there is a clear relationship between quality errors and poor fulfilment of ergonomics requirements (Falck, 2009). This relationship is linked to the physical load level of an assembly item:

High load level:	High physical stress with harmful impact on the body
Medium load level:	Moderate physical stress with potential harmful impact on the body
Low load level:	Low physical stress with minimal risk of harmful impact on the body

The study found that there was a much higher amount of quality errors related to assembly items with high or medium physical load level compared to items with low physical load level. The risk of poor quality was 3 times higher for high load level items and almost 4 times higher for medium load level items compared to low load level items (Falck, 2009). Additionally, another study confirms that high-physical workload is strongly associated with increased error rates and longer absenteeism, and that productivity is much more affected by ergonomics work conditions than ageing (Fritzsche *et al.*, 2014).

The impact of poor product design

Often design engineers do not recognize the consequences of a poorly designed product and work station, due to lack of ergonomic competence and time as the main shortcomings

(Broberg, 1997). Further, a study in the Swedish automotive industry showed that 60-70% of the MSDs are caused by the product design, and 30-40% by the assembly process (Eklund, 1999). Falck (2007) states that this results in poor ergonomics and poor assemblability which in turn result in health problems, productivity and quality losses that ultimately result in increased costs of the final product, see Figure 2.

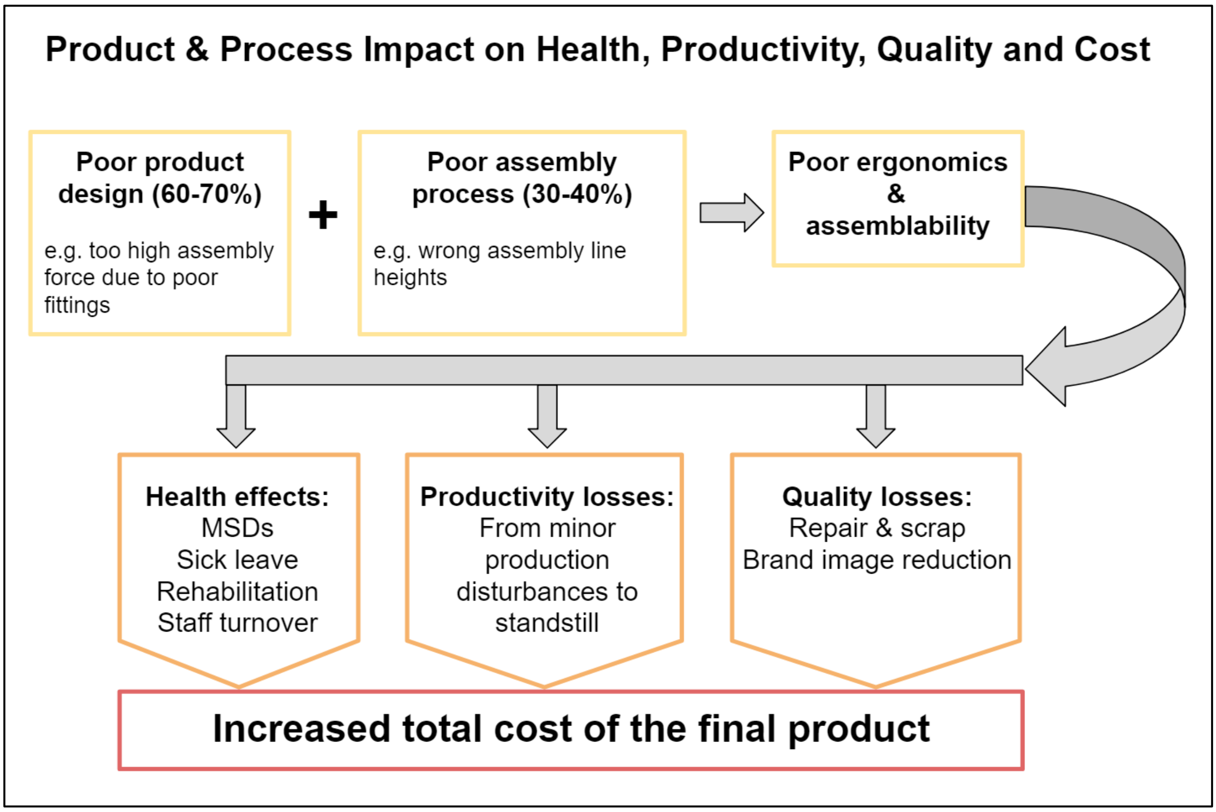

Figure 2 - Flow chart of the impact poor product design and poor assembly process have on Health, productivity, quality and cost. Image adapted from Falck (2007)

Another study states that since the product design is set in the design and planning phases the majority of ergonomic issues that result from the design of the product and its assembly tasks are established early, often years before production even begins (Munck-Ulfsfält *et al.*, 2003). Due to this, the greatest possibilities to influence the ergonomics are in early product development phases; the pre-concept and the concept phase. In these phases major product changes can be made Falck (2007), which can be seen in Figure 3.

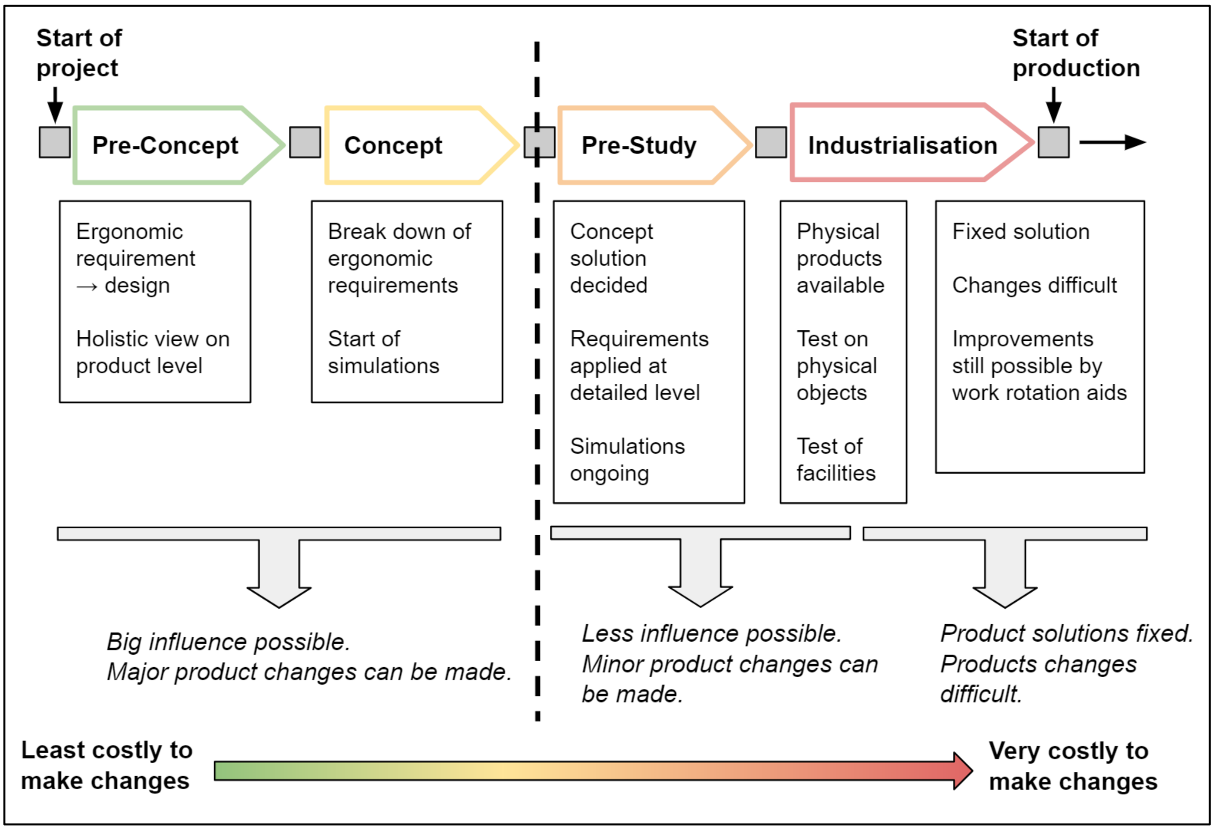

Figure 3 - Description of ergonomic influence during the product development process. Image adapted from Lämkull, Falck and Troedsson (2007)

In later phases, it becomes difficult and very costly to make changes to the product. After the industrialisation phase the product solution is fixed and possible improvements are only made on the assembly process through work rotation (Lämkull, Falck and Troedsson, 2007).

Six levels of control regarding occupational health risks

According to Manuele (2007) occupational health risks, including ergonomic risks, can be addressed using six different levels of control, see Figure 4. They are in descending hierarchical order with respect to their effectiveness of reducing risks. At the first and most effective level, risks are addressed by eliminating them in the design process. At the second level risks are reduced by substitution, e.g. an assembly method is changed to a less-hazardous one. At the third level risks are reduced through incorporate safety devices, in the form of engineering controls; examples include fall prevention systems, conveyors or lift tables. At the fourth level warning systems should be provided, such as signs and alerts in operating procedures or manuals. At the fifth level, which is administrative controls, training of operators, work rotation or similar are included. At the sixth and least effective level is the use of personal protective equipment, such as safety glasses and gloves (ibid.).

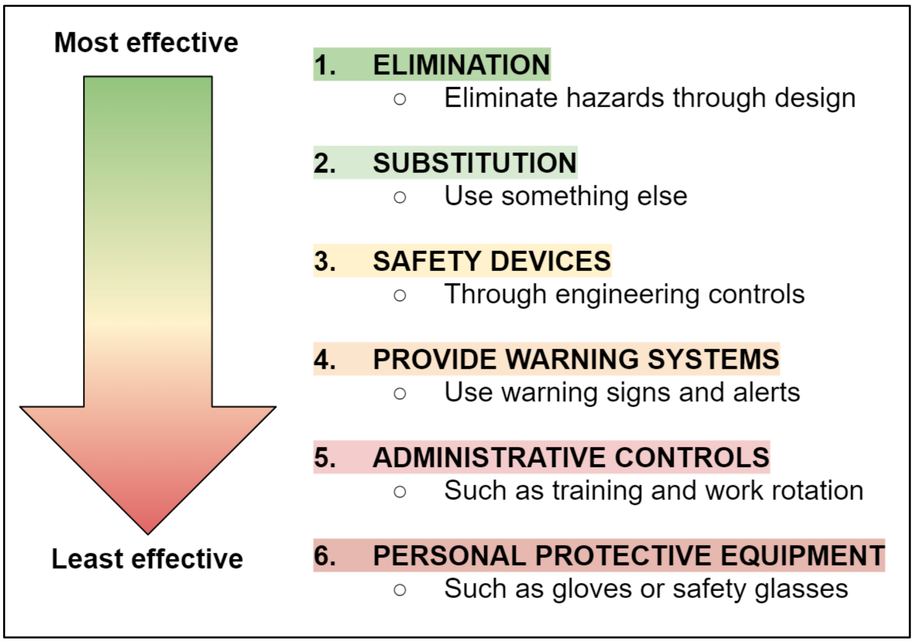

Figure 4 - The six levels of control regarding occupational health risks. Image adapted from Manuele (2007)

Related to implementing improvements, Berlin and Adams (2017) state that these can be implemented with a proactive approach or a reactive approach. A *reactive* approach means that investments in ergonomics are made when the situation becomes so bad the company has to react, i.e. when complaints arise or when a worker reports an injury. Reactive improvements often solve the problem on a short term but seldom solves the root cause of the problem, or provides lasting benefits. Berlin and Adams (2017) further describe that a reactive approach does not prevent ergonomic issues from arising; it rather means that workers are "sacrificed" to the poor design of a product and its assembly operations, before measures to change the situation are made. A *proactive* approach on the contrary, is an approach where investments in ergonomics are planned in years ahead by, designers, decision makers and production engineers which undoubtedly is a superior approach. By adopting a proactive approach, it is possible to establish assembly methods with minimal amount of ergonomics issues (ibid.).

2.1.3 MSDs

Common results of poor ergonomics solutions at work are work-related musculoskeletal disorders, MSDs (Dul and Weerdmeester, 2017). To better understand what an MSD is the musculoskeletal system is presented briefly before the definition of an MSD is introduced.

The musculoskeletal system

The human musculoskeletal systems' primary structures are the skeleton, the muscles and the joints (Tortora and Grabowski, 2004). The skeletal systems primary structures are bones, joints and cartilage, and two main functions of the skeletal system are to support and to enable movement (ibid.). The skeleton forms a rigid framework to which softer tissues and organs are attached, and the bones acts as levers when muscles contract which generates movement around joints (Van de Graaff, Rhees and Palmer, 2013). The muscular system is constituted by different types of muscle tissues depending on what function they have; skeletal, smooth and cardiac muscles (Tortora and Grabowski, 2004).To classify muscles by function they can be divided into several categories e.g. flexors, extensors, pronators and supinators to mention a few. A flexor decreases a joint's angle and the extensor increases it. The pronator rotates the hand so that the palm faces posteriorly and the supinator rotates the hand so that the palm faces anteriorly, see Figure 5 (Van de Graaff, Rhees and Palmer, 2013).

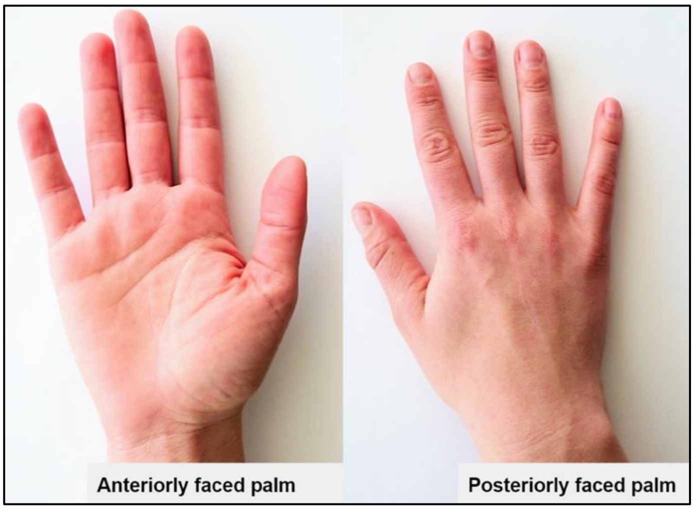

Figure 5 - To the left; the supinator function turns the hand anteriorly and, to the right; the pronator turns the hand posteriorly

When making a movement or trying to maintain a posture, the joints ought to be kept in neutral position as much as possible (Dul and Weerdmeester, 2017). Then the muscles and ligaments are subject to less stress since they are stretched to the least possible extent and hence can deliver their greatest force. A bent wrist is an example of a poor posture where the joint is not in neutral position. It is also known that sudden movements and forces can generate large short-duration stresses, often as the result of an acceleration in the movement. These peak stresses can cause acute pain and thus thorough preparation is necessary before large forces are exerted (ibid.).

Dul and Weerdmeester (2017) state that no posture or movement should be maintained for a long time, even if the posture or movement do not generate any considerable physical load. They state that repetitive movements and prolonged postures are tiring and can in the long run cause injuries on muscles and joints. They also state that these prolonged postures and repetitive movements cause stress on muscles which leads to localized muscle fatigue that eventually reduces the muscle performance. The larger the exerted muscular force, the shorter time it can be maintained (Dul and Weerdmeester, 2017).

To illustrate physical loading risks in a figure the cube-model is a good example, see Figure 6. It is important to consider the interaction between work posture, time, and exerted force when evaluating a work task (Sperling *et al.*, 1993). In the cube model each of the loading components are given three criteria levels of severity, where 1 equals low risk and 3 equals high risk. The cube displays which combinations of posture, time and force that may result in harmful loading or injuries (Berlin, Adams, 2017; Sperling et al., 1993).

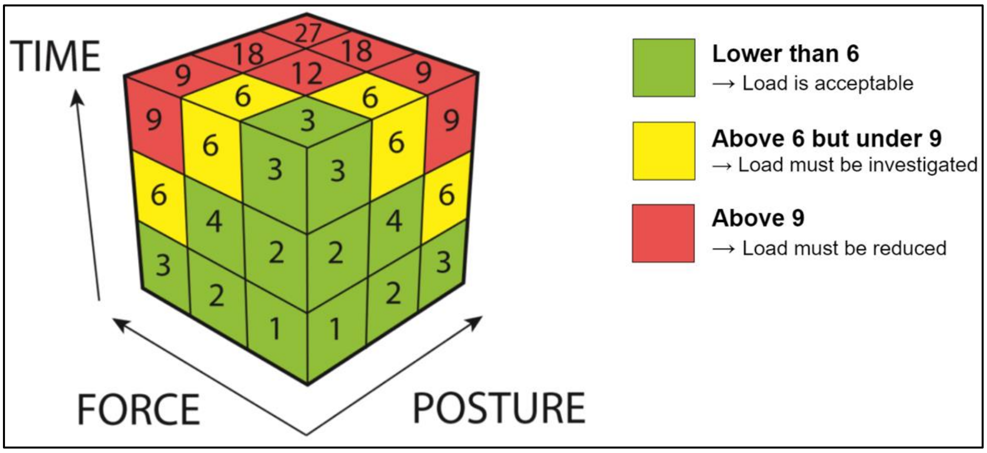

Figure 6 - The cube model illustrates how different risk levels depends on combinations of posture, force and time. Illustration by C. Berlin, based on Sperling et al. (1993), modified by A. Collinder

Musculoskeletal disorders

According to Nunes (2009) Musculoskeletal disorders (MSDS), or work-related musculoskeletal disorders, are related to work and can affect both upper and lower limbs, and the back area. Further, work-related musculoskeletal disorders are defined by impairments of bodily structures such as muscles, joints and tendons. They are caused or aggravated primarily by work itself or by the work environment (ibid.). According to Berlin and Adams (2017) the first sign of a MSD is often pain and discomfort while more evident symptoms are loss of function and not being able to move at full range. If these symptoms grow to affect the workers' ability to move and handle physical loading, they are called work-related musculoskeletal disorder. Berlin and Adams (2017) also propose that these work-related MSDs are possible to avoid with a thought through workplace design where the following factors are minimized:

- forced working postures
- load weight
- static work
- continuous loading of tissue structures
- repetitive working tasks
- time pressure/lack of recovery time
- risks of poor working technique
- risks of poor working attitude
- demotivation, stress
- risks of inappropriate organization

Nevertheless, according to the European Agency for Safety and Health at Work (2007) MSDs are the work-related health problem with the highest impact on both sickness absenteeism and permanent incapacity in Europe, where MSDs constitutes 61% of all reported permanent incapacity cases. Further, they state that blue collar workers face a higher risk of developing an MSD with almost 20 times as many employees experiencing an MSD compared to white collar employees (clerks, legislators and professionals). Among blue collar occupations, they have found that the third most exposed group of contracting MSDs, measured in highest number of reported new MSD cases, are plant and machine operators and assemblers (European Agency for Safety and Health at Work, 2007). In Sweden, the Swedish Work Environment Authority (2016) stated that the total amount of injuries caused by physical loading at work during 2016 were 9 % for women and 7 % for men, including both white and blue collar occupations.

2.2 Hands

Healthy hands and wrists are critical for a human being able to work (Berlin and Adams, 2017) and hence indispensable in assembly work, which is mainly constituted by manual work. In this sub-chapter, basic theory on hand anatomy and common work-related MSDs in hands are presented.

2.2.1 Hand anatomy and function

The execution of a highly advanced hand movement is not hindered by the hands' movability but rather by the brain commanding it (Oberlin and Teboul, 2001). The hand, wrist and arm form a complex and sensitive structure together that easily gets overloaded during physical work (Berlin and Adams, 2017). The bones, muscles and joints of the hand are not anatomically suited for exerting high force, but primarily adapted for high-precision work. This makes it very important to design work tasks that give the best possible conditions for the hand to exert force and precision (ibid.).

Bones

In the hand there are several tightly clustered bones called *carpals* that form a complex structure and protect blood vessels, nerves and important tendons that enable finger movements (Tortora and Grabowski, 2004). These blood vessels, nerves and tendons all pass through a narrow passage called the *carpal tunnel*. After the carpals the *metacarpals* are situated, which are the bones in the palm (ibid.). The finger bones are called *phalanges* and are divided into three sections (ibid.), see Figure 7.

