Redesign of a Cable Tie Tool

Enhancing Ergonomics in Assembly Work

Master's thesis in Product Development

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Cover: The 3D printed design of the final prototype in different views

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Abstract

The Base Module Line (BML) at Volvo Truck's manufacturing plant in Tuve has the highest frequency of tightening and cutting cable ties, resulting in repetitive tasks for assembly operators. This repetitive work has led to work-related injuries, particularly pain and discomfort in the hands, wrists, shoulders, and back. Therefore, Volvo Truck wants to investigate if an existing electric cable tie tool can be redesigned to meet the ergonomic requirements at the BML. This Master's thesis aimed to develop an electric cable tie tool that can tighten and cut cable ties on the BML while ensuring ergonomic interaction for the operators.

Before creating a redesign proposal for the reference tool, it was important to understand the current situation and investigate all stakeholders' requirements and desires for a new tool. Data was gathered, summarized, and analyzed from interviews with operators and ergonomists and observing the work environment. Using a combination of traditional product development and reverse engineering methods, a prototype was then created. The final prototype was primarily produced using 3D-printed parts, integrating mechanical and electrical components from the reference tool.

Key outcomes include ergonomic improvements when using the prototype, particularly in altering operators' work postures, which reduced strain in the hand and wrist areas. Although the prototype is not fully functional, it effectively addresses the ergonomic challenges, contributing to a more comfortable working environment for the assembly operators.

Keywords: Ergonomics, Musculoskeletal Disorders, Cable Tie Tool, Product Development, Assembly Operators, Hand tool, Assembly Line Tools, Ergonomic Design, Industrial Ergonomics

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Stina Andersson Gejnäs and Saga Norin, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BML	Base Module Line
CAD	Computer Aided Design
HE	Heuristic evaluation
HTA	Hierarchical Task Analysis
MSD	Musculoskeletal Disorders
RULA	Rapid Upper Limb Assessment

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1

Introduction

This chapter aims to provide an understanding of the Master's thesis's context and relevance. It explains the project's background and presents its aim, research questions, project scope, and delimitation. Additionally, an outline of the thesis is included to describe the structure of the report.

1.1 Background

Volvo Trucks in Tuve, Gothenburg, manufactures heavy trucks. Volvo Tuve was the first truck manufacturer to produce heavy electric trucks serially, built on the same assembly line as combustion engine trucks. Additionally, the plant manufactures chassis for the trucks, which are then shipped to other factories and assembly facilities worldwide. Volvo Tuve has a yearly production capacity of 87,500 pairs of frame beams for the chassis [1].

During the chassis assembly process, cables are secured onto the frame beams with cable ties. The tightening and cutting cable ties is a repetitive task that poses ergonomic challenges for assembly operators. Currently, operators experience discomfort due to this repetitive task. With the introduction of electric trucks, the number of cable ties has increased, which makes the need for an ergonomic cable tie tool highly prioritized to reduce the risk of work-related injuries.

All trucks produced by Volvo Tuve consist of five physical modules. Each physical module is assembled simultaneously in separate assembly lines. Afterward, each module progresses to the main assembly line, where a complete truck is built. The foundation of the final assembly is called the Base module, which connects the other four physical modules. The production line where the Base module is assembled consists of 15 stations, each 13 meters long, with around four to six balances at each station. A balance represents the tasks that need to be completed by an assembly operator before the truck moves on to the next station of the Base module line (BML). Figure 1.1 visualizes the layout of the BML on a smaller scale.

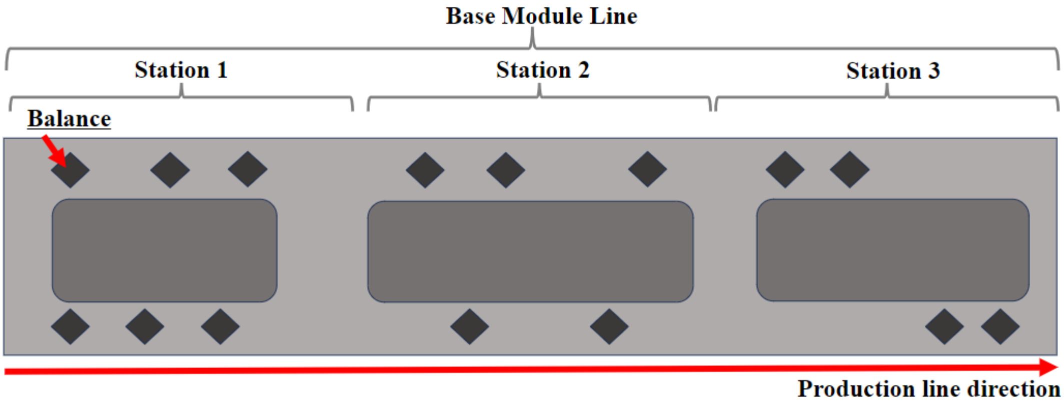

Figure 1.1: Visualization of the BML

According to Volvo Tuve ergonomists [2], the BML has the highest frequency of tightening and cutting cable ties, resulting in repetitive work for assembly operators. Many operators at the BML have reported work-related injuries, particularly pain and discomfort in their hands, wrists, shoulders, and back, primarily linked to ergonomic factors. Therefore, it is imperative to introduce a tool to prevent such injuries from occurring.

At the BML, assembly operators currently use two different tools, one manual and one electric, for tightening and cutting cable ties. However, these tools fail to meet the mechanical and the ergonomic requirements. Therefore, Volvo Tuve aims to introduce a third tool at the BML that can fulfill both needs.

The third tool will be the foundation and reference point for the project. It has been utilized in other areas of the factory where the working environment differs from the BML. The BML is a mixed-model moving assembly line where all operators follow the chassis and work dynamically, while the reference tool has only been used in a static environment adapted for the operators, work postures.

Although the reference tool fulfills the mechanical requirements, it needs to meet the ergonomic demands required at the BML. The goal is to incorporate this tool into the process, modifications are necessary to align it with the stakeholders' requirements, especially requirements from the operators and the ergonomists.

1.2 Aim

The project aims to develop an electric cable tie tool that can tighten and cut cable ties at the BML while ensuring ergonomic interaction for the operators. This will be accomplished by redesigning a reference tool to meet stakeholders' requirements. The primary focus will be on enhancing the ergonomic features of the tool to create a prototype that can ergonomically tighten and cut cable ties.

1.3 Research Questions

The research questions are designed to ensure that the project achieves its aim:

- How can the ergonomics be improved in the reference tool?
- How should the tool be designed to meet the stakeholders' requirements?
- How can the tool be evaluated as an ergonomic hand tool?

1.4 Project Scope

The project will be conducted over 20 weeks by two Master's thesis students (the project team). Its objective is to develop an ergonomic tool for tightening and cutting cable ties on the BML.

The redesigned tool will be based on an existing electrical cable tie tool. Therefore, the mechanical and electrical components will be treated as a ”black box”, focusing solely on the interface between the mechanical and electrical parts, as well as the design of the shell.

A comprehensive review of the reference tool will be conducted to understand the potential changes that can be made.

Additionally, the existing electric tool will undergo ergonomic evaluation in the user environment through testing and analyzing the current state.

Establishing the tool's requirements is crucial to initiate its development. Therefore, it is essential to identify all stakeholders' needs and desires regarding the new cable tie tool. Furthermore, feedback sessions will be conducted to ensure stakeholder satisfaction with the result.

Finally, the project aims to create a prototype that fulfills the requirements provided by the stakeholders. An assessment will be conducted to evaluate the prototype's performance in meeting these requirements.