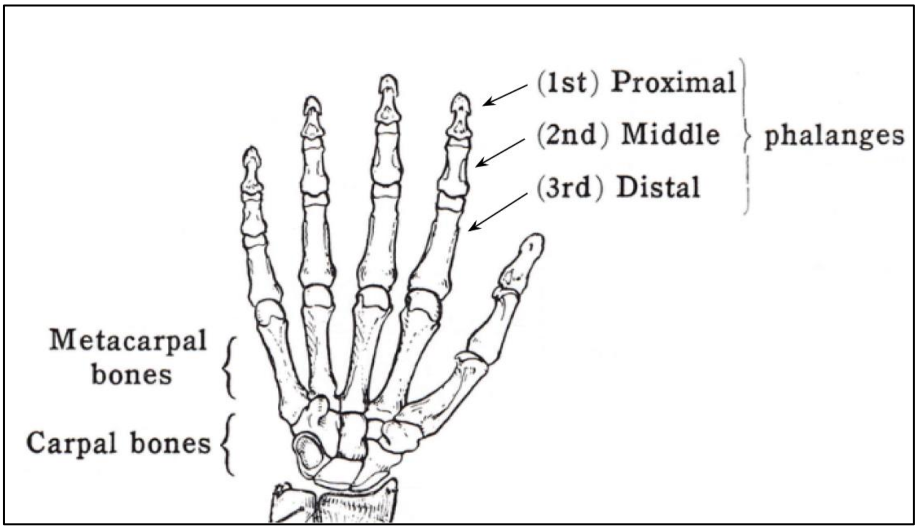

Figure 7 - The bones in the hand. Image adapted from Grant (1962)

Joints

Joints are the structure that links bones to other bones, cartilage or teeth (Tortora and Grabowski, 2004). In the hand a 3-dimensional joint called a *saddle joint* can be found at the base of the thumb and it permits a range of movements in several dimensions. Joints are particularly sensitive to injuries or MSDs caused by physical loading in extreme positions due to their complexity and the presence of several complicated and fragile structures passing through them. Between bones, e.g. the phalanges sections in the fingers, there is cartilage. The cartilage is thickest in the middle i.e. when the joint is in neutral position. On the sides the cartilage layer is thinner meaning that working in extreme joint angles may result in damage to the thinnest part of the protective cartilage layer, see Figure 8. Due to the complex structure of joints with different kinds of tissues and lesser amount of blood flow, injuries to them can take months, even years to heal (ibid.).

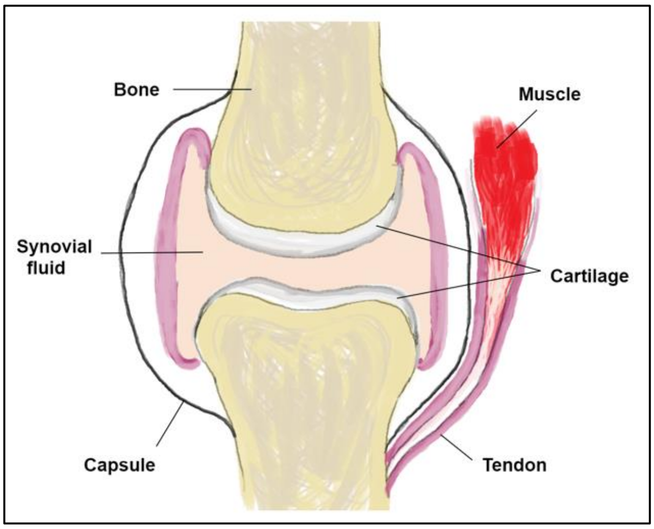

Figure 8 - The protective cartilage layer between bones is thickest in the middle and thinnest at the edges i.e. working in extreme joint angles is not optimal. Image by A. Collinder adapted from Berlin and Adams (2017)

Movements

The motions a hand can perform include the twisting motions supination and pronation (bending of the wrists and fingers), flexion and extension, and radial and ulnar deviation (sideways wrist bending) (Tortora and Grabowaki, 2004); see Figure 9 and Figure 10.

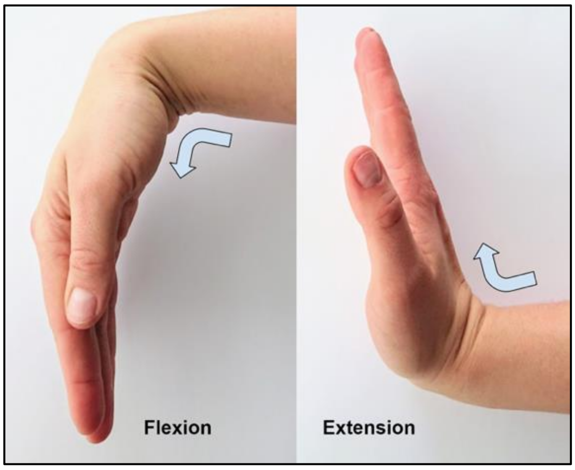

Figure 9 - Extension and flexion of the hand. Image by A. Collinder adapted from Berlin and Adams (2017)

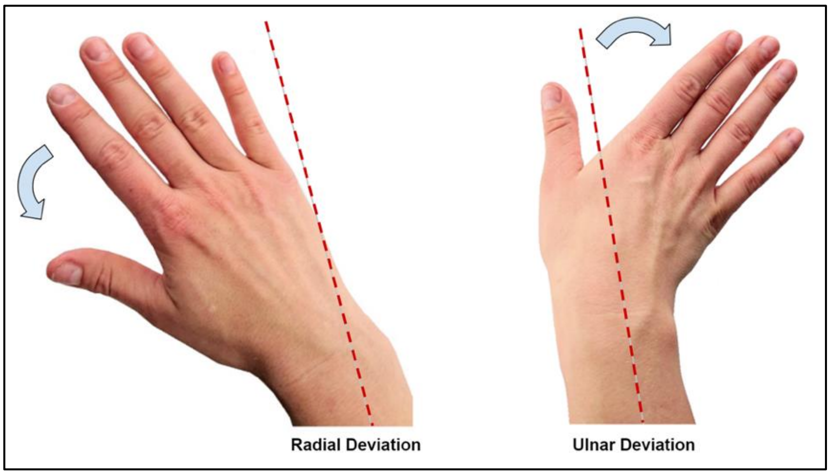

Figure 10 – Sideways (lateral) movements of the wrist and hand. Image by A. Collinder adapted from Berlin and Adams (2017)

Another important function of the hand is the one of a grip tool according to Berlin and Adams (2017). They state that depending on what level of precision that is needed for the task, the hand can take on different functional positions, see Figure 11. They further explain that in the functional resting position of the hand, the pressure on blood vessels, nerves and tendons that goes through the carpal tunnel is at its lowest, the muscles are relaxed, the fingers are slightly curved and the wrist is straight. Since the hands' strength and ability for precision decreases dramatically when working at the extreme ends of their moving range, see Figure 12, Berlin and Adams (2017) propose that work tasks should be designed to be performed as close to the hands' functional resting position as possible. They also state it to be important when designing hand tools; to ensure good conditions for strength and precision development, the hand should be as close to its functional resting position as possible. Further, the complex structure of the hand should not be overloaded with unnecessary twisting and bending while working (ibid.). They mention that common work-related issues that may cause MSDs in hands are:

- high forces
- punctual pressure on a small area
- repetitive tasks
- extreme positions during work (e.g. ulnar deviation combined with supination)
- incorrect grips
- vibrations
- incorrect design of hand tools
- cold and heat

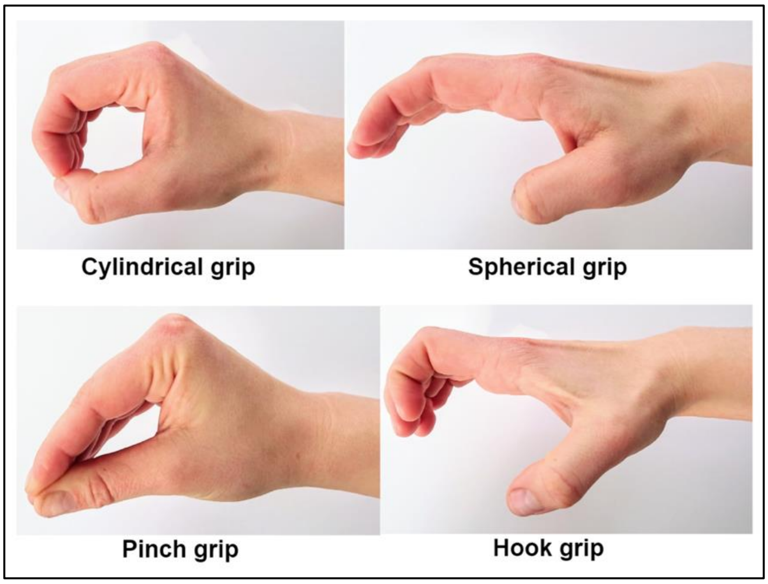

Figure 11 - Different gripping functionalities of the hand. Image by A. Collinder adapted from Berlin and Adams (2017)

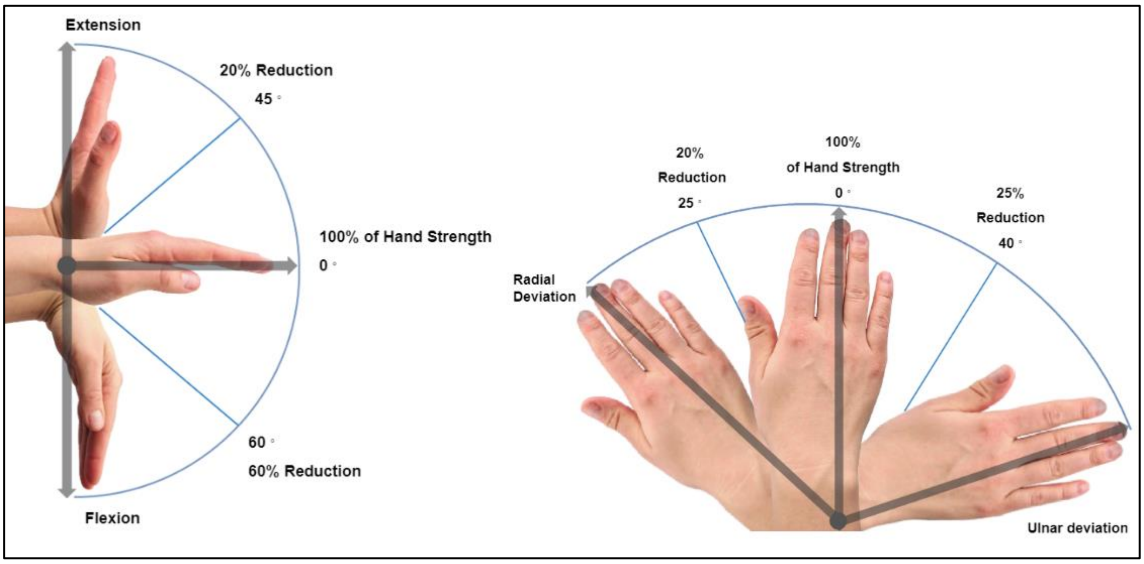

Figure 12 - Decrease of hand strength at different angles of flexion/extension and deviation. Image by A. Collinder adapted from Berlin and Adams (2017)

2.2.2 MSDs in Hands

Working with the hand in a poor posture can lead to specific complaints of the wrist, and a continuously bent wrist can lead to local nerves becoming inflamed and trapped. This results in wrist pain and a tingling sensation of the fingers (Dul and Weerdmeester, 2017). According to the Swedish Work Environment Authority, the total amount of hand injuries in Sweden, caused by physical loading at work, were 3 % for women and 2 % for men, including both white and blue collar occupations (Swedish Work Environment Authority, 2016). In this section two common work-related MSDs in hands, Carpal tunnel syndrome and Trigger finger syndrome, are presented.

Carpal tunnel syndrome

The carpal tunnel syndrome (CTS) is according to Karwowski and Salvendy (1998) one of the most complicated and controversial disorders in the hand. They state that it is the most reported cumulative trauma disorder, i.e. generated over time, in industry with the highest average lost work days. Further, they explain that the carpal tunnel is located on the palm of the hand, where the floor and the walls of the carpal tunnel are formed by the carpal bones, see Figure 13. The pressure inside the carpal tunnel, the *intracarpal* pressure, is at its lowest when the wrist is in neutral position and increases with extreme flexion or extension (Karwowski and Salvendy, 1998). They further state that if the pressure is elevated for a sufficient period of time the blood circulation of the median nerve is stopped which causes numbness or a tingling sensation in fingers. They mention that circumstances where workers press or hit objects with the palms of their hands are also risk factors for CTS. If the CTS is developed at work, during manual work tasks, they state that it is unlikely that the worker will do well if returned to the same work task again. Common treatment is to wear a wrist bracelet during sleep for several weeks or months and if that does not help surgery can be considered (ibid.).

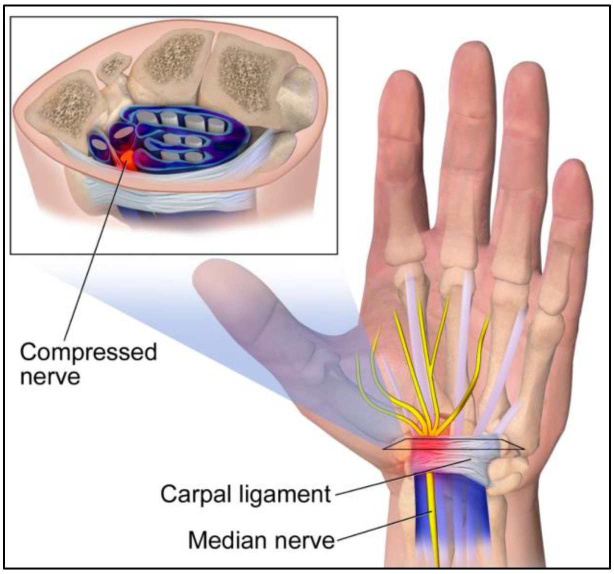

Figure 13 - The carpal tunnel formed by the carpal bones and the transverse carpal ligament in red. Image from Blausen.com (2014) free to use under the Creative Commons Attribution 3.0 license

Trigger finger syndrome

From Karwowski and Salvendy (1998) it can be understood that inflammation in tendons is a condition that makes it painful to perform movements with wrists and fingers due to a sense of pressure and swelling in the knuckles. They state that it is the result of repetitive finger work, or sharp edges on hand tools, that causes irritation in the tendon sheaths. One symptom, called *trigger finger syndrome* (TFS), is when the extension or the flexion of the thumb and forefinger cannot be done in a smooth movement. Instead, the movement is hindered until it "snaps" into position (Karwowski and Salvendy, 1998).

In general, TFS develops gradually but it can also be caused by acute trauma (Karwowski and Salvendy, 1998). TFS is more common among women than men and the thumb is most commonly affected. The usual treatment for TFS is corticosteroid (cortisone) injections, but surgery can also be done if the finger is completely locked. In order to recover, firm gripping or pressure on the palm should be avoided for at least a couple of weeks (ibid.).

2.3 Ergonomics evaluation tools

In this sub-chapter tools that can be used for assessing risks regarding MSDs in hand are presented. First ocular assessments in the form of screening tools are mentioned and then Digital Human Modelling tools using manikins are introduced.

2.3.1 Screening tools

According to Berlin and Adams (2017) a number of different tools are available to assess physical loading. They state that these tools can be categorised into three broad divisions, that further will be explained below:

- Posture-based analysis: observation based scoring of postures
- Biomechanical analysis: use calculations and are strictly defined
- Multi-aspects methods: analysis based on a combination of environmental factors

They explain that the *posture-based* analysis use point-based systems to rank identified areas of concern, and typically the more the posture deviates from the body's neutral position the worse it is, which results in a higher score. They are purely based on observations which makes them somewhat vulnerable to interpretation. *Biomechanical analysis* tends to be based on evaluations that include moving a load from one place to another through lifting, pushing, pulling or carrying it. These evaluations include biomechanical calculations and take longer time to conduct. Analyses based on a combination of several factors, or *multi-aspects methods*, can both include posture-based analyses and biomechanical analysis but also considers additional aspects such as time, speed, frequency, intensity etc. (ibid.). Two screening tools that assess ergonomic risks related to hands are:

- KIM III - multi aspects method
- HARM - posture-based analysis

2.3.1.1 KIM

According to Occupational and Environmental Medicine in Uppsala (2012) the *Key Indicator Method* (KIM) is a screening tool developed to assess ergonomic risks regarding manual handling of loads. They state that there are three different variants of KIM; one for analysing work tasks involving lifting, holding and carrying (KIM I), a second for pulling and pushing (KIM II) and third for manual handling operations (KIM III). According to them, KIM III was developed after the other two with the purpose of evaluating hand intensive work with predominant load on the finger-hand-arm area. It is structured in the same way as its precursors and the assessment is conducted during several working cycles (ibid.). They state that the following risk categories are evaluated:

- Total duration of the work task per shift
- Force transfer / gripping conditions
- Average holding/moving time
- Hand/arm position and movement
- Work organization
- Working conditions
- Posture

These categories are ranked and given a score. The overall score is the risk assessment graded in risk levels; green, yellow, orange or red, see Figure 43 in Appendix D (ibid.).

2.3.1.2 HARM

Hand Arm Risk assessment Method (HARM) is a posture-based tool that has been developed from KIM III (Douwes and De Kraker, 2012). It was developed to be used by people without education in ergonomics, and assesses ergonomic risks for hands, arms, shoulders and the neck during hand and arm intensive work tasks with duration longer than 1 hour. The evaluation is made for one isolated work task at a time and includes six categories; time, hand that is most active during the work task, force, posture, vibrations and other risk factors. For these categories a risk score is rated and then put together. The overall score is the risk assessment graded in risk levels; green, amber or red, see Figure 44 in Appendix D (ibid.).

2.3.1.3 Standards

Ergonomics standards are often used to ensure that a work task does not harm the worker (Swedish Work Environment Authority, 2012). In Sweden the AFS 2012:2 is the latest standard with legal status that concerns physical loading. An example of what is included are for instance workplace height design guidelines. These height guidelines show that the overlap between the tallest and the shortest workers' ideal work height might be rather slim, see Figure 14 (ibid.).

At Volvo Cars, there are internal standards used in addition to the guideline documents with legal status. Volvo Cars ergonomics standard is called VCS 8003,29. The latest issue, number five, was released in 2014. It is based on directives by the Council of the European Communities from 1990. This standard applies to all factories, but should be used in addition to local regulations and in Sweden, it is used together with the AFS 2012:2.

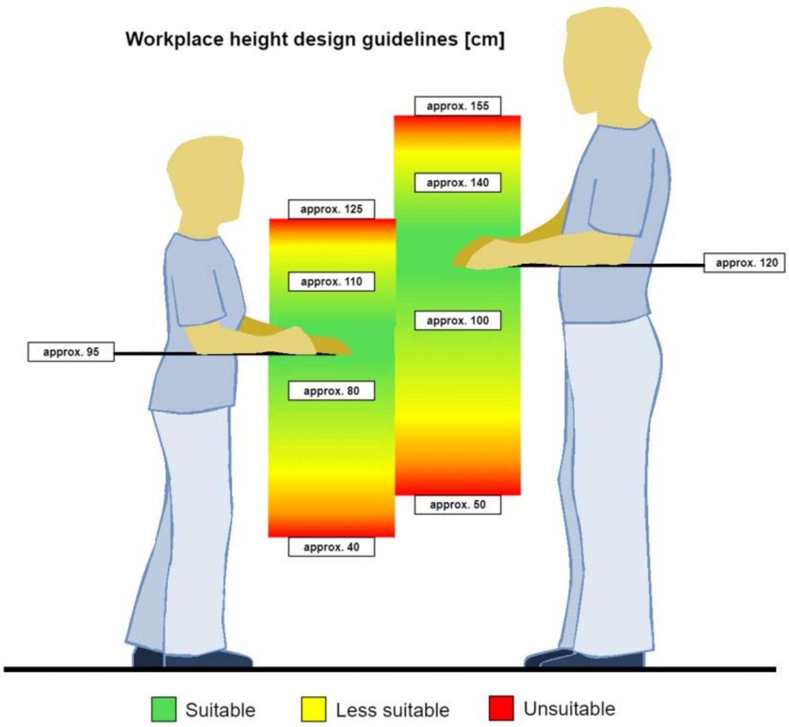

Figure 14 - Working height guidelines from AFS 2012:12. Image by A. Collinder adapted from Swedish Work Environment Authority (2012)

Working in red zone is unsuitable since most employees risk being affected by MSDs in the short or long term. Such work postures should immediately be rectified to reduce the risk. For the hands, this means being far away from the body e.g. above shoulder height (Swedish Work Environment Authority, 2012). Gaudez, Wild and Aublet-Cuvelier (2015) state that many standards recommend measuring only external force regarding force exertion, in contrast to the internal forces in the bio-mechanical structure of the body. They further state that when it comes to the clip-fitting task, which is a frequently encountered assembly operation in automotive industry used to secure two parts together, it is insufficient to only measure external force for evaluating the physical workload. Gaudez et al., (2015) claim that this is due to that the physical workload is different depending on whether external force or muscle activity results are considered. This task is in general performed manually and can cause upper limb pain (ibid.).

2.3.2 Digital Human Modelling and anthropometry

To test assembly solutions before they are implemented *Digital Human Modelling* (DHM) enables simulations and analyses of ergonomics in virtual environments (Brolin, 2016). The DHM-tools are computer tools that utilize 2D or 3D human models called manikins in virtual environments. These tools are more or less integrated to different *Computer Aided Design* (CAD) tools to visualize and/or analyse the manikins' interaction with their environments, that is made up of 3D graphic components describing products and process equipment. Additionally, these tools include biomechanical analysis methods (Lämkull, 2009). The last two decades a number of ergonomic simulation packages have been developed, among which some are research project and some are commercially available. Berlin and Adams (2017) state that the benefits of using DHM-tools are among others:

- Can be used in early phases of production development when there is no access to the real workstation environment
- Enables numerous alternative assembly solutions to be compared and to test with different measurements across genders and nationalities
- Visualises the proposed work design layout and its effects on physical ergonomics
- Easy to adopt a proactive design approach regarding ergonomics

Even though DHM-tools include a set of ergonomics methods to evaluate working postures and physical workloads these do not seem to be frequently used (Sundin and Sjöberg, 2004; Lockett *et al.*, 2005). The majority of made analyses with DHM-tools are related to reachability and space studies; workload analyses are rarely done (Laitila, 2005). This can lead to that ergonomics evaluations with DHM-tools differs from reality. Lämkull, Hanson and Örtengren (2009) states that the incapability of evaluating pressure/pull forces are sometimes the reason behind deviations between simulation results and reality. Another reason for deviation is an underestimation, or an exaggeration, of the required space for the hand/arm (ibid.)

Anthropometric data

The size measures DHM manikins are based on anthropometric databases which enables a number of different models of different percentiles to be used in the same virtual workplace

(Berlin and Adams, 2017) Within a population the variability is such that most designs of work places, e.g. work benches, lifting tools or alike, are only suited to 95% of the population (Dul and Weerdmeester, 2017). This leaves 5% of the users to endure a design that is less than optimum for their bodies. Hence, this group require individual ergonomics measures. Groups of users that from an ergonomic perspective require additional attention are short or tall persons, overweight people, old and young persons, the handicapped and pregnant women (ibid.).

To consider relevant anthropometric measures when designing a workplace is moreover related to social sustainability (Berlin and Adams, 2017). Social sustainability can according to them, be divided into three different categories of concerns; individual, industry and society concerns. Examples of concerns regarding health at work are; for the individual to be provided well-fitted, healthy and understandable work tasks, for industry to design and build workplaces that ensure maximum safety and health, and for society to decrease the level of work-related illness and ill health, avoiding costly economic damage. Ignoring any of these categories may lead to unbalanced workplace solutions (ibid.).

2.4 Risk prevention models

In this sub-chapter two models that can be used for preventing risks are presented, followed by a description of how these are combined and applied in the present study.

2.4.1 Human-Technology-Organization (HTO)

To consider e.g. a work task from a *Human, Technology and Organization* (HTO) perspective is to see how the human, technology and organization interact when risks occur. This means to search for risk sources in the workers' (humans) knowledge regarding a work task, in the equipment (technology) as well as in regulations, instructions and controls (organization). The reason for using the HTO-perspective is that accidents and poor health often occur as the result of a combination of human, technological and organizational factors (Martelius, Bron Säkkon and Östergren, 2016). A human risk factor could be lack of education, a technological factor could be damaged equipment and an organizational factor could be that instructions or control systems are missing. When these factors are aligned additional risks can arise, for example if the equipment is out of order this can generate stress that worsen the effect of a human lacking in education. Since a functioning HTO interplay leads to less poor health there are also economic benefits when prioritizing such interplay; through preventing risks an organization can avoid the drawbacks that accidents bring - which often is proven to be less costly (ibid.).

The HTO-perspective is useful in at least two work environment situations (Martelius, Bron Säkkon and Östergren, 2016). First, it is important when risk assessments are made to identify the relation between humans, technology and the organization. Second, it is essential when conducting investigations of accidents to understand what factors; human, technological and organizational, that caused the accidents (ibid.).

2.4.2 Swiss Cheese Model (SCM)

The Swiss Cheese Model (SCM) was published by Reason in 1997 with the aim of understanding how hazards, defences and potential losses/accidents relate to each other in complex organizational environments. Reason (1997) describes that individual and organizational accidents are different because the organizational accidents are rarer, often have more devastating effects and often affect uninvolved populations, assets and the environment. Presented the other way around, Reason (1997) describes that individual accidents often have specific persons or groups as both the agent and the victim of the accident.

The SCM by Reason (1997) use layers of Swiss cheese (slices of cheese with holes) as a visualisation of the defences organizations use to prevent losses or accidents, see Figure 15.

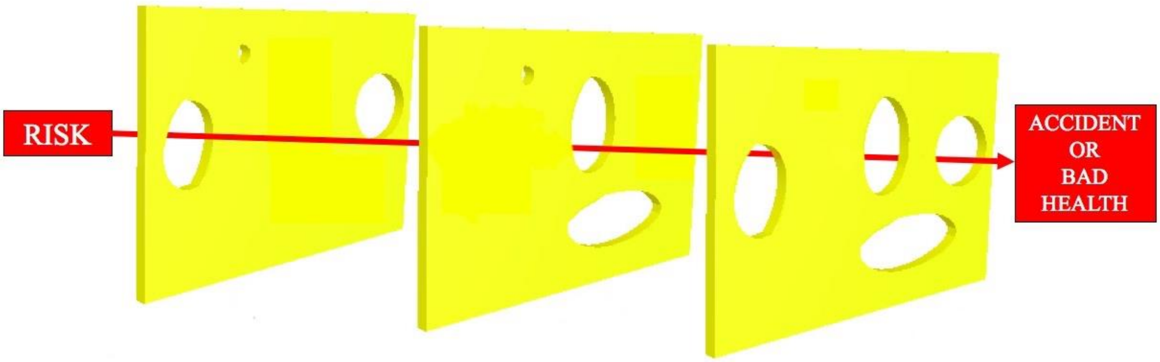

Figure 15 – The Swiss Cheese Model.. Image by E. Ekstrand adapted from Reason (1997)

Reason (1997) states that in an ideal world all these layers would be intact, allowing no penetration by possible accidental trajectories. In reality however, each layer has weaknesses, shown as the holes in the slices of cheese and accidents occur whenever the holes are aligned. In the real world these holes are not fixed and static as in the figure; instead they are in constant flux. Each hole within one layer is shifting around, coming and going, shrinking and expanding in response to e.g. operators' actions or local demands (ibid).

2.4.3 SC/HTO Model

In the present study, a freely modified version of the SCM by Reason (1997), combined with the HTO definitions by Martelius, Bron Säkkon and Östergren (2016), is used as framework for data analysis and presentation, see Figure 16. The model is referred to as the SC/HTO Model and is created by the authors of the present study.

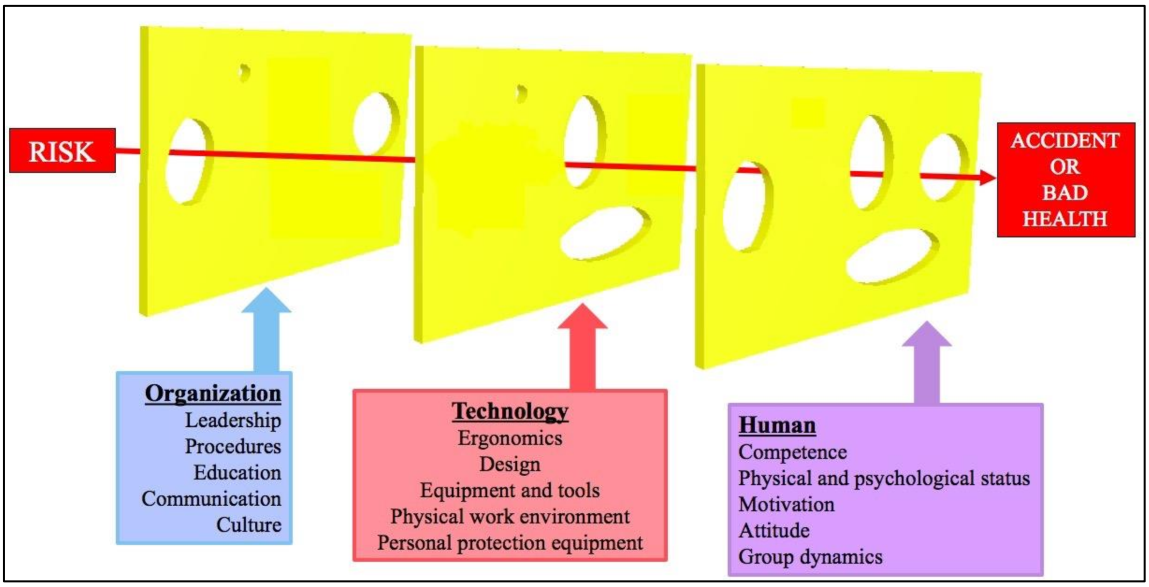

Figure 16 - Illustration of the SC/HTO-Model. Image by E. Ekstrand, based on a combination of the Swiss Cheese Model by Reason (1997) and the HTO-perspective by Martelius, Bron Säkkon and Östergren (2016)

2.5 Theoretical framework summary

- Ergonomics can both serve social goals of well-being and economic goals of performance.
    - at a society level, the costs of work-related MSDs can decrease if ergonomics is used to improve working conditions (Dul and Weerdmeester, 2017)
    - the ability to perform work is dependent on a person's physical health (Berlin and Adams, 2017)
- There is a clear relationship between quality errors and poor fulfilment of ergonomics requirements (Falck, 2009)
- Design engineers do not recognize the consequences of a poorly designed product and work station, due to lack of ergonomic competence and time as the main shortcomings (Broberg, 1997)
- MSDs are the work-related health problem with the highest impact on both sickness absenteeism and permanent incapacity in Europe, where MSDs constitutes 61% of all reported permanent incapacity cases (European Agency for Safety and Health at Work, 2007)
- Healthy hands and wrists are critical for a human being able to work (Berlin and Adams, 2017) and hence indispensable in assembly work
- The hand, wrist and arm form a complex and sensitive structure together that easily gets overloaded during physical work (Berlin and Adams, 2017)
- Joints are particularly sensitive to injuries, or MSDs, caused by physical loading in extreme positions due to their complexity. Injuries to them can take months, even years to heal (Tortora and Grabowski, 2004)
- A broad division within screening tools is biomechanical analysis. These evaluations include biomechanical calculations and take longer time to conduct (Berlin and Adams, 2017)
- The majority of made analyses with DHM-tools are related to reachability and space studies; workload analyses are rarely done (Laitila, 2005)
- To consider relevant anthropometric measures when designing a workplace is moreover related to social sustainability. Social sustainability can be divided into three different categories of concerns; individual, industry and society concerns (Berlin and Adams, 2017)
- To consider e.g. a work task from a *Human, Technology and Organization* (HTO) perspective is to see how the human, technology and organization interact when risks occur (Martelius, Bron Säkkon and Östergren, 2016)
- The Swiss Cheese Model (SCM) describe how hazards, defences and potential losses/accidents relate to each other in complex organizational environments (Reason, 1997)

3. Methodology

The following chapter presents the research method used for the present thesis. First the research approach and the research strategy are introduced along with the methodology for data collection and analysis. Second, the types of data used in the present thesis are presented and linked to theory of how it should be analysed. Lastly ethical considerations are elaborated upon.

Three Research Questions were formulated based on the purpose and aim of the present study. The purpose of the study led to the formulation of RQ1 and RQ2 and the aim of the study led to the formulation of RQ3. An overview of these relations can be seen in **Fel! Hittar inte referenskälla.** below.

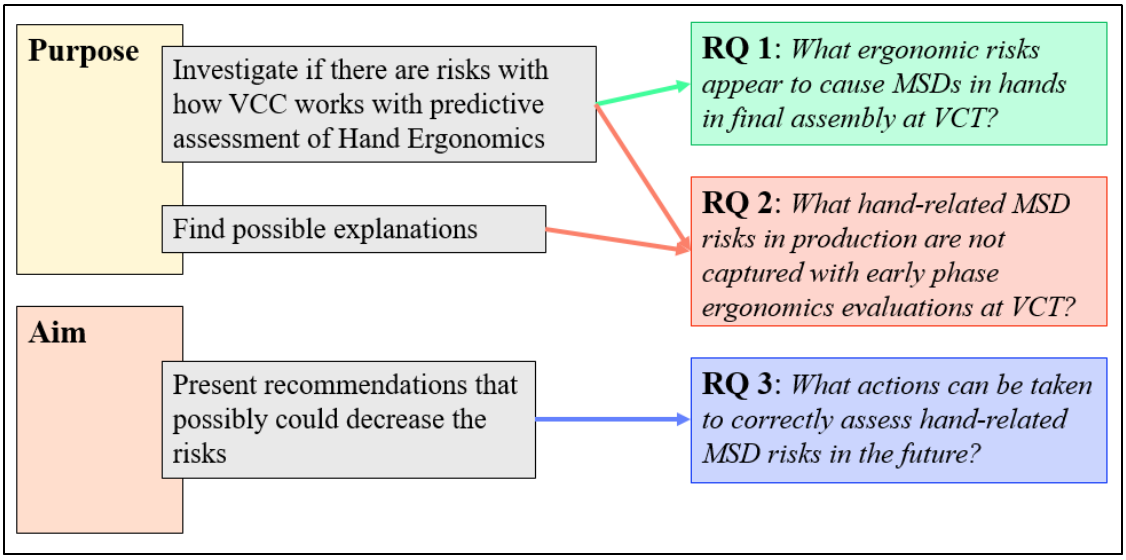

Figure 17 – Relation between the purpose, the aim and the Research Questions

The findings from the investigation of these three Research Questions are presented in Chapter 4 and an analysis/discussion of the results are presented in Chapter 5.

3.1 Research design

According to Patel and Davidson (2011), there are three main research approaches that constitute the relationship between reality and theory. A visualization of these relationships can be seen in Figure 18.

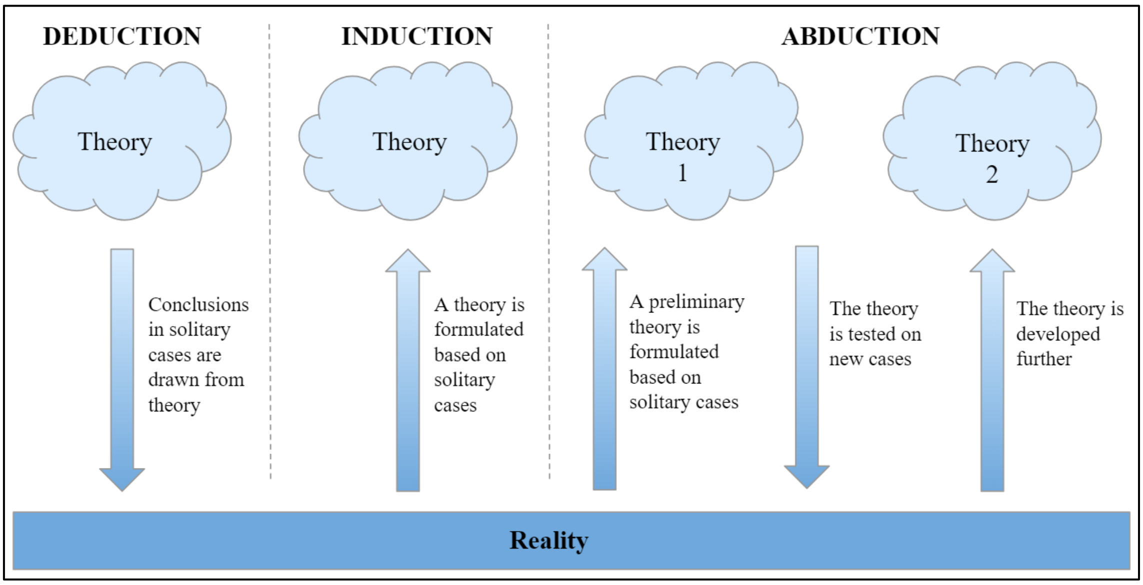

Figure 18 - The relationships between theory and reality. Image by E. Ekstrand adapted from Patel and Davidson (2011)

According to Patel and Davidson (2011), deductive research is when theoretical frameworks are used to draw conclusions in new cases and inductive research is when case studies are used as basis for new theories. Further, abductive research is a combination of inductive and deductive research which makes it possible to combine the strength of both approaches.

In the present study, the abductive approach has been applied by combining theoretical frameworks and empirical data. The issues identified by VCC, in addition to the findings from the injury statistics, gave a preliminary theory of what might had caused the increasing number of MSDs in hands. This theory was then combined with literature and used as a basis for the qualitative data gathering. When all data were gathered, the preliminary theory was adjusted and finalised. Different types of literature were used as support in the different phases, see Sub-chapter 3.2. In Figure 19, a schematic overview of the research process in the present study can be seen.

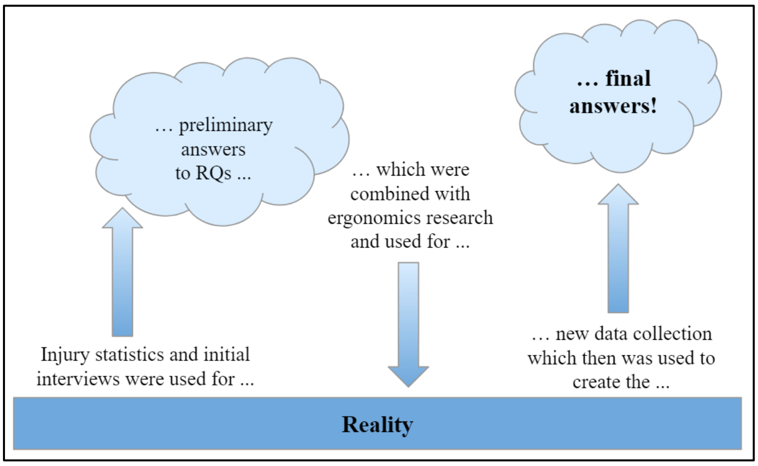

Figure 19 – Schematic overview of the research process

3.1.1 Triangulation strategy

Denscombe (2014) define a research strategy as “a plan of action designed to achieve a specific goal”. Examples of research strategies are Case studies, Experiments, Action research and Mixed methods. Each strategy has different purposes and their applicability depends on the aim of the specific study (ibid.).

In the present study, the Mixed methods strategy has been applied which made it possible to compare different perspectives on the issue of hand-related MSDs in the TC-factory. According to Denscombe (2014), the mixed methods approach is a form of triangulation which facilitates for validation of the data. It also facilitates for obtaining a more comprehensive overview of the studied subject. In addition, since the approach mixes different methods that have different pros and cons it is possible to combine the methods so that the cons are compensated for (Denscombe, 2014; Saunders, Lewis and Thornhill, 2016). However, the mixed methods strategy can lead to increased time consumption and the researchers must also develop skills in both quantitative and qualitative research (Denscombe, 2014).

3.1.2 Research methodology for data collection and analysis

Data can either be collected specifically for a study (primary data) or it can be collected from existing documentation (secondary data). Primary data can be highly time consuming but is often preferred since it can be unclear under which circumstances the secondary data was originally collected (Eriksson and Wiedersheim-Paul, 2008). For instance, some secondary data might be based on other secondary data in several steps which increases the risk of misinterpretations (Denscombe, 2014).

Denscombe (2014) states that different tools can be used to collect data, i.e. questionnaires, interviews, observation and documents. The data is commonly divided into qualitative or quantitative. Examples of qualitative data are interview transcripts, images, videos and company reports while examples of quantitative data are numerical answers from questionnaires, measurements from experiments and official statistics such as injury data (ibid.). The data analysis follows five main stages; (1) Data preparation, (2) Initial exploration of the data, (3) Analysis of the data, (4) Presentation and display of the data and (5) Validation of the data (ibid.), see Table 1. How the data was analysed in the present study is presented in each respective section below.

Table 1 - The five main stages of data analysis (Denscombe, 2014)

	Quantitative data	Qualitative data
1 Data preparation	Coding (which normally takes place before data collection) Categorizing the data Checking the data	Cataloguing the text or visual data Preparation of the data and loading to software (if applicable) Transcribing the text
2 Initial exploration of the data	Look for obvious trends or correlations	Look for obvious recurrent themes or issues Add notes to the data. Write memos to capture ideas
3 Analysis of the data	Use of statistical tests (e.g. descriptive statistics, factor analysis, cluster analysis) Link to research questions or hypotheses	Code the data Group the codes into categories or themes Comparison of categories and themes Look for concepts (or fewer, more abstract categories) that encapsulate the categories
4 Presentation and display of the data	Tables Figures Written interpretations of the statistical findings	Written interpretations of the findings Illustration of points by quotes and pictures Use of visual models, figures and tables
5 Validation of the data	External benchmarks, internal consistency Comparison with alternative explanations	Data and method triangulation Member validation Comparison with alternative explanations

3.1.3 Validity and Reliability of data

Denscombe (2014) describes how validity and reliability can be defined in research projects. For quantitative research, data validity (internal validity) can be defined as “the accuracy and precision of the data” and also “the appropriateness of the data in terms of the research questions being investigated”. External validity refers to the generalization of the findings from research, meaning whether or not the findings can be applied to other cases than the specific cases used for the research in question. Reliability of the method/instrument used to collect the data can be defined as “whether a research instrument is neutral in its effect and consistent across multiple occasions of its use” or simply if the instrument measures consistently every time with all other variables held constant (ibid.).