1.5 Delimitations

To reach the purpose of the project, delimitations are needed. Therefore, the following points will be excluded from the project:

- The project will not focus on optimizing material and manufacturing for the tool due to time constraints.
- Given the existing interest in the product, a comprehensive market study is deemed unnecessary.

- Cognitive ergonomics will not be the focus of development.
- The scope of this study does not include alterations to the truck assembly process to achieve optimal ergonomics.
- The project will not investigate whether the product reduces the number of Musculoskeletal disorders (MSDs) due to time constraints.
- The project will not develop a process for implementing a new tool. However, the topic may be discussed if insights about tool acceptance or rejection are found in the collected data.
- The project does not include a design adapted for all work positions where a cable tie is attached on the BML.

1.6 Outline of Master´s Thesis

The master's thesis consists of multiple chapters that are outlined below:

Chapter 2: Theoretical Framework - The chapter covers topics related to the development of an ergonomic tool.

Chapter 3: Methodology - The chapter explains the development process and methods used for the development of an ergonomic cable tie tool.

Chapter 4: Current Situation - The chapter outlines the current ergonomic situation at the BML and introduces the reference tool.

Chapter 5: Results - The chapter presents the results obtained from the methods used.

Chapter 6: Discussion - The chapter discusses the methods used, the results, and the ethical aspects of the Master's thesis.

Chapter 7: Conclusion - The chapter presents the conclusion and answers the research questions for the Master's thesis.

2

Theoretical Framework

This chapter provides a theoretical framework on ergonomics, focusing on hands and MSD, as well as physical load, and hand tool design guidelines. This knowledge was applied to the project's ergonomic evaluation and concept generation.

2.1 Ergonomics

The term ergonomics comes from the Greek words *ergon* and *nomos*, which mean work and law, respectively, and it is roughly defined as the study of people in their working environment [3]. Ergonomics is typically classified into three primary types: physical ergonomics, cognitive ergonomics, and organizational ergonomics [4]. Physical involves designing tools, equipment, and workstations to reduce the risk of injury and discomfort. Cognitive ergonomics refers to how information can be presented and processed in a way that is easy to understand and use. Organizational ergonomics concerns how the organization's overall structure, policies and process affects people [4]. The theoretical framework will be focused on physical ergonomics due to the project scope and delimitation.

2.1.1 The Hands

The hand is a crucial body part for humans as it enables them to work. Injuries to the hand can hinder daily life and prevent people from working [3]. The hand is also for communicating, conveying emotions, and expressing personality. The hand consists of several segments, including bones, joints, nerves, tendons, ligaments, muscles, arteries, and veins. Together with the wrist and arm, it forms a sensitive structure that can get overloaded and injured by physical work. Consequently, it is imperative to tailor the design and development of work tasks to accommodate the specific needs and capabilities of the hands [3].

The hand´s skin is equipped with thousands of sensors called receptors, which enable humans to sense temperature, pressure, and pain [3]. In addition to their ability to sense temperature, pressure, and pain, the hand is also capable of moving in various directions and gripping in different ways. Figure 2.1 explains the different motions, and Figure 2.2 illustrates the types of grip.