For qualitative research, it is more complex to define validity and reliability since all data is interpreted by the author or authors. Denscombe (2014) suggest that the best way of solving this is by convincing the readers that it is "reasonably likely" that the data are valid, which can be achieved by following the three steps:

- Respondent validation: Having the respondents confirm the findings
- Grounded data: The authors spend time "on location" to collect empirical data
- Triangulation: To use contrasting data sources

Further, the best way of declaring the level of reliability is to be as transparent as possible when describing how the data was analysed and how the conclusions were drawn from the data. This is because it gives the readers the opportunity of deciding for themselves if they would have drawn the same conclusions (ibid.).

How validity and reliability of quantitative and qualitative data have been considered in the present study is included in the respective sub-chapters below and is discussed in Chapter 5.

3.2 Literature study

The literature study was conducted with three main aims. The first aim was to map the current state of research related to hand ergonomics to ensure that the present study would contribute with new findings. The second aim was to establish a theoretical framework, which according to Bryman and Bell (2011) is the foundation upon which the research approach is based. The third and final aim was to aid the answering of the research questions. A schematic overview of how literature has been utilized can be seen in Figure 20.

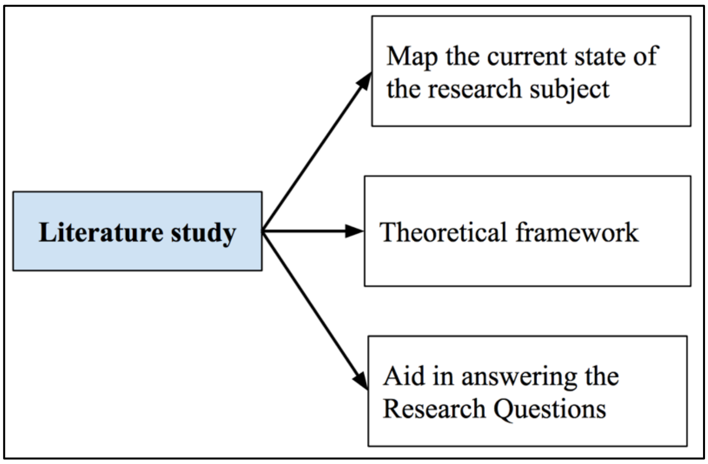

Figure 20 - Schematic overview of how literature has been utilized

In the present study, bibliographic databases such as Scopus, ScienceDirect, Summon Chalmers Library and Google Scholar were used to find published research papers. Search words included: *Ergonomics, Screening, Risk Assessment, Musculoskeletal disorders, Exoskeletons, Automotive, Manufacturing, Manual Assembly, Final assembly, Hands, Wrists, Fingers and Simulation.* Physical libraries were used to find scientific books and printed research theses.

The literature was prioritized based on publication date, number of citations and relevancy in a manual assembly context. For instance, research conducted in a blue collar context was prioritized over a white collar context. In addition, only peer-reviewed research papers were deemed as valid in the literature study.

Due to the abductive research approach in the present study, the literature study was conducted in parallel with the data collection and data analysis as the research narrowed down to a more detailed level.

3.3 Quantitative data

The quantitative data used in the present study was collected from an Excel-copy of Volvo Cars' TIA-system, which is a system used to document injuries in the factories. The TIA-system contains a number of predetermined headings that are to be filled in when an injury is reported. It is the production leaders' responsibility to update the TIA-system so that other stakeholders can follow up on the statistics. The data is anonymized but very detailed which makes it possible to track specific injuries to specific parts of the factory. The used data concerned only operators from the TC-factory, and was taken from the following columns in TIA: date of report, work unit, sex, age, injured body part, event heading, event description, perceived cause of injury by operator and investigation description. All quantitative data used in the present study were secondary data since it was not collected from the operators specifically for the present study.

Due to the launch of a new car model in 2015, many changes in assembly operations came as a result of the new product design. In order to perform a relevant analysis that represented the most recent causes and relations between injuries reported in the TC-factory, only statistics from 2016 and 2017 were used. In addition, more emphasis has been put on percentages rather than absolute numbers since it was indicated by Volvo Cars that there are missing injuries in the statistics.

Three types of software have been used to analyse the data; SAS JMP Pro, IBM SPSS Statistics and Microsoft Excel. JMP Pro was used to create a preliminary overview of the problem with hand ergonomics which then was used to create the interview guide. SPSS Statistics was used to calculate injuries per sex, injuries per work unit, ANOVA and cross-tabulations. Microsoft Excel was used for sorting and filtering the data in the first step of the analysis. Data from the years 2016 and 2017 was gathered in one file which then was analysed and coded so that specific injuries could be identified by the filters in Excel. This made it possible to remove all data not concerning hand-related MSDs, which in turn made it possible filter injuries per work unit.

All reported injuries in the TIA-system included four columns with descriptive text that described possible causes of the injury. These were read and analysed in order to receive quantitative frequencies. A description of the four columns can be seen in Table 2. Causes of each MSD in hands were identified in the text columns and linked to a cause-category, i.e. the asserted cause of the injury. The identified numbers in each cause-category were added together and compared to the total number of hand-related MSDs to obtain percentages of different causes to MSDs in hands.

Table 2 - Descriptions of the columns used for cause analysis of hand-related MSDs

Column in TIA	Description
Event heading	The title of the reported injury
Event description	What had led up to the injury. It is stated what events that took place before the injury and which work tasks that caused the most pain
Perceived cause of injury by operator	The operators' own theory of obtaining the injury
Investigation description	To find out the root cause, three questions in the following format were asked: "What was the cause of the incident?" Answer: "A" "What was the cause of A?" Answer: "B" "What was the cause of B?" Answer: "C"

3.4 Qualitative data

The qualitative data was collected from interviews with stakeholders, observations from the shop floor in the TC-factory and documents provided by VCC. The data gathered from the interviews and the observations was primary data and the data gathered from documents was secondary data (Eriksson and Wiedersheim-Paul, 2008).

3.4.1 Documents

Several types of documents have been used as qualitative data in the present study. The present study was initiated by a problem description written by the present study's company supervisor Dan Lämkull, who was responsible for the Global Ergonomics Strategy at VCC. In the planning phase of the present study, additional information was provided in the form of PowerPoint presentations. During the entire duration of the present study, additional qualitative data was provided by Dan Lämkull in the form of informal meetings and emails. However, the only document analysed and presented in the result chapter is a PowerPoint with identified ergonomics issues.

3.4.2 Shop floor observations

Denscombe (2014) divides observation studies into unstructured and structured observations. While the unstructured observation study tries to capture the normal state of tasks and behaviour in general and without disrupting, the structured observation study involves disruption and aims to capture an understanding of specific tasks. The structured approach means that the observed participant is asked to do specific tasks that are considered relevant in a specific study. These two approaches both have disadvantages; unstructured observations give limited possibility to ask for explanations and structured observations require much more knowledge from the observer that chooses relevant tasks (ibid.).

In the present study, the shop floor observations were preceded by analysis of documents and injury statistics provided by VCT, which made it possible to visit specific stations in the TC-factory that were reported to have the highest number of MSDs in hands. At the stations, the operators were informed about the purpose of the present study and also asked to work as close to normal as possible while describing what they felt was most awkward with the assembly at the specific station. Some work postures that were deemed as bad from an ergonomic point of view were captured with a camera and then used as part of the qualitative data analysis. This approach was very similar to what Denscombe (2014) state to be structured observation studies. The observation was structured in the sense that only stations with many injuries in hands were visited but it was unstructured in the sense that no questions were prepared beforehand which made every interview different from the other.

3.4.3 Interviews

In the present study, 12 interviews were conducted as part of the qualitative data collection. The interviewees were selected based on a stakeholder analysis, see Appendix C. An overview of the interviewees can be seen in Table 3.

Table 3 - Overview of the interviewees

Stakeholder Department	**Number of interviewees**
Global Strategy and Process Development in Ergonomics	1
Core Manufacturing Engineer in Ergonomics	1
Interior engineering	2
Electrical engineering	1
Manufacturing engineering	2
Industrial engineering	1
Occupational health service, ergonomists	2
Health and Safety	1
FCC- Fraunhofer Chalmers research Centre	2 (one occasion)
Operators	3 (unstructured interviews during the shop floor observations)

The operators were only interviewed informally during the shop floor observations due to that the operators could not be disturbed more than necessary. The interview with FCC was held based on a slimmed down version of the interview guide that focused on future possibilities with simulation software.

The concept of stakeholders has different definitions throughout literature (Bryson, 2004) but the general idea is to identify “any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 2010). The stakeholder analysis was based on a method developed by Berlin, Berglund and Lindskog (2016) in which the stakeholders are classified depending on the type of influence they might have on the present study. From the stakeholder analysis and the abductive research approach, a semi-structured interview guide was developed, see Appendix A. In a semi-structured interview, most questions are decided beforehand but both the interviewer and the interviewees are allowed to bring up additional subjects (Denscombe, 2014).

The interviews were first recorded, then transcribed into text and then thematised/coded. Saldaña (2011) state that there are different kinds of codes which can be used for different purposes. Grounded codes can be used to find completely new themes without any preconceptions, A priori codes can be used to find subjects that are presupposed as interesting and Analytical codes can be used to find interactions, connections and meanings in the text (ibid.). In the present study, the interviews were coded a priori which means that observations presupposed as interesting emerge into patterns which then emerge into theory. Further, all interviews were held in Swedish which meant that the quotes presented in section 3.4.3 had to be translated to English. These translations were done by both authors in order to minimize the risk of compromising the content.

3.5 Ethical considerations

Ethical aspects are imperative to consider when performing a study. Within research ethics there are several principles that should be considered such as respecting dignity of all participants, protecting privacy, ensuring that no harm is done to the participants and making sure that the confidentiality is not compromised (Easterby-Smith, Thorpe and Jackson, 2015).

In the present study these ethical aspects concerned primarily to protect privacy and to ensure confidentiality of the interviewees. These aspects have been respected by explaining, both in the invitation and before start of each interview, that the person in question could decide to what extent she/he wanted to be anonymous. The aim of recording the interviews was declared to all participants and were only done so with consent. In order to protect the privacy of all participants only the name of the participants' department was included in the present study. The interview recordings and transcripts have been carefully handled only by the authors of the present study. After the termination of this project all collected data will be deleted to fulfil the confidentiality aspect. The data from the TIA-system will be handled accordingly. No data used from the TIA-system can be related to any individual working in final assembly at VCT. Regarding photos taken from the shop floor observations all identification possibilities has been removed and pictures were only taken with consent.

Lastly, the authors of the present study are given an honorarium after the completion of the project and have at the best of their ability tried to be objective towards all information given, as during the discussion of found results. The results of the present study are not influenced towards any preconceived direction with regards to this payment.

4. Results

In this chapter the results of the present study are presented. First, tables of all findings are given. Then, the findings are presented in three sub-chapters based on the Research Question the findings relate to.

The present study was initiated with the aim of answering three Research Questions. An overview of the three questions can be seen in Table 4.

Table 4 - Overview of Research Questions

Research Questions
RQ1: What ergonomic risks appear to cause MSDs in hands in final assembly at VCT?
RQ2: What hand-related MSD risks in production are not captured with early phase ergonomics evaluations at VCT?
RQ3: What actions can be taken to correctly assess hand-related MSD risks in the future?

The findings from the data analysis are presented in separate sub-chapters depending on which Research Question the result from the analysis related to. A summary of the findings can be seen in Table 5, Table 6 and Table 7 below.

Table 5 - Overview of findings related to RQ1

Finding - RQ1	**Source of finding**
● High pressure forces caused by bad clips, lack of assembly response and stiff components (66 % of all MSDs in hands)	**Quantitative:** Injury statistics **Qualitative:** Interviews, Documents and Shop Floor Observations
● High torque is the second most common cause (10 % of all MSDs in hands)	**Quantitative:** Injury statistics **Qualitative:** Documents
● Many bad working postures	**Qualitative:** Documents and Shop Floor Observations
● Female operators are affected more than males by bad hand ergonomics	**Quantitative:** Injury statistics
● MSDs in hands constitute half of all injuries in TC	**Quantitative:** Injury statistics
● MSDs in hands is a problem in a majority of all work units	**Quantitative:** Injury statistics
● No relation between age and hand-related MSDs	**Quantitative:** Injury statistics
● Repetitive tasks	**Qualitative:** Interviews

Table 6 - Overview of findings related to RQ2

Finding - RQ2	**Source of finding**
• It is not possible to simulate pressure forces	**Qualitative:** Interviews
• The ergonomics standard is nonspecific	**Qualitative:** Interviews
• Physical builds with the wrong material, making it hard to evaluate forces	**Qualitative:** Interviews
• Screening tools are seldom used	**Qualitative:** Interviews

Table 7 - Overview of findings related to RQ3

Finding - RQ3	**Source of finding**
• Emerging technology	**Qualitative:** Interviews **Literature review**
• Education in ergonomics	**Qualitative:** Interviews
• Improved and updated databases	**Qualitative:** Interviews
• New simulation software for simulation of pressure forces	**Qualitative:** Interviews
• Shared responsibility across departments for ergonomics (DFA)	**Qualitative:** Interviews
• The TIA-system	**Qualitative:** Interviews
• Knowledge transfer	**Qualitative:** Interviews

4.1 Findings related to RQ1

The first research question was formulated to investigate the present state of the TC-factory from an ergonomics point of view. It was formulated as “What ergonomic risks appear to cause MSDs in hands in final assembly at VCT? “. The qualitative results and the quantitative results are presented in two sections below.

4.1.1 RQ1: Qualitative data analysis

This section includes the qualitative results regarding RQ1. These results are based on interviews, document analysis and shop floor observations.

4.1.1.1 RQ1: Interviews

The themes found from interviews that related to RQ1 are presented below and an overview of the themes can be seen in Figure 21.

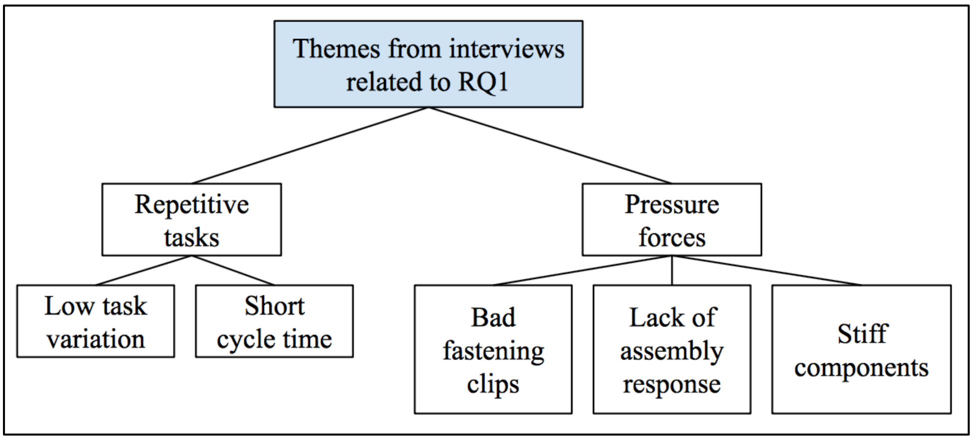

Figure 21 - Overview of themes related to RQ1

<u>Repetitive tasks</u>

The first theme from the thematising was related to the set-up of the production system. The tasks in the TC-factory have low variation and should be finished and repeated 60 times per hour. The two sub-themes are presented below.

Low task variation from the introduction of scalable platforms

Four of the interviewees all stated that the task variation has decreased since the introduction of new car models that are all built upon the same scalable platform (SPA) because the cars are all built the same way. This is in contrast to earlier car models that were less similar to each other. The old way of having different solutions on different car models made the production system less sensitive to bad solutions from an assembly point of view.

One interviewee stated: *“...we have tried to standardise the cars and reuse product solutions… which have resulted in that all cars have the same problems”.*

Another interviewee stated: *"Now everything is very similar, whether you get a door on the XC60 or the XC90 they more or less look the same, it is exactly the same muscular groups and such that you use…".*

Short cycle time with 60 cars per hour

Two of the interviewees agreed that the time available for one set of assembly tasks, the cycle time, has decreased with the increased takt in the production system, which has increased the repetitiveness. According to one interviewee this is an effect of the increased number of workstations. With more stations, the number of operations performed in each cycle has decreased.

One interviewee stated: *"with 60 cars per hour, people will most likely get injured… but we would reduce that by having lines that could unburden the hands and the arms… we do not have that anymore".*

High pressure forces in the manual tasks

The second theme from the thematising was related to the high pressure forces required to fasten the components. Three sub-themes emerged which are presented below.

Bad fastening clips that require high pressure forces

All eleven interviewees at VCC mentioned the fastening clips as one possible explanation of why the operators get MSDs in their hands. Further, the interviewees claimed that the pressure forces have increased dramatically from the change from plastic to metal clips. In addition, two of the interviewees stated that the increased use of electronics and batteries leads to both more and thicker cables which in turn have increased the required pressure forces to fasten the clips.

One interviewee stated: *"At the places where I have been in the TC-plant it has been a lot of hands (injuries) because there are many panels, many clips and such that requires pressure forces…"*

Lack of assembly response from clips

Two of the interviewees stated that the clips used for fastening of for instance panels and cables are required to give the operator some form of feedback/response when the clips are mounted correctly. Further, the interviewees state that a common issue is that the operators press too hard when they do not perceive the response from the clips.

One interviewee stated: *"...but if you do not get any feedback, then you press too hard due to the will of doing good".*

Stiff parts with narrow tolerances

Two of the interviewees stated that VCC's ambition to move further towards what is known as the premium-segment of the car market has led to new demands on robustness, vibrations

and stiffness. Related to MSDs in hands this becomes a problem with the interior panels which are much more rigid and therefore tougher to assemble to the car.
One interviewee stated: *"every detail is really a bit stiffer, a bit harder. And that means more problems for the operators"*.

4.1.1.2 RQ1: Document Analysis

A number of stakeholders responsible for improving and sustaining the ergonomics in the VCC TC-plant had written a PowerPoint presentation with the main identified ergonomic issues in early 2018. This presentation was analysed by the authors of the present study with focus on bad hand ergonomics. The result of this analysis is presented below along with pictures from the PowerPoint and sorted based on the identified ergonomics issue.

High pressure forces
It was identified that many components on the SPA-cars were designed so that the pressure force needed to assemble the components were considerably above the accepted limits stated in the Volvo Cars Standard (VCS) 8003,29. For example, the door panels were measured to require at least 300 N from the operator to be fastened, which highly exceeds the 50 N that is stated to be the limit for pressure force with one hand in the VCS 8003,29.

The reasons for high pressure forces were several. On some components it was the result of clips being aligned in different directions on the same component, making it hard to fasten into end position, see Figure 22.

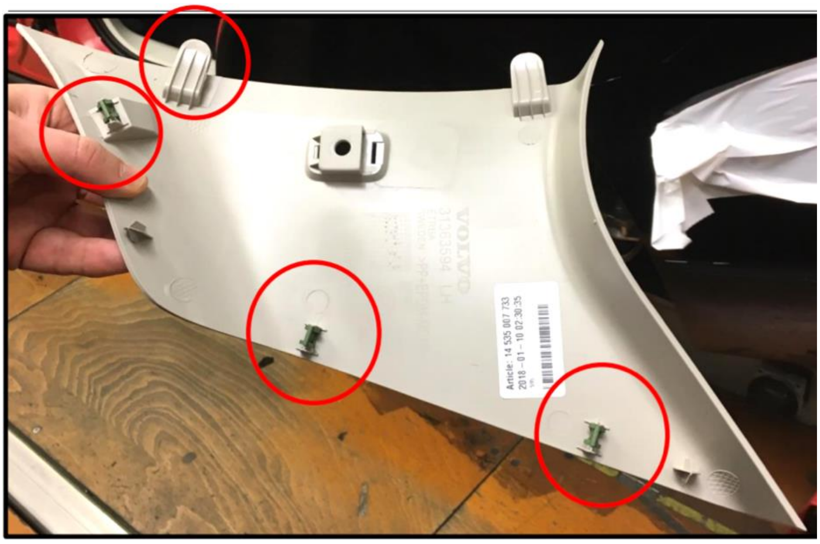

Figure 22 - Upper D-panel on car model XC60, clips are aligned in different directions which increases the pressure force needed to fasten the panel. Photo used with permission from Volvo Car Corporation.

On other components, the high pressure force was the result of misaligned holes where clips and guiding pins were to be entered. This misalignment forced the operators to press very hard (200 N - 500 N) in order to fasten the component. In some cases the guiding pins were destroyed, as in the case with a the sill moulding, see Figure 23.

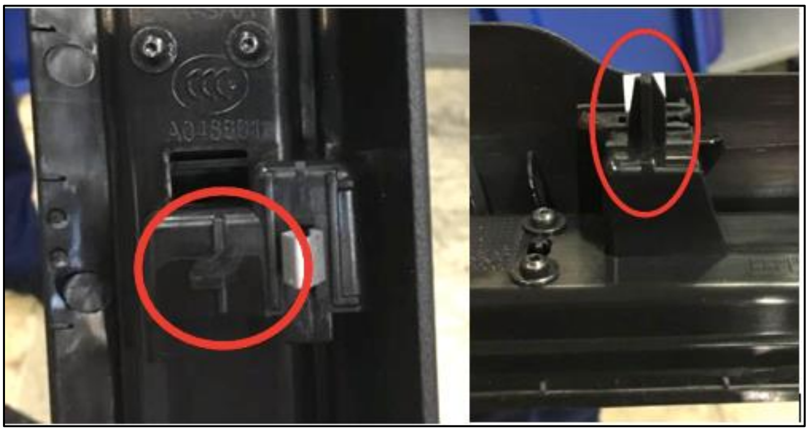

Figure 23 - On sill mouldings the guiding pins are destroyed during assembly. To the left; guiding pin and metal clip shown from above. To the right; guiding pin shown from the side Photo used with permission from Volvo Car Corporation.

A third reason for high pressure forces were stiff cable harnesses that either were to be assembled with clips or pulled through narrow holes causing the cables to frequently get stuck. The stiffness of the cables in the floor harness causes fatigue in wrists but also the numerous amount of clips that are to be fasten per harness causes a substantial workload on hands and wrists, see Figure 24.

Figure 24 - To the right; A tailgate harness is being entered in a narrow hole, carried out in a red working zone, too high up. To the right; a floor harness placed in the middle of the car floor before assembly is carried out. Photo used with permission from Volvo Car Corporation.

Heavy equipment in bad postures

On one of the identified stations, it was found that the operators had to use a heavy screwdriver in what was called “bad working height” causing physical work load on wrists, see Figure 25.

Figure 25 - Fastening of antenna amplifier with a heavy screwdriver in an awkward posture and in red zone. Photo used with permission from Volvo Car Corporation.

The aspect of bad assembly height was identified on several stations. Several of the work sequences include work in a red zone, meaning that the work distance is too far away so that the operator has reaching issues to perform the work task or that the distance is too high up so that the work tasks are performed with hands above shoulder height.

4.1.1.3 RQ1: Shop floor observations

The TC-factory was visited by the authors at two times, once with an ergonomist from the external occupational health service and once with an industrial engineer responsible for ergonomics issues in the factory. Photos were taken with consent of the involved operators. Instead of visiting all stations, stations that had been identified as bad from a hand ergonomics point of view were prioritized. This was done both by using the result from the quantitative study and the results from the document analysis.

High forces with hand in extended posture

Berlin and Adams (2017) state that the human hand differs in strength depending on the different angles of flexion/extension that is possible to achieve by the wrist. The hand has maximum strength when held with zero degrees angle towards the wrists. At VCT, several tasks that required high forces also required the hand to be highly extended, see Figure 26 below. Two of the operations shown include fastening of panels with clips and one operation include pressing a window with high forces into a door.

Figure 26- Wrists in extended postures at three workstations. Photo used with permission from Volvo Car Corporation

Hook grip to position heavy battery away from body

When the operators are to position the battery, which weighs 4,5 kg (44 N), the operator must do so with the posture seen in Figure 27. The weight is much heavier than what is accepted in the VCC standard. In the VCS standard 8003,29 issue 5 it is stated that an overhand grip is allowed to carry a maximum of 0,5 kg (5 N). In this case the grip force is almost nine times higher than what is accepted in the VCS standard. One of the authors to the present study tested this work task during the second shop floor observation and could confirm a discomforting strain in the hand and wrist.

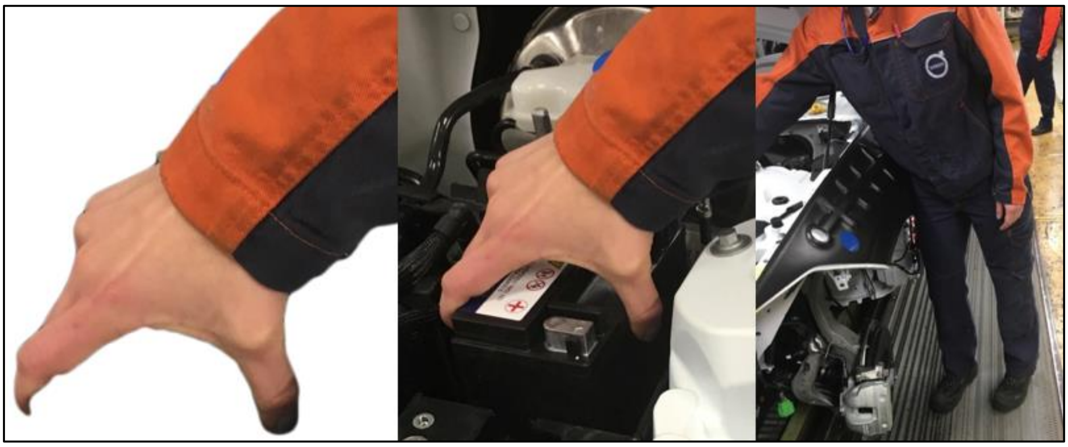

Figure 27 - Positioning of the battery with hook grip, abducted arm and bent back. Photo used with permission from Volvo Car Corporation

Pulling of grommet close to sharp edge

The doors are mounted on fixtures where the operation of pulling a grommet through a narrow hole is performed. This work task can be done without space issues on some fixtures but on several fixtures, there is a sharp edge close to where the operator's hand is positioned to pull out the grommet from its hole. In addition, the required force for this pulling action was measured to be over 100 N which makes it hard to avoid the sharp edge, see Figure 28. The result, according to the industrial engineer guiding the authors during the second shop floor observation, is that many operators have scratch marks and bruises on the side of the hand that gets hit by the fixture during this operation. One of the authors to the present study tried to perform this work task and could confirm that the high pressure force combined with trying to not get hit by the fixture was impracticable.

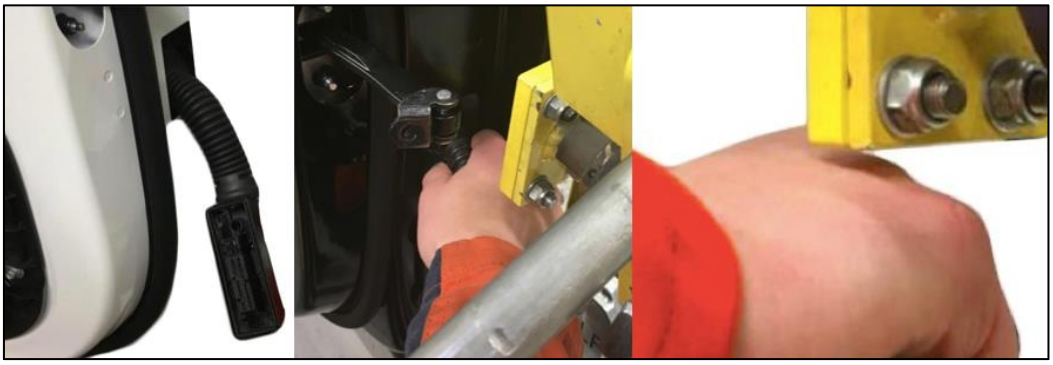

Figure 28 - Pulling of grommet with much force close to sharp edge. Photo used with permission from Volvo Car Corporation

High pressure forces on A-panels and B-panels

On the A-pillars and the B-pillars the operators fasten interior panels. Due to the narrow space inside the car, this is done from outside the car. In addition to the operators limited visibility during this work task, it was observed that the panels often are hard to fasten due to the design and the positioning of the clips, see Figure 29. The clips are aligned in different directions which makes it impracticable to fit the panel smoothly due to the high pressure force needed.

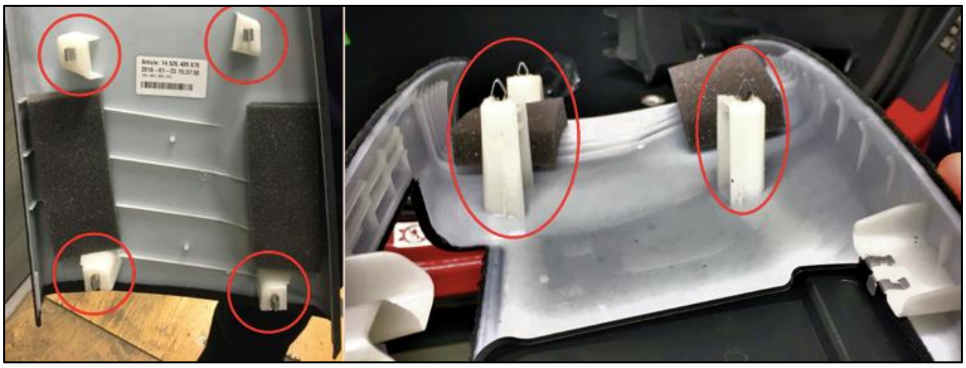

Figure 29 - Clips aligned in different directions on B-panels. To the left; lower panel, and to the right; upper panel. Photo used with permission from Volvo Car Corporation

In Figure 30, it can be seen that the operator was struggling to fasten the A-panel. In order to exert the required force to fasten it, the operator was swinging backwards while holding firmly onto the panel. This work procedure exposes the operators' hands and wrists to high periodic loads. The operator was also required to step into the car due to the high working height. It was identified, from talking to several operators at the workstation, that there was a footstool available to use in situations of reaching issues but that no one used it. The main reasons for that was perceived lack of time to go and fetch the footstool but also that it did not provide enough stability for the operator to be able to exert the force needed to fasten the A-panel. In general, the observed operator was dissatisfied with the work task procedure of the station and ranked it as one of the toughest to work at.

Figure 30 - Fastening of A-panel by swinging the body backwards. Photo used with permission from Volvo Car Corporation

In Figure 31, it can be seen that the operators are using high pressure force to fasten the B-panels. There are two B-panels, one upper and one lower panel. The lower panel is fastened by first pressing it down into a spacing in the floor carpet. Then it is pressed towards the B-pillar to engage the clips on the inside of the panel. The observed operator explained that the carpet sometimes was placed slightly off i.e. not aligned with the area in the car body where the lower panel is first entered. On some car models the carpet is thick and if the carpet is not correctly placed on those models it forces the operator to press extra hard to fit the lower B-panel into place.

The first step when fastening the upper B-panel is to enter two guiding pins into the roof. Then the whole panel is pressed firmly onto the B-pillar. When observing the operators perform this work task the authors noticed the difficulty they had to enter the guiding pins due to non-existent visibility. If the operators wanted to see where to enter the pins they had to lean into the car. When talking to an operator performing this assembly it was stated that it requires a considerable amount of technique to correctly fasten the panel. Sometimes when operators press the panel onto the pillar the metal clips get bent due to not being exactly aligned to their position on the pillar. It was stated to be difficult to know if the clips were correctly engaged due to lack of assembly response. This also caused the operators to exert more force than necessary in order to make sure the panel was fastened.

Figure 31 - Fastening of upper (left picture) and lower (middle and right picture) B-panel. Photo used with permission from Volvo Car Corporation

High pinch and pressure forces from wire harnesses

At the stations where the floor wire harness and the engine bay wire harness are assembled it was observed that the cable harnesses were cumbersome to handle for the operators. The harnesses' centres of gravity are irregular and it is not obvious how to carry them. The main issue observed was multiple clips and contacts to fasten, where precision and force exertions are combined, along with stiffness of cables, see Figure 32.

What was identified to be an issue with the floor harness was the torque force needed to bend the cables and fasten the clips. At the beginning it was easier but towards the end of the assembly the stiffness of the cable harness increased as it was fastened to the floor. The more clips fastened, the harder it got to bend the last part of the cable into place and fasten the remaining clips. The fingers have to endure extensive load due to these force-exerting pinching grips.

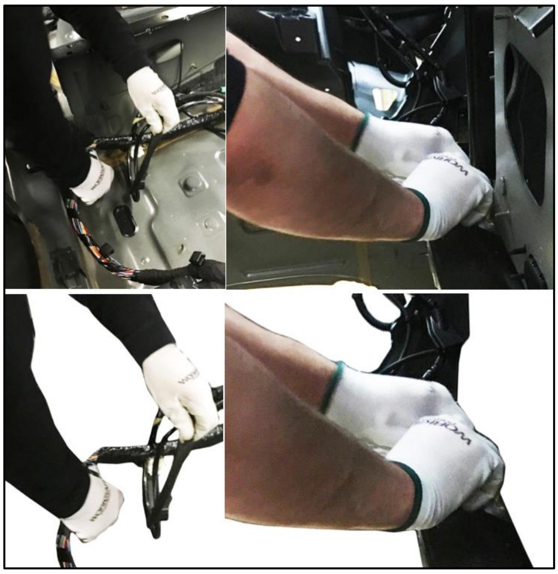

Figure 32 - Fastening of wire harness in the floor and the engine bay. Photo used with permission from Volvo Car Corporation

Both the ergonomist and the industrial engineer explained during the shop floor observations that previously the floor harness was not preheated and thus extremely stiff and hard to bend, which resulted in many hand injuries among the operators. This led to the purchase of an oven, see Figure 33. The oven is used to preheat the floor wire harness up to 65°C, which makes it easier to bend and fasten. The engine bay wire harness is not preheated before assembly since its cable thickness is not as great as the floor wire harnesses. However, the ergonomists opinion was that it needed preheating as well, due to its stiffness.

One last observation regarding the engine bay wire harness was the lack of space to put it during assembly; the operator must hold it or try to press it to the engine bay frame with the body while fastening the numerous contact and clips.

Figure 33 - Oven used for heating of wire harness. Photo used with permission from Volvo Car Corporation

4.1.2 RQ1: Quantitative data analysis

In this section, the results from the analysis is divided into two sub-sections; Descriptive statistics and Cause analysis.

4.1.2.1 RQ1: Descriptive statistics

To create an overview of the issue of MSDs in the TC-factory a number of descriptive analyses were performed. These were complemented by ANOVA (Analysis of Variance) in cases where the descriptive results indicated that deeper analysis was needed. It was not possible to collect descriptive statistics of the operators that were not injured, instead different factors within the injury statistics were analysed. The findings are divided into two sub-sections presented below.

Hand-related MSDs are a problem in the majority of all work units

322 operators were reported as injured from the TC-factory during 2016 and 2017. 155 out of these reports involved MSDs in the hands, wrists or fingers (48 %). These MSDs were spread across 30 out of the 34 work units with injuries, see Figure 34.

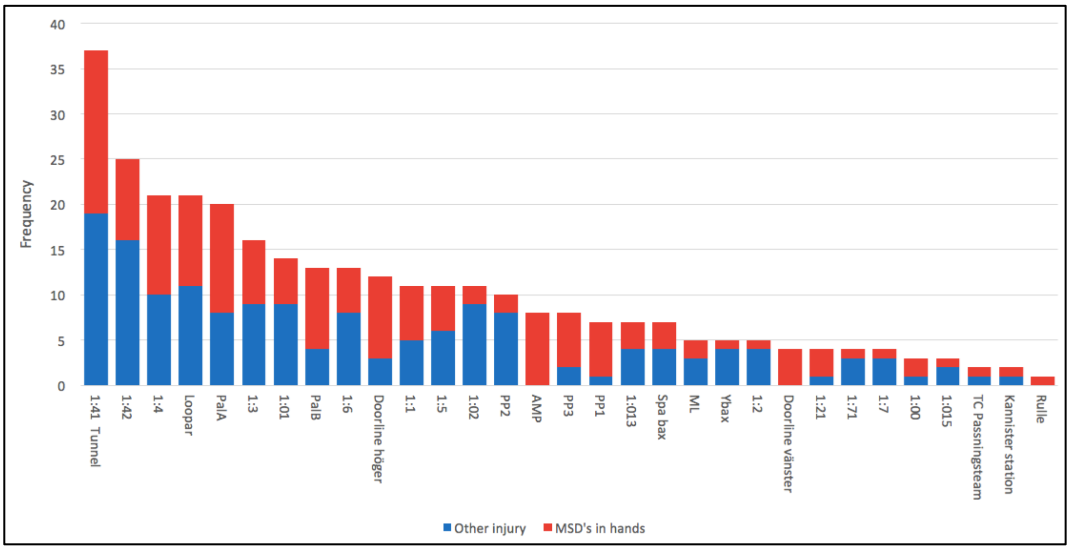

Figure 34 - Comparison of hand-related MSDs as part of all injuries

Female operators are affected more than male operators by bad hand ergonomics

It was found from analysing all injuries in the TC-factory that 50 % of the injured operators were men, 48 % were women and 2 % were of unknown sex. When only considering hand injuries (MSDs) it was found that 42 % of the injured operators were men, 57 % were women and 1 % were of unknown sex, see Table 8 and Table 9.

A one-way independent ANOVA showed a significant difference in Hand injuries between Men (M = .41, SD = .493) and Women (M = .57, SD = .496), $F(1, 312) = 8.75$, $p = .003$. Operators with unknown sex (N = 8) were excluded from the ANOVA due to the sample size. The calculation was done to compare the groups men and women with either injury in hands or other injury.

Table 8 - Descriptive statistics of injuries reported in the TIA-system

Number of injuries	**Males with injuries***	**Females with injuries***	**Number of hand injuries**	**Males with hand injuries***	**Females with hand injuries***
322	50 %	48 %	155	42 %	57 %

Table 9 - Cross-tabulation of Sex and Injury type

		Injury involved hands		
		No	**Yes**	**Total**
Sex	**Male**	59 %	41 %	160
	Female	43 %	57 %	154
	Unknown	75 %	25 %	8
	Total	167	155	322

No relation between age and MSDs in hands

The age of all injured operators ranged from 18-65 years (M = 31.5, SD = 9.6) and the age of operators with hand injuries ranged from 18-65 years (M = 31.0, SD = 9.4). In Figure 35, it can be seen that both normal distributions are positively skewed. It was indicated by VCC that the operators working in the TC-plant are relatively young but this could not be confirmed by the HR-department. No significant difference was found from calculations. The calculation was done to compare the age groups with either injury in hands or other injury.

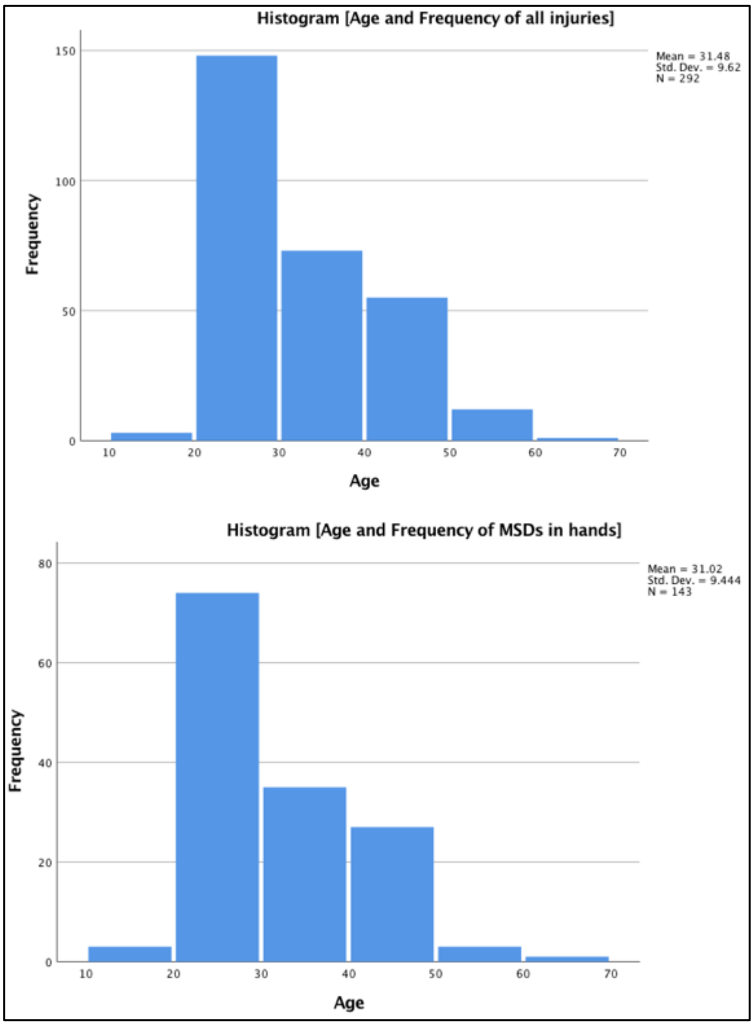

Figure 35 - Histogram comparison of the age of all injured operators (top) and the age of the operators with injured hands/wrists (bottom)

4.1.2.2 RQ1: Cause analysis

For every reported injury in the TIA-system, a cause analysis was included in the form of a descriptive text. Based on these descriptive columns a number of cause categories and their frequencies were identified. The result was that 66 % of the hand injuries were presumably caused by high pressure forces, see Figure 36. The second largest assumed cause of hand-related MSDs in hands at 10% were the recoil from hand held machines due to their torque. The other cause categories constituted 24 % together.