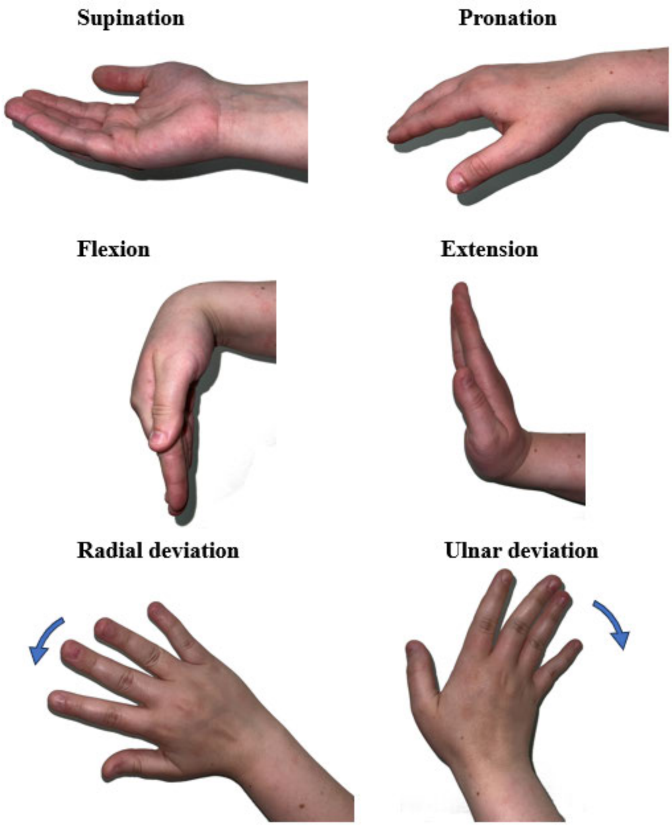

Figure 2.1: The hands' different motions inspired by C. Berlin & C. Adams [3]

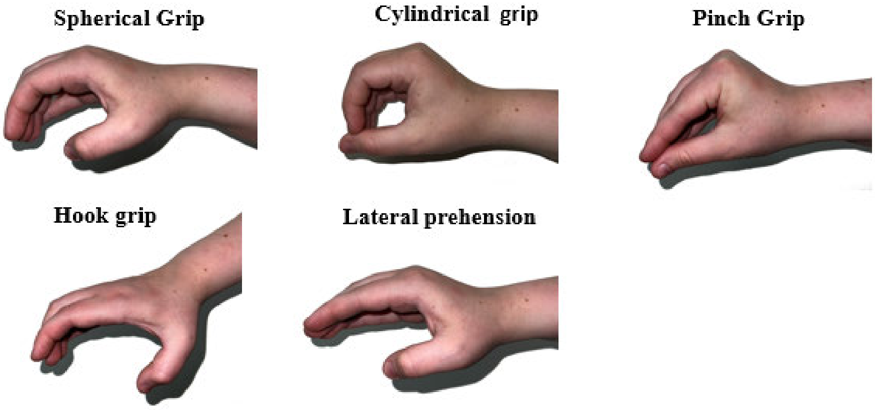

Figure 2.2: The hands' different grips inspired by C. Berlin & C. Adams [3]

Aside from the hand's ability to move and grip, each finger on the human hand possesses unique strength and gripping abilities. Based on statistical analysis, the middle finger is considered the strongest, while the little finger is the weakest. Statistically, the index, middle, ring, and little fingers generate forces of approximately 21%, 34%, 27%, and 18%, respectively [5].

2.1.2 Musculoskeletal Disorders

A human's ability to work depends on physical health [3], especially in the production industry where physical work is necessary. One result of pushing the limits of what the human body can tolerate in the production industry is the development of work-related MSDs. MSDs are injuries or disorders of the muscles, nerves, tendons, joints, and cartilage caused by multiple physical factors in the work environment, which can include limitations in muscle power, restricted range of movement, and loss of function [6]. MSDs have the highest impact on sickness absenteeism in Europe and are associated with the highest rate of permanent work incapacity due to health problems. However, operators are one of the work groups at the greatest risk of being affected by MSDs due to manual labor [3].

2.1.3 Physical Load

There are two variants of physical load when discussing ergonomics: full-body and local stress [7]. As the names imply, local stress is more about a concentrated area of the body part, and full-body stress involves large sections of the body's musculature. However, both variants can cause a high risk of injury to the human body due to hard physical work.