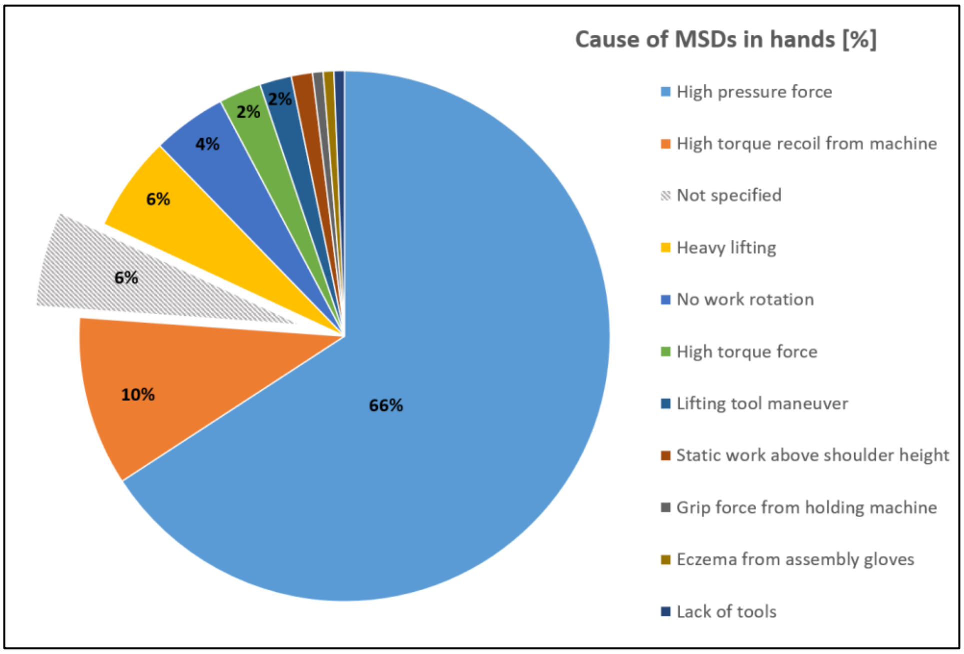

Figure 36 - Cause analysis of MSDs in the TC-factory

In Figure 37, the MSDs caused by high pressure forces are plotted per work unit and it can be seen that they are spread across 25 out of 34 work units.

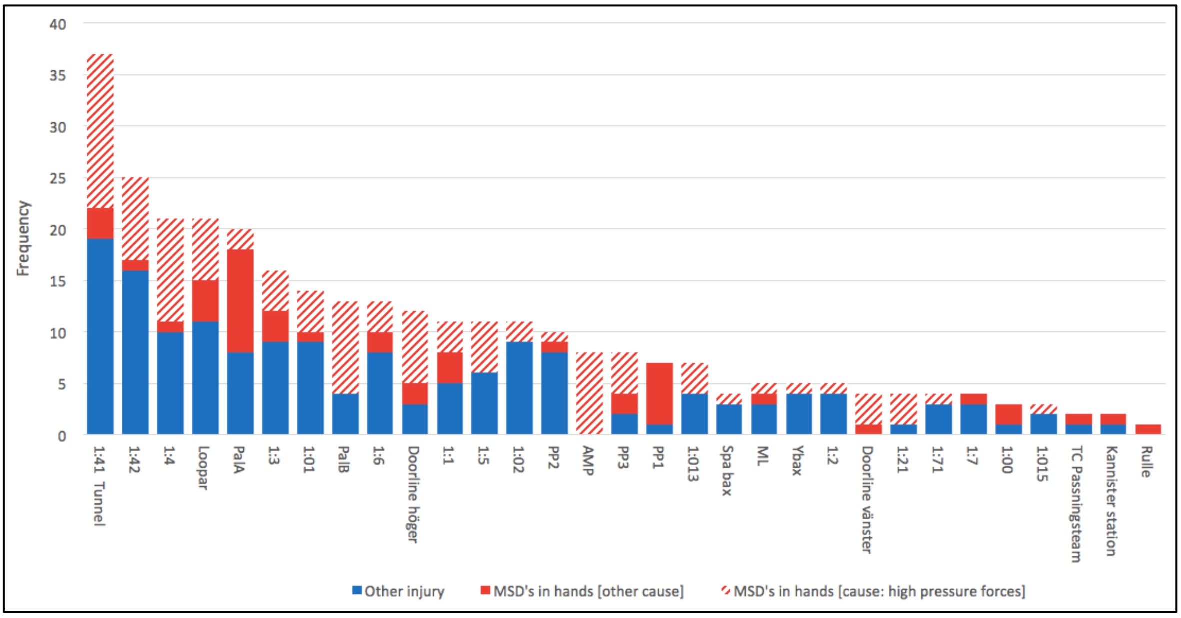

Figure 37 – Hand-related MSDs caused by high pressure forces per work unit

4.2 Findings related to RQ2

The second research question was formulated to investigate the ergonomics evaluations conducted in early phases of product- and production development at VCT. Specifically, the aim was to capture "What hand-related MSD risks in production are not captured with early phase ergonomics evaluations at VCT?". The themes found from thematising the interviews that related to RQ2 are presented below and an overview of the themes can be seen in Figure 38.

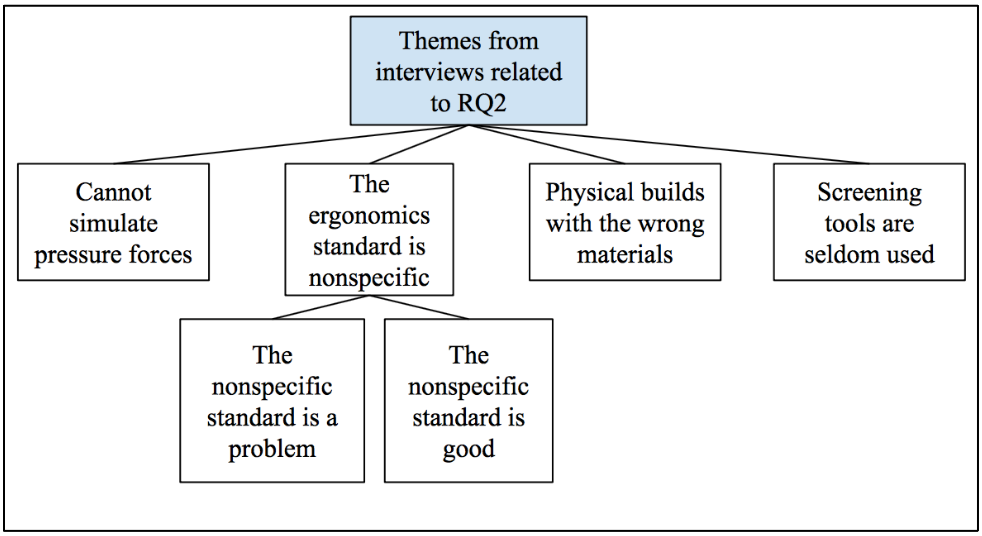

Figure 38 - Overview of themes related to RQ2

Cannot simulate pressure forces

Six of the interviewees agreed that VCT cannot simulate what pressure forces that are needed in the final assembly. It is possible to simulate wrist angles, grip position and access but not the actual force. Instead, the designers must rely on their own knowledge and comparisons with old solutions. This also means that clips are not verified virtually.

One interviewee stated: *"If we could simulate the pressure forces in a way that actually showed a result and considered the flex of the material, the friction against the steel plate… in addition to testing different tolerances… that would have been the dream".*

Another interviewee stated: *"…when we do simulations, we unfortunately do not see anything regarding the hands or fingers. We see the position of the hand… We cannot simulate forces with the tools we have today".*

A third interviewee stated: *"When you fasten something rigid with screws, then it only is one contact surface, but this one (b-pillar inner panel) has contact surfaces with both the roof, the lower part and the car body… You can assess if there is access but force is really difficult".*

The VCC standard

VCC has an internal ergonomics standard called VCS 8003,29. From the thematising, two contrasting sub-themes emerged which are presented below.

The nonspecific standard is a problem

Five interviewees agreed that the ergonomics standard is too coarse since it does not consider frequency, time or force in combination to the different working zones. These factors are only considered individually. This means that a movement will be deemed as red (not accepted) very easily. According to the interviewees, this is a problem for the R&D organization since it becomes very hard to fulfil the requirements of the standard.

One interviewee stated: *"the standard was reduced with the motivation that the suppliers must be able to understand it… but I believe that it gets even harder to grasp the standard when it is so little amounts of text…"*

Another interviewee stated: *"the forces (in the standard) needs to be differentiated, at least, depending on what zone you are in. 75 NM might be ok in the green zone, but when you work under-up then 50 NM is too much… The standard is too black and white".*

Another interviewee stated: *"... to get some more parameters to work with. Today it is only one or zero. It gets hard for the design department to work around".*

The nonspecific standard is good

Two interviewees stated that the standard is good with high usability in its present form, even though it has been reduced in length by more than 50 %. According to one interviewee, it was reduced in length so that both the operators working with ergonomics evaluations, and the supplier can understand it.

One interviewee stated: *"I think it (the standard) is rather good and rather clear, it is just a shame that the standard is not lived up to".*

Physical builds with the wrong material

Three interviewees discussed the influence of material properties in the early builds, referred to as slow builds, where the car is built physically for the first time. According to the interviewees, the material used for these builds are sometimes not the same as the one used in real production. Instead, it is common to use the 3D-printed material Fused Filament Fabrication (FFF). The material is good for testing of fitment and tolerances, but sometimes differs is rigidity and strength, which makes the pressure forces used for assembly lower or higher than in the real production system.

One interviewee stated: *"As soon as you have a physical detail then the problem is: how representative is it? Unless it is the final product... but then it is too late to make any changes anyhow…".*

Another interviewee stated: *"the products should be as close to production status as possible so that the high pressure forces are not dismissed and then let through to production"*

Screening tools are seldom used

Four interviewees mentioned that ergonomic screening tools are seldom used, neither by the engineers or the ergonomists. The only screening tool used is a tool called RAV (Risk Assessment Volvo), which is used by the operators themselves when assessing risks at a workstation. According to the interviewees, there are two main reasons why the production development organization do not use systematic methods such as screening tools. These are time consumption and that the tools are not made for the production system at VCT since it includes many work rotations per day.

One interviewee stated: *"Very few are designed for screening of rotations… which makes it very hard to use the tools in a good way"*.

Another interviewee stated: *"we do not use them very often because KIM III is quite granular and takes long time to finish and KIM I does not consider hands at all, so no there is no method accurate enough that also is quick…"*.

4.3 Findings related to RQ3

The third research question was formulated to investigate possible ways to move towards improved ergonomics evaluations. Specifically, the aim was to capture "What actions can be taken to correctly assess hand-related MSD risks in the future?". The quantitative results and the results from literature are presented in two sections below

4.3.1 RQ3: Qualitative data analysis

This section includes the qualitative results regarding RQ3. The results are based on a literature study and an interview. An overview of the themes can be seen in Figure 39.

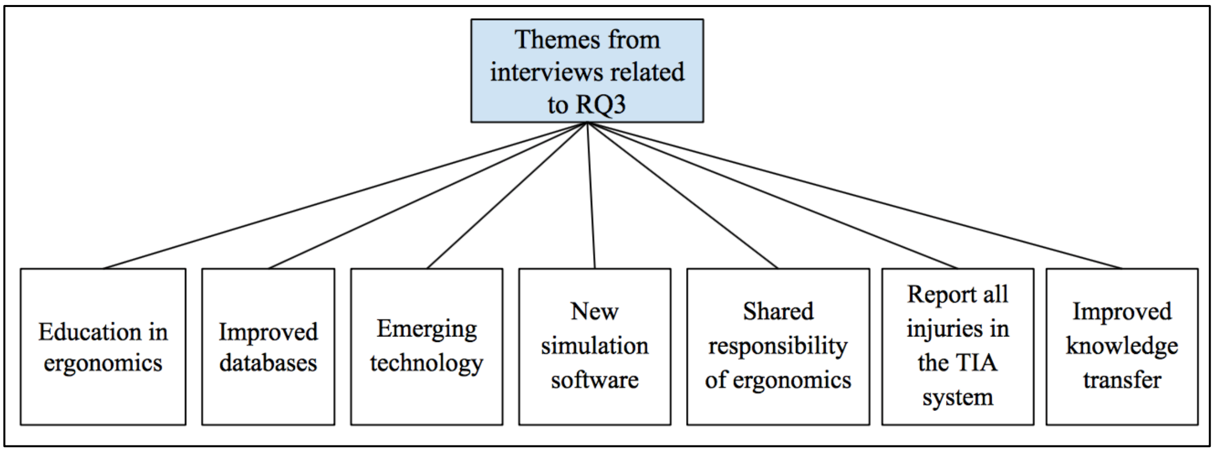

Figure 39 - Overview of themes related to RQ3

Important to educate the operators who verify the early builds

Four interviewees described possible improvements in the physical builds where trained operators assess the new operations. Since it was found that pressure forces are not verified virtually, see Sub-chapter 4.2 above, the physical verification must be able to assess this aspect. However, the interviewees stated that since the physical verification is done only a few times and in an environment that differs from the physical work environment in production, it is very important that the operators have knowledge in ergonomics. For instance, they should be able to take into consideration that the operation should be manageable 60 times per hour.

One interviewee stated: *"we should not let pressure forces pass through… we must invest in educating the frötallar [operators doing the first assemblies]"*

Another interviewee stated: *"We must have a foundation, we cannot ask one person… you must ask a range maybe 10, 15 people doing the same thing and also consider the high repetitiveness."*

The databases with clips could be improved

Four interviewees stated possible ways of supporting the ergonomics evaluations in the future by updating and improving the database with clips. When the simulation engineer does the simulations, she or he import geometries and other data from this database into the software. According to the interviewees, there are two main areas of improvement. The first to make sure that old clips that have been found to be bad should be removed out if the system so that no one will risk using the same bad solution again. The second is to add information about the clips such as required pressure forces, which then can be used in the simulations. The latter is however not possible to do yet but could be in the future.

One interviewee stated: *"... specifically the clips-standard-database is below contempt… no one updates it and we must ask each other to find out which clips that works"*.

Emerging technology can complement simulations

Six interviewees discussed how new and emerging technology can complement the simulations in evaluating ergonomics of new products. Volvo Cars are involved in different research projects that evaluates both smart materials and virtual/augmented reality (AR/VR) tools. The smart materials can support the ergonomic evaluations by gathering much data which then can be used to analyse the operations in a reliable way. The AR/VR tools can support the ergonomic evaluations by having actual humans testing new operations and remove the manikins which, according to the interviewees, are possible to position in unrealistic ways. The AR/VR tools could also collaborate with a software that complements the subjective testing with objective data analysis.

One interviewee stated: *"we have tested some different AR/VR tools that were very time consuming and expensive, but to have something that analyses my body when I am fastening the screw or whatever and immediately tells if I am doing something wrong and also analyses* *forces and the muscles and can calculate if the body can do such operations 8 hours per day".*

Another interviewee stated: *"I would like these smart textiles to analyse the average workload over a whole day and also what specific operations that are bad"*.

New simulation software could make it possible to simulate pressure forces

The two interviewed developers at Fraunhofer Chalmers Centre (FCC) discussed the issue of simulating pressure forces and its effect on hand ergonomics. According to the interviewees, it is very likely that a software could be used to solve the problem since most parts are already developed. There are methods to predict how cables rotate when they are assembled and successively requires higher pressure forces and there are also methods on how different forces affect the biomechanical structure of the hand. It should therefore mostly be a question of making these different pieces of calculation and simulation software together. However, it would require pilot projects to start with before it is absolutely certain that it would work.

One interviewee stated: *"We have all components in some form so it should be possible to put the whole chain in place… You could start with one study to see if it is in the right direction and then move on with a bigger one. When you have the forces, then you can move on with how it affects the structure of the hand with a hand model"*.

The other interviewee stated: *"A case where it is known that the pressure forces are for instance 300 N and then you can see if you get the same result from the simulations"*.

All injuries should be reported into the TIA-system

Three interviewees discussed the validity of the injury statistics reported into Volvo Cars' TIA-system. According to the interviewees, there are a large number of injuries that never get reported into the system, which has led to that some people do not analyse the statistics and use it as a basis for improvement work. Since it is the production leaders' (PL) responsibility to report any injury, the statistics are dependent on the production leaders' leadership and the organizational culture under him or her.

One interviewee stated: *"The TIA-system… you should be aware of that it is a lot that is not reported there. But I believe that it has been better lately"*.

Another interviewee stated: *"It is up to the production leaders to hunt down the employees that are home from work and ask why they are home"*.

Responsibility of ergonomics should be included in all parts of the organization

Four interviewees discussed the importance of Design for Assembly (DfA) since changes in manufacturability is cheapest in the design phase and most expensive when the design is already decided. According to the interviewees, the R&D (P&Q) organization lack knowledge in ergonomics and there is a number of ways to improve this aspect. One way is to force all designers to work in the factory for one day or week to assemble their own components to see for themselves how hard or easy it is. Another way is to make ergonomics a mandatory part of the introduction when new employees are hired.

One interviewee stated: *"I wish we would have concentrated more on Design for Assembly. Much more actually"*.

Another interviewee stated: *"There is a three-day education for the manufacturing engineers [beredarna], but our problem is to have R&D wanting to attend our educations… they are really important because they are the designers"*

Improved knowledge transfer between projects
Four interviewees discussed what they perceived as lacking knowledge transfer between projects. The interviewees argued that it is common that ergonomics is improved in one car model but that the same problem occurs when a new model is released. Further, this extra work could be reduced or removed completely if the knowledge from one projects would be transferred into the next. According to the interviewees, this could also be improved if new employees could work for a couple of days with the person they will replace in the organization.

One interviewee stated: *"its different project leaders for the different models and it does not seem like they learn from the results… instead when the next model comes its really bad hand ergonomics again when we had a better solution. I wish someone would catch those good solutions"*.

Another interviewee stated: *"The grommet was bad in the first SPA-car, got worse with the next (V90) and now even worse on the V60… Unfortunately, it is like we learned nothing"*.

4.3.2 RQ3: Literature findings

To aid the answering of RQ3, literature was revisited after the completion of the interviews. The findings all related to new technological trends that can provide objective assessments of ergonomics.

A report by Occupational and Environmental Medicine in Lund (2017) describe how new emerging technological solutions and products could disrupt the current praxis of how to conduct ergonomics evaluations. According to the report, the regulation of ergonomics in Sweden (Ergonomics for the prevention of musculoskeletal disorders AFS 2012:2) is formulated in a vague way with recommendations of subjective evaluation tools. The authors of the report therefore recommend quantitative and objective measurements in combination with knowledge of how physical loads correlate with the risk of ill health. The outcome of the report are action levels created from such quantitative and objectively gathered data. These actions levels could potentially be implemented in solutions used by for instance ergonomists in occupational health care and safety representatives in an industrial context. (ibid.).

The authors stated: *"It is possible to measure the physical load during entire work days with measurement equipment worn by the workers". By placing electrodes and sensors on the* *skin, we can collect quantitative and objective measurements on work postures and movements, on the demanding the work is with regards to forces and also the time available for rest/recovery during work. We can also measure times and variation in loads".*

Several emerging technological solutions that uses exoskeletons for increased strength were also found, see Table 10. However, the Smart Glove Research project was the only one found to be applicable in a preventative evaluation context.

Table 10 - Emerging technologies related to hand ergonomics

Type of technology	**Description**	**Sources**
Smart Glove	Integration of sensors and cables in a soft robotic glove for industry and healthcare. Cooperation between Smart Textiles and Bioservo Technologies	Smart Textiles Research Project: http://smarttextiles.se/st-194-integrering-av-sensorer-och-kablage-i-mjuk-robothandske-for-industri-och-halsovard/
Exoskeleton for hands	Bioservo: "Assistive bionic glove that strengthens the operator's grip and increase endurance". Festo: "Pneumatic exoskeleton that is pulled on like a glove to improve strength and stamina". Can also be used interactively with a robot that mimics the movements of the human hand in real-time.	Bioservo: http://www.bioservo.se/industri/ironhand/ Festo: https://www.festo.com/group/en/cms/10233.htm

5. Discussion

The present study was initiated with the purpose of investigating how VCC work with predictive assessment of hand ergonomics in early phases of production development and to find possible explanations to the recent increase of injuries in hands and wrists among operators in final assembly. The following chapter discusses how the findings presented in Chapter 4 are related to the purpose of the study. The chapter also provides a discussion related to the aim of the study; to present recommendations that possibly could decrease the risk of designing assembly tasks where hand ergonomics is compromised, before start of production.