Physical load, in ergonomics, is based on three related components: force, posture, and time [3]. Force refers to external loading caused by weight and actions like pulling, pushing, lifting, dragging, or pressing. Posture involves the distribution of internal forces across different parts of the body, as well as the body's position. The third factor affecting the body is time, which refers to the duration and frequency of exposure to a load, rather than the load itself. Physical load is therefore described according to Equation (2.1) [3].

$$\textbf{Physical loading} = \textbf{Force} \times \textbf{Posture} \times \textbf{Time} \tag{2.1}$$

The cube model visualizes the relationship between force, posture, and time [8]. Each side of the cube represents one of the three factors and is divided into three different levels of severity: low, moderate, and high, resulting in 27 subcubes. Figure 2.3 illustrates the cube model with the different severity levels, illustrating that while a high level of one factor may be acceptable, it may not be so when considering all factors together [3]. The degree of severity is indicated by a color scheme, with red representing high risk, yellow indicating medium risk, and green denoting low risk.

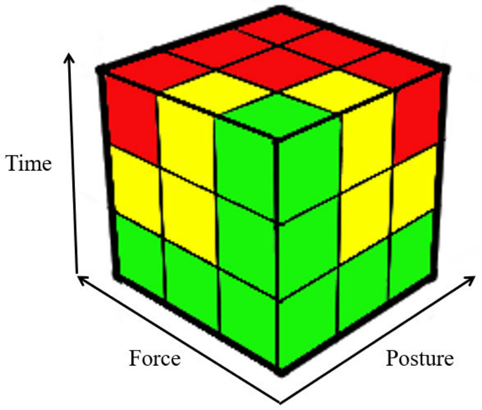

Figure 2.3: The cube model by Sperling et al.[8] illustrated by S.Anderson Gejnäs & S.Norin, based on C.Berlin and C.Adams [3]

2.2 Design of Hand Tools

It is common knowledge that hand tools have been used and produced for over hundreds of years. It was not until the Industrial Revolution that the design of hand tools began to be standardized [7]. Nowadays, when designing hand tools, it is of value to follow ergonomic guidelines and standards to ensure they are adapted to the human body. The design aims to minimize the risk of long-term injuries, making good design a priority [3].

In general, several principles should be followed when designing a hand tool. First, the hand and tool should have a large contact area to ensure maximum stability and even force distribution, resulting in low surface pressure [7]. It is also advisable to allow for varying postures to relieve strain on the hand. Secondly, the tool should be lightweight; for non-precision tools, the recommended maximum weight is 2.3 kg. Thirdly, to prevent MSDs while using tools, natural hand grips should be used to maintain a functional hand position, avoiding bending and twisting [7]. Additionally, it's important to avoid vibration, particularly in the injury range of 5 to 2000 Hz [3]. Furthermore, objects with sharp edges should be avoided in all circumstances, as they pose a significant risk of injury. Similarly, finger-form handles should be avoided, as they are only compatible with a specific hand [5]. These precautionary measures will help ensure the safety and well-being of all individuals involved in the task or activity.

2.3 Volvo Trucks Ergonomical Guidelines

When designing a tool for manufacturing, Volvo Trucks [9] has produced its own guidelines based on various ISO standards in ergonomics. The guidelines have three recommendation levels: low, medium, and high, to describe the ergonomic impact. Table 2.1 describes the definition of the three recommendation levels.

Table 2.1: The recommendation levels and definitions from Volvo Group [9]

Recommendation level	**Definition**
Low-impact	"The level of physical and / or cognitive workload means that no one or few employees are exposed to risks within both short and long term."
Medium-impact	"The level of physical and / or cognitive workload means that several employees are exposed to risks within both short and long term."
High-impact	"The level of physical and / or cognitive workload means that most of the employees are exposed to risks within both short and long term."

The guidelines [9] divides the posture into different colored areas to define a more or less ergonomic working position, see Figure 2.4. The green area is defined as the optimal working area with a low-impact recommendation level. It is recommended that operators spend as much time as possible working in this area to reduce the risk of injuries or MSDs. The yellow area is defined as an acceptable working position for a short duration, and falls under the medium-impact recommendation level. Lastly, the red area indicates a high-impact recommendation, which should be avoided as much as possible.

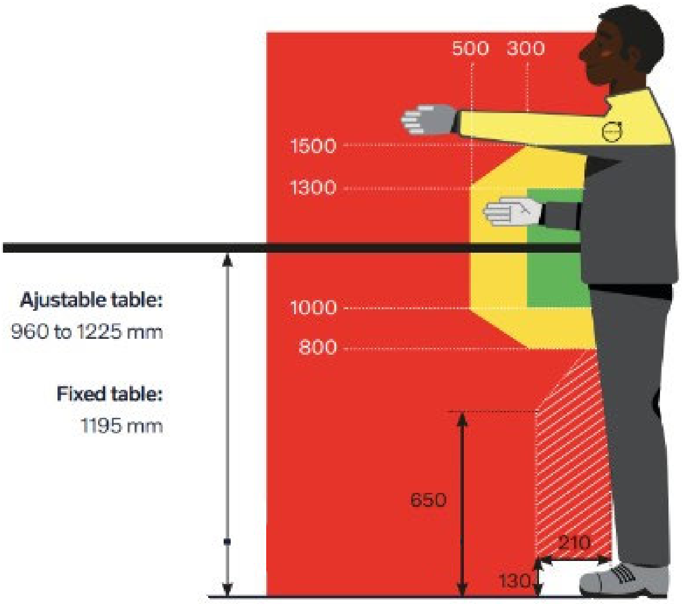

Figure 2.4: Visualization of ergonomic working areas [9], used with permission

3

Methodology

This chapter presents the methodology utilized in conducting the research outlined in the introduction. The methodology serves as the framework for addressing the research question and achieving the aim. By outlining the methods, procedures, and approaches used, this chapter offers transparency and insight into the systematic process undertaken to fulfill the aim of the study.

The project consisted of four different phases, see Figure 3.1. The initial phase focused on acquiring knowledge and understanding of the problem. In the second phase, solutions and ideas were generated to address the issue. The third phase involved selecting a concept and developing a prototype. Finally, the fourth phase entails conducting tests and evaluations to verify the prototype and the selected concept.

Figure 3.1: Project overview

3.1 Preparing for Concept Development

The phase of preparation for product development consists of three stages: data gathering, current state analysis, and identification of stakeholder needs. The primary purpose of the data collection and current state analysis was to generate knowledge and an understanding of the stakeholders' needs. The results from the stages served as the basis to create a product specification, which describes the requirements and desires for a new tool. The process is illustrated in Figure 3.2.

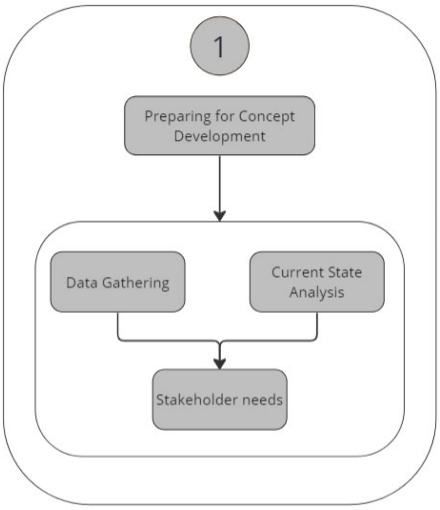

Figure 3.2: Overview of phase one of the project

3.1.1 Data Gathering

312Data was collected continuously throughout the project. The stakeholders included assembly operators at the BML and ergonomists at Volvo, who significantly influenced the design of the new cable tie tool. The data was primarily collected through interviews and observations, and internal statistical data was also utilized to access information about the current ergonomic situation. The database gathers information and statistics about reported accidents, work-related diseases, incidents, and risk observations.

Interviews

Semi-structured interviews were conducted to gather information from stakeholders and understand their needs. A semi-structured interview is a research method that blends the strengths of structured and unstructured interviews [10]. It uses a predetermined set of questions and allows the interviewer to ask supplementary questions. The aim was to gain information while allowing for additional details if needed.