Three research questions were formulated in order to fulfil the purpose and aim of the study. The first research question aimed at capturing the present state in the TC-factory with focus on hand-related MSDs. The second research question aimed at capturing what MSD risks that are not captured in the early phase ergonomics evaluations. These two questions relate considerably to each other. Ideally, the risks that are not captured in the evaluations should have resulted in similar injuries in the factory. However, many factors must align in order for an injury to actually occur in a complex human system such as the production system at VCT, which can be illustrated by the Swiss Cheese Model (SCM) (Reason, 1997).

To relate this to the present study, a freely modified version of the SCM by Reason (1997), combined with the HTO definitions by Martelius, Bron Säkkon and Östergren (2016), has been used as framework for data analysis and presentation, see Figure 16. The SC/HTO Model was further used to capture how the product- and production development process and the running production process relate to each other and what mechanisms that lies behind an injury, see Figure 40.

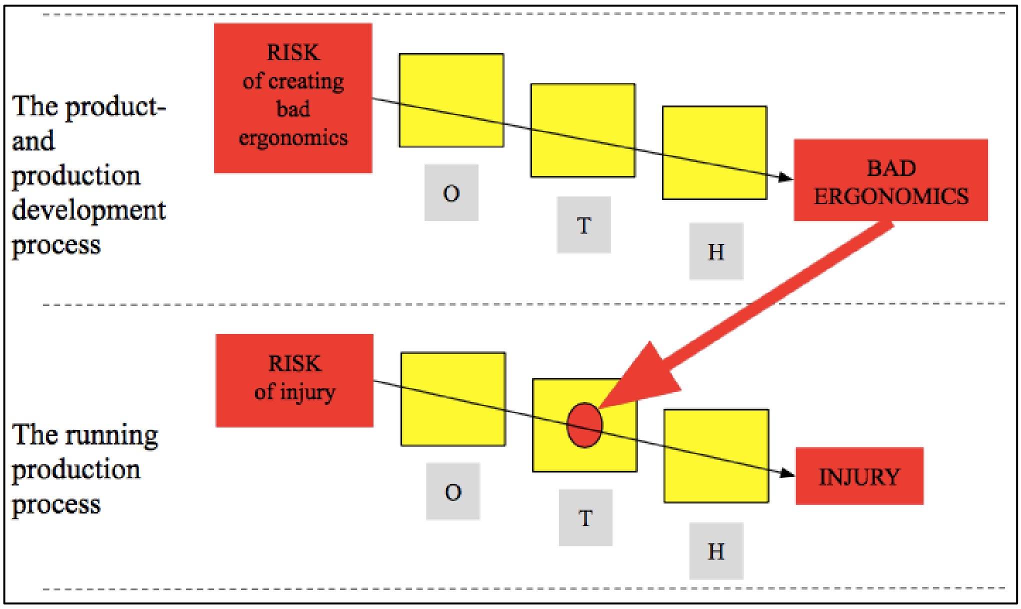

Figure 40 - Schematic overview of how the SC/HTO Model has been applied in the present study

Ergonomics is according to Martelius, Bron Säkkon and Östergren (2016) part of the technological layer of the production system, but in the present study it is also seen as the output of the development process. This means that hand-related MSDs are the result of (1) a development organization with problems in all three HTO layers and (2) a production system with problems in all three HTO layers. Based on the scope and delimitations of the present study, focus is on the product- and production development process.

The findings for RQ1 are based on both qualitative and quantitative data. In addition, three types of qualitative data were used. This mixed methods approach is a form of triangulation which facilitates validation of the data. It also facilitates obtaining a more comprehensive overview of the studied subject. In other words, if the same finding can be found from different data sources it is more likely that the finding is valid. This was the case regarding some findings related to RQ1 in the present study, hence more emphasis has been put on these. The findings for RQ2 are based solely on interviews, however only results found from more than one interviewee are included. All interview data were analysed the same way. The findings for RQ3 are based on interviews and literature findings.

Below the main findings from the first two Research Questions are discussed, followed by actions that VCC can consider to potentially solve the identified issues in the future, RQ3. Finally, strengths and weaknesses of the present study’s methodology and data sources are discussed.

The main findings

The most prominent finding in the present study is the issue of high pressure forces. It was identified from RQ2 that the ergonomics evaluations in early phases have several problems related to assessing the forces required to assemble components with clips, such as interior panels and cable harnesses. It was also identified from RQ1 that 48 % percent of all injuries during 2016 and 2017 included hand-related MSDs and 66 % percent of them were presumably caused by high pressure forces. These injuries were spread across the majority of all work units, see Figure 37. In short, a clear relationship can be seen between what is not captured in the early phase ergonomics evaluations and the injuries that actually occur in production.

Related to the SC/HTO Model, is required that all three layers (Human, Technology and Organization) have failed in preventing the high pressure forces, which also seems to be the case at VCT based on the findings in the present study, see Figure 41. The results are in line with Lämkull (2009) who identified that some simulation (DHM) software were incapable of evaluating pressure/pull forces. The results are also somewhat in line with other findings that indicated that physical workload is seldom evaluated with DHM software (Sundin and Sjöberg, 2004; Laitila, 2005; Lockett *et al.*, 2005). However, the ergonomics evaluations at VCC are not based solely on simulations but also on early builds where operators can evaluate assembly operations. Unfortunately, these builds are done with materials that often differ from the final material used in production, which makes it practically impossible to evaluate the ergonomics. In addition, it was found that the screening tools are seldom used due to their large time consumption and low applicability. These findings are in line with Berlin and Adams (2017) who stated that biomechanical screening tools, which can assess physical strain during movement of physical loads rather than static posture observations, take relatively long time to conduct.

The ergonomics standard was also found to be nonspecific, which was a problem according to some interviewees but a strength according to other interviewees. The interviewees who saw problems with the standard described that it does not consider frequency, time or force in combination with different working zones which makes the standard difficult to apply. This is in line with Gaudez (2015) who stated that it is insufficient to only measure external force when it comes to clip-fitting tasks. Clips were one of the main reason for the high pressure forces in the present study. From the quantitative data analysis, it was found that 30 out of the 34 work units with injuries had one or more hand-related MSD, which can be seen as further evidence of systematic errors in the early phase ergonomics evaluations.

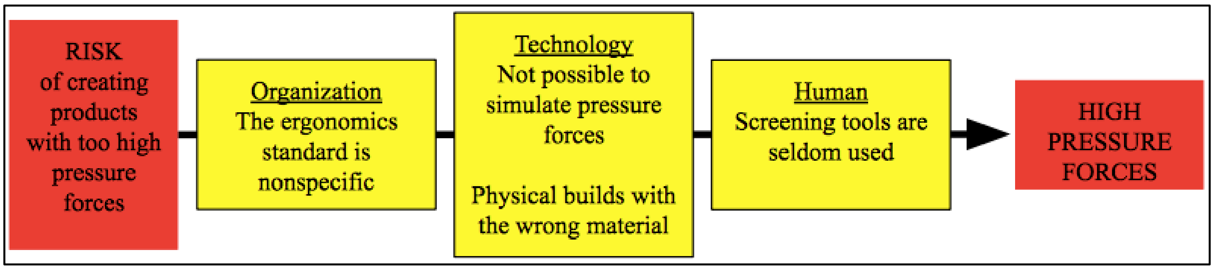

Figure 41 - Schematic overview of how the ergonomics evaluations miss the high pressure forces in early phases of production development

Other findings

A statistically significant difference was found between women and men regarding MSDs in hands ($p = .003$). 57 % of the operators with injuries in hands were women, 42 % were men and 1 % were of unknown sex. These findings are partly in line with official statistics published by the Swedish Work Environment Authority (2016) who stated that the total amount of hand injuries in Sweden, caused by physical loading at work, were 3 % for women and 2 % for men, including both white and blue collar occupations. However, when comparing all injuries at VCC there was no difference between the sexes, which differs from the Swedish Work Environment Authority (2016) who stated that the total amount of injuries caused by physical loading at work in Sweden was 9 % for women and 7 % for men, including both white and blue collar occupations. At VCC, it was found that 48 % of all injuries were hand injuries which is not completely in line with the statistics published by AV (2016), in which it can be seen that injuries in hands roughly constitute a third of all injuries for both men and women in Sweden. However, European Agency for Safety and Health at Work (2007) reported that the blue collar occupation that includes assemblers is the third most exposed group of contracting all types of work-related MSDs, which could be an explanation of why the results differ. Another explanation can be found from the interviewees who stated that the work tasks at VCC are exceptionally repetitive compared to other industries.

That women are more exposed to work-related injuries can also be linked to anthropometry and social sustainability, since women and men differ in average strength and size. On an individual level, socially sustainable work concerns for instance that the work tasks are well-fitted and understandable. Examples of how this should be managed can be found in the working height guidelines by Swedish Work Environment Authority (2012). In other words, the findings from the present study could possibly suggest that the work tasks at VCC are less suitable for female operators. However, no interviewee mentioned any relation between the sex of the operators and risk of injuries and it was therefore concluded that more investigation is needed on the subject before any definitive conclusions can be drawn.

No statistical relationship was found between age of the injured operators and hand injuries even though a majority were relatively young, i.e. under 30 years old. This can be a result of that it was not possible to collect statistics from the HR department regarding the age of all operators in the TC-factory. Instead, a comparison was made between operators with any type of injury and operators with hand injuries. The interviewees did indicate that the average age was low in the TC-factory, but no official statistics were available and therefore the issue requires further investigation to guarantee the validity of the finding.

Lastly, it was found from the interviews that the operations in the TC-factory are highly repetitive and from the document analysis and shop floor observations that the operations are carried out in several bad working postures. Based on the Cube model by Sperling *et al.* (1993), see Figure 6, the risk of injury is the product of force, time and posture. Examples of bad postures that were identified to be present in the TC-factory were (1) Wrists in extended postures, (2) Hook grip with heavy load and (3) Heavy parts/equipment far away from body. It was also found that there was not sufficient space for the operator’s hand in one fixture, which can be related to Lämkull, Hanson, Örtengren (2009) who identified that simulations sometimes underestimate or exaggerate the required space for the hand/arm.

The identified issues can be related to increased risk of contracting Carpal Tunnel Syndrome (CTS) and Trigger Finger Syndrome (TFS). Risk factors are static wrist postures in extreme angles, as well as pressing and hitting objects with the palm of the hand. TFS generally develops gradually but it can also be caused by acute trauma. Recovery from these injuries differs from case to case but it is generally harder to recover from CTS. For both syndromes it is sometimes required to use surgery (Karwowski and Salvendy, 1998). In the present study, it was not investigated if any relation could be found between specific MSDs such as CTS and TFS and the identified repetitiveness and bad postures. However, it is concluded that the risk is increased with the identified issues.

The identified issues were triangulated from several data sources but no explanation could be found related to why the development organization has missed these risk factors. Rather, it was found from the interviews that postures are possible to evaluate by using the tools currently available to VCC. Based on this, further investigation is needed to understand the causation.

How VCC can move towards improved ergonomics for hands

What actions can be taken to correctly assess hand-related MSD risks in the future? Volvo Cars have the goal of offering and maintaining a safe work environment for their employees. Support for why this goal is worth investing in can be found in many sources. For instance; good ergonomics reduces both societal and company costs while providing competitive advantages for the company (Berlin and Adams, 2017; Dul and Weerdmeester, 2017), high physical workloads are linked to bad product quality (Falck, 2009), increased error rates, longer absenteeism and lower productivity (Fritzsche *et al.*, 2014). Several other sources support the idea of working proactively in the early phases of production development instead of reactively, i.e. after the humans in the production system are injured. For instance; the greatest possibility to influence the ergonomics in a production system are in the early product development phases (Munck-Ulfsfält *et al.*, 2003), the most effective way of addressing ergonomic risks are to eliminate them through design of the product (Manuele, 2007) and reactive approaches seldom solve the root cause of the problem or provide lasting benefits (Berlin and Adams, 2017). Based on all of the above, it is motivated to discuss how Volvo Cars can move towards improved ergonomics evaluations in the early phases.

The aspect of future potential improvements was captured based on the third research question. In Figure 42, the findings from RQ3 are summarized based on the SC/HTO Model.

Human Improvements	**Technological Improvements**	**Organizational Improvements**
Education in ergonomics for operators who verifies early builds	Improved databases Emerging technology New simulation software	Shared responsibility of ergonomics across departments (DfA) Improved reporting in TIA Improved knowledge transfer

Figure 42 - Future possibilities of improvement in evaluation of hand ergonomics based on the SC/HTO Model

Three of the findings presented in Figure 42 relate to education of ergonomics. The first is that the operators who verify the early builds should have the knowledge to evaluate if specific tasks are ergonomically acceptable in a context with 60 cycles per hour. The second is that the R&D department must take part in the preventative work with ergonomics by working with DfA. The third is that knowledge of good/bad solutions from an ergonomics point of view should be transferred from one project to another. These findings are in line with Broberg (1997) who stated that design engineers often do not recognize the consequences of a poorly designed product and work station, due to lack of ergonomic competence and time as the main shortcomings. In addition, Eklund (1999) stated that 60-70% of the MSDs in a production system are caused by the product design, and 30-40% by the assembly process which can be seen as further motivation of why education in ergonomics for the employees at the R&D department is important.

The other four findings all relate to technology and the usage of technological resources. The first is related to the database used for storage of components such as clips. According to the interviewees, old clips that are known to be bad should be removed and ergonomics data, such as required pressure forces, should be added. The latter relates to the next finding, the need for new simulation software. The findings in the present study clearly point out that VCC lack the possibility of simulating pressure forces. However, from the interview with Fraunhofer Chalmers Centre (FCC) who developed the IMMA software currently used by VCC, it was indicated that it is possible to solve this problem. The next step is to create a pilot case together with FCC or some other developer that can investigate how to create a commercial solution. Then, a virtual model of the hand should be used in order to see how the known force affects the hand. Again, Gaudez (2015) stated that it is insufficient to only measure external force when it comes to clip-fitting tasks, which was found to be one of the most problematic tasks at VCC.

It was also found that emerging technology such as AR/VR and smart textiles could be important resources for VCC when evaluating hand ergonomics. The smart materials can support the ergonomic evaluations with reliable data collection and the AR/VR tools can support the ergonomic evaluations by replacing the manikins with actual users, see section 2.3.2 for description of manikin simulations. Support of this finding was also found in literature; Occupational and Environmental Medicine in Lund (2017) described how new emerging technological solutions and products could disrupt the current praxis of how to conduct ergonomics evaluations. New technology can provide quantitative and objective measurements in combination with knowledge of how physical loads correlate with the risk of ill health, see section 4.3.2. Support for why objective measurements are needed can be found in Berlin and Adams (2017) who stated that posture-based screening tools are vulnerable to interpretation. However, this aspect requires further investigation that lies outside the scope of the present study.

The fourth finding related to the injury statistics in the TIA-system, which was used in the present study for quantitative analysis. According to the interviewees, many injuries are never reported in this system mainly due to unknown causes. This is a problem since the statistics in the TIA-system are the only reliable data of mapping the ergonomics of the factory, in comparison to depending on informal communication channels between the development organization and the production organization. This finding could not be linked to any literature finding in the present study. Organizational aspects in the TC-factory were delimited from the scope of the present study and were therefore not investigated further.

Strengths and Weaknesses of the present study

The Research Approach: The present study was based on an abductive approach, which theoretically combines the strengths of both the inductive and the deductive approach by combining theoretical frameworks and empirical data. Initially, a preliminary theory of what might had caused the increasing number of MSDs in hands was established which then was combined with literature which in turn was used as a basis for further data gathering. When all data were gathered, the initial theory was adjusted and finalised. In addition, literature was used both for mapping the current state of ergonomics research and for support in answering the research questions. Both qualitative and quantitative data were used and collected in the present study which did increase the complexity of the data analysis. The strength of the approach is however an increased validity in the findings that could be triangulated from more than one source of data. It can also be noted that the time frame of the present study was not exceeded.

The quantitative data: All quantitative data used in the present study were secondary data since it was not collected from the operators specifically for the present study. This could potentially lower the validity of the data since it is unknown under which circumstances the data was collected (Denscombe, 2014). For instance, the operators might have misinterpreted some questions that the production leader asked them when he or she reported the injury in the TIA-system. However, a relatively large sample was used in the present study which ideally moderates such individual errors. In addition, all data was manually checked for errors such as spelling which potentially would lead to new errors when the data was analysed with automatic commands. The reliability of the data could not be controlled due to that only secondary data was used. However, the reliability of all calculations was moderated by running the calculations several times and also by different persons. The external validity of the quantitative data was interpreted as “are the findings valid for all operators working in the TC-factory at VCC”. In other words, no generalisation was made regarding operators in general, since that would require data samples from more than one factory.

The qualitative data: The validity of the qualitative data was moderated by triangulating the findings to the largest extent possible and by having grounded/empirical data from the shop floor observations. However, the third step of increasing validity in qualitative data analysis proposed by Denscombe (2014), respondent validation, was not possible to fulfil due to limited time. In accordance with Denscombe (2014), the reliability of the qualitative data and findings have been presented in the most transparent way possible in order to give the readers the chance of deciding for themselves if the conclusions drawn from the data are reasonable or not.

External validity: The present study has been conducted in cooperation with Volvo Cars and as a Master’s thesis within the Production Engineering program at Chalmers University of Technology. A majority of the empirical data were collected from Volvo Cars but some were collected from the external company Fraunhofer Chalmers research Centre. Although the internal validity of the findings from the present study is relatively high, the external validity is relatively low. The findings can be valid in other contexts such as for manufacturers of cars, trucks or buses but that would require samples of data from more than one manufacturer. Further, it could not be established from the interviews how far ahead or behind of the competitors Volvo Cars were with the predictive ergonomics assessments. Such finding could have increased the external validity if for instance it was found that all car manufacturers have experienced similar issues to the same extent as Volvo Cars.

6. Conclusions

The following conclusions were drawn from the present study:

- The main findings: Half of all injuries in the TC-factory involved hand-related MSDs and the product- and production development organization could not predict them:
  - A majority of the hand-related MSDs were caused by excessive pressure forces, often in combination with awkward postures
  - The problems in the development phase were a combination of organizational, technological and human aspects
- Recommendations on how to improve the ergonomics evaluations at VCC are:
  - Education and shared competence of ergonomics in all development phases
  - Technological investments in a pilot study that investigates how to simulate pressure forces
  - Consider new emerging technology such as smart gloves that can provide objective assessments in early phases
- The findings in the present study have a relatively high internal validity due to extensive triangulation
- The findings in the present study have a relatively low external validity, thus if used in other contexts this should be considered

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Appendix A - Interview guide

The interviews were conducted as semi-structured, which meant that the following questions were always included but not strictly in order and additional questions were added when needed. All interviews were held in Swedish with translated questions.

1. On a general level, what do you know about work injuries in the TC-factory?
2. Injuries in hands and wrists constitute 48 % of all injuries in the TC-factory, what do you think are the reasons for this?
3. Do you have any ideas on how to deal with the problem of preventing injuries on hands and wrists before they occur?
4. Do you know of any screening method applicable for hands?
5. If so, are they used at VCC?
6. Do you have any other methods or tools to evaluate hand ergonomics?
7. Do you get any feedback from the factory on the work you do?
8. If so, in what way and after how long time?
9. What activities do you and your work group do to make sure of that the operators are not injured from work?
10. Do you work with benchmarking of the competitors' ergonomics methods?
11. a) To engineers:
    In general, how much time is devoted to ergonomics in your work?

    b) To ergonomists/health specialists:
    How much are you involved in the development of a new product?
12. Have you experienced any change with the new SPA-platforms?
13. If you could wish and get exactly what you wished for, how would a good tool for ergonomic evaluation be designed?
14. There is a Volvo Cars standard with limits for allowed pressure forces on fingers and hands. Are you aware of its existence and if so, do you think it is sufficiently extensive?
15. Have you thought of or encountered any possible acute solution to the problems with hand injuries?