The interviews were conducted with both operators and ergonomists. An interview template was prepared beforehand, which included two types of questions: open-ended and probing. Open-ended questions were used to get a general and broad viewpoint of the current situation. The probing questions were designed to expand on the participant's response. The questions used for the interviews can be found in Appendix A.1 and Appendix A.2. During the interviews, the reference tool was provided to help the participants interact with the product and express their needs. The project team documented all interviews through notes and then summarized directly afterward to ensure that everything was noted. Before each interview, participants were asked to give consent in compliance with the General Data Protection

Regulation [11].

Fifteen assembly operators at the BML were interviewed, and each interview lasted for approximately fifteen minutes. The interviews aimed to gain insights from the operators regarding the current situation and their needs. These interviews were conducted face-to-face at the BML. Moreover, interviews were conducted with five assembly operators from other production lines to investigate how the reference tool operates, and explore its strengths and weaknesses.

Two formal interviews were conducted with two ergonomists working at Volvo Trucks. The purpose of the interviews was to gather insights about their needs and establish a strong understanding of the ergonomic situation at the BML. Each interview lasted for an hour and was conducted face-to-face. Additionally, the project group has maintained continuous meetings with the ergonomists, collaboratively discussing and analyzing the progress to achieve a satisfactory result.

Observation

Observation is a method employed in user research to understand how participants interact with an existing product [12]. Observing their behaviors, actions, and reactions can uncover valuable insights and identify specific needs that can inform the development of a new tool. Observations can take different forms, from passive observation of user behavior to active engagement during user interactions with the product [12]. The primary goal of these observations was to gain a understanding of the current situation at the BML and to evaluate the functionality of the tools being used in the area.

During a passive observation session, the ergonomists explained which positions operators were compromising their work posture to tighten and cut cable ties. The ergonomists communicated and demonstrated the risks involved with these positions and suggested alternatives. Based on the observations, the ergonomists, together with the project group, decided on four work positions to focus on when redesigning the reference tool. The observation session served as preparation and groundwork for upcoming events and was documented with pictures and notes.

Another observation was an active interaction, where the development team gained firsthand user experience. The observation took place at the BML and lasted for three hours. During that time, the development team performed the task and observed how assembly operators interacted with the cable tie tools and what positions they worked in. The observations involved working at various stations at the BML to examine a range of balances. The active observation provided valuable insights into the critical positions operators faced and offered firsthand experience in using the existing tools.

3.1.2 Current State Analysis

To begin the development process, it was necessary first to map out the current situation. This involved examining the ergonomic conditions under which the reference tool will be implemented, as well as how the existing tools were utilized. Additionally, it was essential to study the reference tool in order to gain a understanding of how it could be redesigned.

Identification of Ergonomic Situation

The ergonomic situation at the BML was identified by using various methods, including interviews, observations, and meetings with ergonomists, described in Section 3.1.1. The process also involved heuristic task analysis (HTA), heuristic evaluation (HE), and Rapid Upper Limb Assessment (RULA).

HTA is a method used to break down complex tasks into simpler, more manageable subtasks [3]. This process involves identifying the overall goal of a task and then decomposing it into smaller steps or actions required to achieve that goal. Each of these tasks is then further divided into subtasks, and observations creating a hierarchical structure that maps the entire task in detail. HTA is used in ergonomics to understand the physical demands placed on users, allowing for designing user-friendly systems and tools.