Appendix B - Statistics

Statistics of injuries during 2016 and 2017

	Number of reported injuries	Males with injuries*	Females with injuries*	Number hand injuries	Males with hand injuries*	Females with hand injuries*
2016	124	65 (52 %)	56 (45 %)	61 (49 %)	28 (46 %)	32 (52 %)
2017	198	95 (48 %)	98 (50 %)	94 (47 %)	37 (40 %)	56 (60 %)
Total	322	160 (50 %)	154 (48 %)	155 (48 %)	65 (42 %)	88 (57 %)
* Some of the operators were of unknown sex						

Frequency of hand injuries at the stations during 2016 and 2017

		Frequency hand injuries	Percentage hand injuries	Cause of injury according to the injured operators*	
1	**1:41 Tunnel**	18	49 %	High pressure force High torque recoil from machine No work rotation	15 (83%) 1 (6%) 2 (11%)
2	**PalA**	12	60 %	Heavy lifting High pressure force High torque force	8 (67%) 2 (17%) 2 (17%)
3	**1:4**	11	52 %	High pressure force High torque force	10 (91%) 1 (9%)
4	**Loopar**	10	45 %	High pressure force High torque recoil from machine Not specified	6 (60%) 3 (30%) 1(10%)
5	**PalB**	9	39 %	High pressure force	9 (100%)
6	**1:42**	9	36 %	High pressure force Static work above shoulder height	8 (89%) 1 (11%)
7	**Doorline Right**	9	75 %	High pressure force Not specified	7 (78%) 2 (22%)
8	**AMP**	8	100 %	High pressure force	8 (100%)
9	**1:3**	7	44 %	High pressure force High torque recoil from machine No work rotation	4 (57%) 2 (29%) 1 (14%)
10	**PP3**	6	75 %	High pressure force High torque recoil from machine No work rotation	4 (67%) 1 (17%) 1 (17%)
11	**1:1**	6	55 %	High pressure force High torque recoil from machine No work rotation	3 (50%) 2 (33%) 1 (17%)
12	**PP1**	6	86 %	High torque recoil from machine No work rotation	5 (83%) 1 (17%)
13	**1:6**	5	38 %	High pressure force Not specified	3 (60%) 2 (40%)
14	**1:01**	5	36 %	High pressure force Static work above shoulder height	4 (80%) 1 (20%)

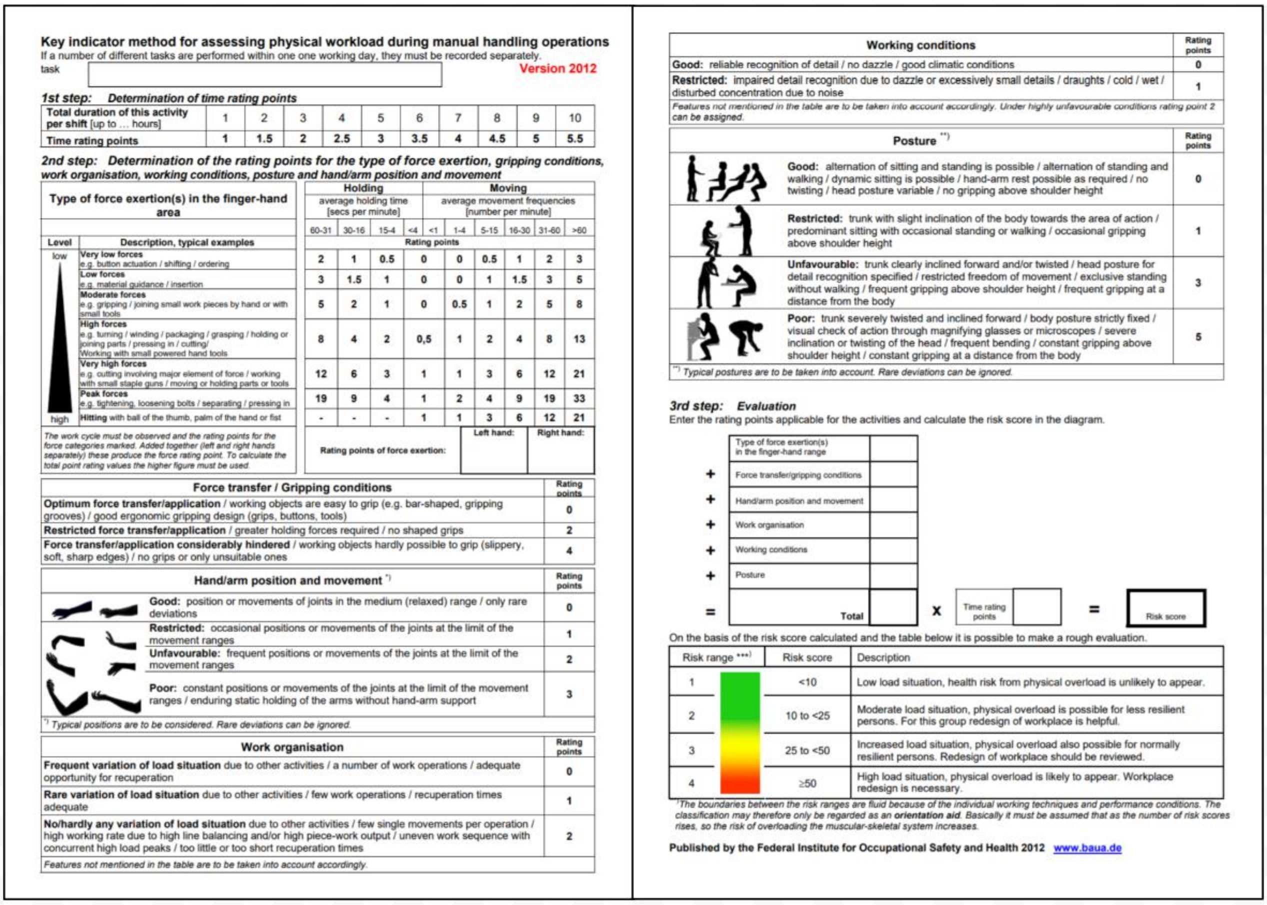
15	**1:5**	5	45 %	High pressure force	5 (100%)
16	**Doorline Left**	4	80 %	High pressure force High torque recoil from machine	3 (75%) 1 (25%)
17	**1:013**	3	43 %	High pressure force	3 (100%)
18	**1:21**	3	75 %	High pressure force	3 (100%)
19	**ML**	2	40 %	High pressure force Not specified	1 (50%) 1 (50%)
20	**SPA bax**	3	43 %	High pressure force Lifting tool manoeuvre	1 (33%) 2 (33%)
21	**1:02**	2	18 %	Not specified	2 (100%)
22	**PP2**	2	20 %	High pressure force No work rotation	1 (50%) 1 (50%)
23	**1:00**	2	67 %	Heavy lifting Lifting tool manoeuvre	1 (50%) 1 (50%)
24	**Ybax**	1	20 %	High pressure force	1 (100%)
25	**Kannister station**	1	50 %	High torque force	1 (100%)
26	**1:71**	1	25 %	High pressure force	1 (100%)
27	**1:2**	1	20 %	Grip force from holding machine	1 (100%)
28	**1:015**	1	33 %	High pressure force	1 (100%)
29	**SPA bax**	1	25 %	Eczema from assembly gloves	1 (100%)
30	**1:7**	1	25 %	Not specified	1 (100%)
31	**Rulle**	1	100 %	High torque recoil from machine	1 (100%)
32	**TC Passningsteam**	1	50 %	Lack of tools	1 (100%)
	*Identified keywords from the TIA-system				

Appendix C - Stakeholder analysis

	Initiators	Sponsors	Change owners	Subjects	Solution builders	Documenters	Blockers	Convinsers
Authors - Erik & Anna	Project owners				Carries out the project	Writes thesis		
Examiner - Cecilia		Advisor / Expert						
Supervisor - Dan	Project owner	Advisor / Expert	His area of responsibility				Restrictions in time and energy	His area of responsibility
Volvo		Official employeer				Stores the resulting thesis		
Commodity Engineers				Affected			Restrictions in time and energy	
Chalmers		Course owner				Stores the resulting thesis		
Operators		?		Indirectly affected				
Interior designer		?		Affected				
Electrical designer		?		Affected				
R & D				Affected				
Industrial Engineers		?		Affected				
The Union		?						
Occupational health service		?						
Laws and regulations							?	

The stakeholder analysis was a CHAI-analysis, originally developed by Berlin, Berglund and Lindskog (2016).

Appendix D - Figures



Key indicator method for assessing physical workload during manual handling operations
If a number of different tasks are performed within one one working day, they must be recorded separately.
task
Version 2012

1st step: ***Determination of time rating points***

Total duration of this activity per shift [up to … hours]	1	2	3	4	5	6	7	8	9	10
Time rating points	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**

2nd step: ***Determination of the rating points for the type of force exertion, gripping conditions, work organisation, working conditions, posture and hand/arm position and movement***

Type of force exertion(s) in the finger-hand area		**Holding** average holding time [secs per minute]				**Moving** average movement frequencies [number per minute]				
		60-31	30-16	15-4	<4 / <1	1-4	5-15	16-30	31-60	>60
Level	**Description, typical examples**	**Rating points**								
low	**Very low forces** e.g. button actuation / shifting / ordering	**2**	**1**	**0.5**	**0**	**0**	**0.5**	**1**	**2**	**3**
	Low forces e.g. material guidance / insertion	**3**	**1.5**	**1**	**0**	**0**	**1**	**1.5**	**3**	**5**
	Moderate forces e.g. gripping / joining small work pieces by hand or with small tools	**5**	**2**	**1**	**0**	**0.5**	**1**	**2**	**5**	**8**
	High forces e.g. turning / winding / packaging / grasping / holding or joining parts / pressing in / cutting/ Working with small powered hand tools	**8**	**4**	**2**	**0,5**	**1**	**2**	**4**	**8**	**13**
	Very high forces e.g. cutting involving major element of force / working with small staple guns / moving or holding parts or tools	**12**	**6**	**3**	**1**	**1**	**3**	**6**	**12**	**21**
	Peak forces e.g. tightening, loosening bolts / separating / pressing in	**19**	**9**	**4**	**1**	**2**	**4**	**9**	**19**	**33**
high	**Hitting** with ball of the thumb, palm of the hand or fist	-	-	-	**1**	**1**	**3**	**6**	**12**	**21**

The work cycle must be observed and the rating points for the force categories marked. Added together (left and right hands separately) these produce the force rating point. To calculate the total point rating values the higher figure must be used.

Rating points of force exertion: Left hand: Right hand:

Force transfer / Gripping conditions	Rating points
Optimum force transfer/application / working objects are easy to grip (e.g. bar-shaped, gripping grooves) / good ergonomic gripping design (grips, buttons, tools)	**0**
Restricted force transfer/application / greater holding forces required / no shaped grips	**2**
Force transfer/application considerably hindered / working objects hardly possible to grip (slippery, soft, sharp edges) / no grips or only unsuitable ones	**4**

Hand/arm position and movement *)	Rating points
Good: position or movements of joints in the medium (relaxed) range / only rare deviations	**0**
Restricted: occasional positions or movements of the joints at the limit of the movement ranges	**1**
Unfavourable: frequent positions or movements of the joints at the limit of the movement ranges	**2**
Poor: constant positions or movements of the joints at the limit of the movement ranges / enduring static holding of the arms without hand-arm support	**3**

*) *Typical positions are to be considered. Rare deviations can be ignored.*

Work organisation	Rating points
Frequent variation of load situation due to other activities / a number of work operations / adequate opportunity for recuperation	**0**
Rare variation of load situation due to other activities / few work operations / recuperation times adequate	**1**
No/hardly any variation of load situation due to other activities / few single movements per operation / high working rate due to high line balancing and/or high piece-work output / uneven work sequence with concurrent high load peaks / too little or too short recuperation times	**2**

Features not mentioned in the table are to be taken into account accordingly.

Working conditions	Rating points
Good: reliable recognition of detail / no dazzle / good climatic conditions	**0**
Restricted: impaired detail recognition due to dazzle or excessively small details / draughts / cold / wet / disturbed concentration due to noise	**1**

Features not mentioned in the table are to be taken into account accordingly. Under highly unfavourable conditions rating point 2 can be assigned.

Posture **)	Rating points
Good: alternation of sitting and standing is possible / alternation of standing and walking / dynamic sitting is possible / hand-arm rest possible as required / no twisting / head posture variable / no gripping above shoulder height	**0**
Restricted: trunk with slight inclination of the body towards the area of action / predominant sitting with occasional standing or walking / occasional gripping above shoulder height	**1**
Unfavourable: trunk clearly inclined forward and/or twisted / head posture for detail recognition specified / restricted freedom of movement / exclusive standing without walking / frequent gripping above shoulder height / frequent gripping at a distance from the body	**3**
Poor: trunk severely twisted and inclined forward / body posture strictly fixed / visual check of action through magnifying glasses or microscopes / severe inclination or twisting of the head / frequent bending / constant gripping above shoulder height / constant gripping at a distance from the body	**5**

**) *Typical postures are to be taken into account. Rare deviations can be ignored.*

3rd step: ***Evaluation***
Enter the rating points applicable for the activities and calculate the risk score in the diagram.

	Type of force exertion(s) in the finger-hand range	
+	Force transfer/gripping conditions	
+	Hand/arm position and movement	
+	Work organisation	
+	Working conditions	
+	Posture	
=	Total	

x Time rating points **=** Risk score

On the basis of the risk score calculated and the table below it is possible to make a rough evaluation.

Risk range ***)	Risk score	Description
1	<10	Low load situation, health risk from physical overload is unlikely to appear.
2	10 to <25	Moderate load situation, physical overload is possible for less resilient persons. For this group redesign of workplace is helpful.
3	25 to <50	Increased load situation, physical overload also possible for normally resilient persons. Redesign of workplace should be reviewed.
4	≥50	High load situation, physical overload is likely to appear. Workplace redesign is necessary.

*) *The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an* ***orientation aid****. Basically it must be assumed that as the number of risk scores rises, so the risk of overloading the muscular-skeletal system increases.*

Published by the Federal Institute for Occupational Safety and Health 2012 www.baua.de

Figure 43 – Screen shot of the KIM III assessment form without instruction manual (Federal Institute for Occupational Safety and Health, 2012). The full form is available from https://www.baua.de/DE/Themen/Arbeitsgestaltung-im-Betrieb/Physische-Belastung/Leitmerkmalmethode/pdf/KIM-manual-handling-2.pdf?__blob=publicationFile.

Assessment form

Hand Arm Risk-assessment Method (HARM)

Version: Nov-08

Task	....	Date	....
Department	....	Filled out by	....

Step 1. Task duration score

Step 1A:	Total time duration for which the task occurs 'on average during a working day (all time periods should be added together)'. Indicate the time duration only for the days that the task actually occurs (maximum of 1 decimal point)	... hours - 0,5 = ...
Step 1B:	How many days per week does the task occur? - 1 or 2 days per week: deduct 1 point from the score: - 3 or more days: score remains the same:	- 1 - 0
Step 1C:	Is a break of at least 7.5 minutes* taken every 1.5 hours? - yes: deduct 1 point from the score: - no: score remains the same:	-1 -0
* Read in the annex for an explanation of what is meant by a break		
Step 1D:	Calculate the task duration score — If the task duration score is less than 1, then the score is 1	....

Step 2. Most active hand Circle the most active arm/hand used during the task: **right / left / both**

Step 3. Force score

Step 3A Indicate: Indicate which is the most active hand used during the task (R, L, B)		Step 3B Duration of the force exertion (seconds per minute)			Step 3C TD Number of exertions of force per minute (frequency)		
		< 4	4-30	30-60	< 4	4-30	≥ 30
Amount of force	**Description and examples**						E
Extremely light: Weight: <100 g Force: <1 N	Light pressure applied with the fingers (e.g. holding a pencil with 2 or 3 fingers, sorting items, pressing with the fingers, pushing light object over a smooth surface)	0	1,5	3	1	2,5	4
Average: W: 100-1000 g F: 1-10 N	Using fingers/hand to hold small motorised tool Grasping/gripping, holding or attaching parts, pressing firmly	0	2,5	4	1	2,5	4
Somewhat high: W: 1-3 kg F: 10-30 N	Holding firmly with the hand (use of a knife/pliers, using tools, pushing heavier objects (e.g. cashier operator)	0	3,5	6	2	3,5	6
High: W: 3-6 kg F: 30-60 N	High force exertion by the arm (heavy tools; operating a heavy lever)	0	4,5	7	2	4,5	7
Peak force	Striking with flat hand/fist	-	-	-	3	5	8

Step 3D Force score = highest score circled = ...

In the event of **extremely high forces**: *Please note!* If the force exertion is more than 6 kg, these must be assessed using a different method (e.g. lifting, or pushing/pulling risk assessment method).

Step 4A Posture score for the HEAD/NECK and SHOULDER/UPPER ARM

	Percentage of the task duration that the posture occurs: 0-10%	10-50%	More than 50%
The head is tilted further forward than shown in the first photograph, or is tilted back / The head is tilted further to the side than in the first photograph, or is turned to one side	0	1,5	3
The head is tilted forward **and turned at the same time**	0	2	4
The head is tilted backward **and turned at the same time**	0	3	4
Head (chin) pushed (extended) forward	0	1,5	3
The upper arm is raised further forward or to the side than shown in the photograph, or is raised backward **without** support for the arm	0	2,5	3,5
Shoulders raised (high)	0	3	4
Determine the 'neck/shoulder posture score' = highest score =	....		

Step 4B Posture score for the WRIST/LOWER ARM

	Percentage of the task duration that the posture occurs: 0-10%	10-50%	More than 50%
The elbow is markedly bent or extended	0	1	2
The lower arm is rotated further (in the direction of the arrows) than shown in the photographs below	0	1	2
The hand is bent sideways at the wrist (in the direction of the little finger and/or thumb) so that the position of the wrist is between the positions shown in the photographs.	0	1,5	3
The hand is bent at the wrist so that the position of the wrist is between the positions shown in the photographs	0	1,5	3
Determine the 'lower arm/wrist posture score' = highest score =	....		

Step 5. Vibration score

Are vibrating tools used?

- **No, insert '0' for the vibration score in the grey boxes below and proceed to step 6**
- **Yes, is the vibration intensity known?**
  - **No, go to 5A: Assessment if the vibration intensity is unknown**
  - **Yes go to 5B: Assessment if the vibration intensity is known**

Step 5A The vibration intensity is unknown

Which of the situations applies? Circle the corresponding score and place this in the grey box at the bottom.	**Duration of exposure within the task**	
	0-4 hours	**4-8 hours**
Description	**Score**	
Hardly any vibration, or no vibrations perceived or visible to the assessor and user	0	0
Vibrations not visible, but are perceived by the user (quivering sensation) and visible to the assessor	2	2
Vibrations just visible to the lower arm/hand, clearly perceived by the user and visible to the assessor	2	4
The hands, arms or shoulders can be clearly seen to vibrate and vibration clearly perceived by the user	4	4
Score for vibration: use the circled score:	......	......

Step 5B The vibration intensity is known

	Score	
Which of the situations applies? Circle the corresponding score and put this in the grey box at the bottom.	**Duration of exposure within the task**	
Vibration intensity	**0-4 hours**	**4-8 hours**
< 2,5 m/s2	0	0
≤ 2,5 - 5 m/s2	2	2
≤ 5 – 10 m/s2	2	4
≥ 10 m/s2	4	4
Score for vibration: use the circled score:	......	......

Step 6. Other factors:

Indicate for each situation whether it applies to the task	**Circle the correct answer**
Set breaks times (as opposed to at the employee's discretion)?	Yes/no
Unfavourable environmental conditions (e.g., cold and/or draughts)?	Yes/no
Disruption to concentration (only if work requires concentration)?	Yes/no
Poor contact with material and tools, as a result of wearing gloves for instance?	Yes/no
Having to perform high precision work with the hands or fingers?	Yes/no
Score for other factors	**Circle score:**
For 0 times 'yes' the score is:	**0**
For 1 time 'yes' the score is:	**1**
For 2 or more times 'yes' the score is:	**2**

Step 7. Calculate total risk score

Use the scores from steps 1 through 6	**Scores:**
Force score (step 3)	....
Neck/shoulder posture score (step 4A)	....
Lower arm/wrist posture score (step 4B)	....
Vibration score (step 5)	....
Score for other factors (step 6)	.... **+**
Calculate total score (A):	....
Insert task duration score (from step 1) (T)	.... **X**
Calculate risk score (task duration score (T) X total score (A))	....

Step 8. Risk assessment:

Determine the risk of the task using the table below:

Total score	**Risk**	Meaning
<25	GREEN	**No increased risk** of arm, neck or shoulder symptoms for virtually the entire working population.
25-50	AMBER	**Increased risk** of arm, neck or shoulder symptoms for some employees. In order to reduce the risk and provide optimum protection for all employees, it is important to take **measures** to lower the risk.
≥50	RED	**High risk** of arm, neck or shoulder symptoms. It is important to take **immediate action/measures to reduce the risks.**
Health complains		**If there are health complaints that are suspected to be related to the task, it is ALWAYS important to identify possible causes and take action!**

Figure 44 – Screen shot of the HARM assessment form (TNO, 2017). The full form is available from https://www.fysiekebelasting.tno.nl/sv/instrumenten/valkommen-till-hand-arm-riskbedomningsmetod-harm/.