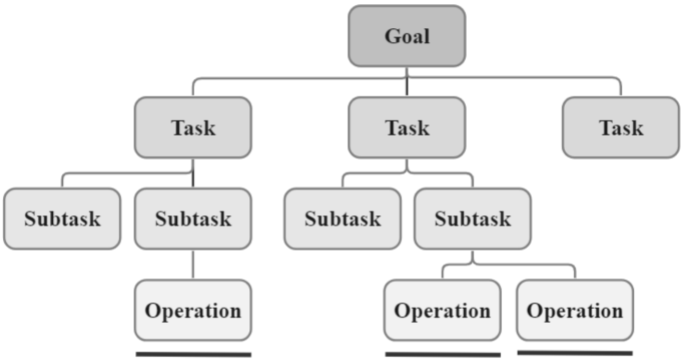

Figure 3.3: HTA structure, inspired by C.Berlin & C.Adams [3]

To evaluate the HTA, a heuristic evaluation (HE) [3] was utilized. The method evaluates the broken-down tasks according to a set of accepted principles to identify critical operations. The principles are based on theoretical knowledge about ergonomics, human ability, and physical limitations. A HE can be structured, unstructured, or semi-structured. A structured HE is when all the heuristics are predefined before the analysis and evaluation, while an unstructured HE can develop a heuristic list during evaluation [3]. A semi-structured HE is a blend of structured and unstructured heuristic evaluation. The evaluation applies a color-coding system to prioritize changes and visualize the severity of problems for each task. The color level indication has been defined in Table 3.1 and is based on the information presented in Section 2.3.

Table 3.1: The HE color coding and their meaning

Color	Definition
Green	No ergonomic problem. Consider as okay
White	Inconvenience problem. No need to be fixed unless time is available
Yellow	Minor or mayor ergonomic problem. Needs to evaluate more, but important to fix
Red	Serious ergonomic problem. Need to be fixed

The initial step in performing the HTA was to determine the main goal of the task, which was defined as tightening and cutting cable ties using the existing electric tool. The motivation for executing a HTA on the existing electric tool was to replicate the current situation for cutting and tightening cable ties.

Afterward, the goal was divided into tasks and subtasks. This breakdown helped identify the specific postures and movements used by the operators during task performance. By examining each subtask in detail provided insights into the ergonomic challenges present in the assembly process at BML. This involved considering factors such as repetitive motions, unergonomic postures, and potential strain points, all of which are crucial for evaluating and improving ergonomic conditions.

The HE was conducted in collaboration with an ergonomist to identify where and why a task is critical. The result was presented by coloring the different tasks and subtasks in the previously formulated HTA.

A RULA was executed to evaluate the ergonomic situation at the four selected work positions. RULA is an evaluation tool for upper-body work tasks [13]. The method evaluates the working postures of the arms, wrist, neck, legs and back, as well as the frequency and load. The evaluation tool utilizes a coordinate system to generate a list of actions. The result of the evaluation is used to indicate the level of actions needed to reduce the risk of injuries.

RULA evaluates two categories; the first category, Table A, evaluates the position of arms and wrists. The second category, Table B, examines positions of the neck, back, and legs [13]. In each category, there are several evaluation criteria for each body part. Each criterion is assigned a score based on the angle and posture of the body part. After scoring each body part, the values are combined to result in a total score for each category.

Once the total score for each category has been determined, an analysis of the frequency and load is then conducted. The score assigned from Table A is combined with the frequency and load scores, resulting in a combined score, value C. The same process applies to Table B, resulting in value D.

Thereafter, an additional table is used to give a combined final value for both categories, which describes the level of action required for the particular work posture. Table 3.2 describes the different action levels deepening on the RULA result number.

Table 3.2: Action levels of RULA inspired by J.Axelsson & J. Karltun [13]

Level	RULA result	Definition
1	1, 2	Acceptable
2	3, 4	Investigate further
3	5, 6	Fast action
4	7 +	Immediate action

To evaluate the full range of human body statistics, the project team decided, together with ergonomists, to focus on extreme scenarios for each biological gender during the review of working posture. As a result, the evaluation involved assessing one candidate at the 10% lowest percentile range of human height and another at the 90% highest percentile range of human height [14]. The percentile range for the two extreme scenarios is showed in Table 3.3. This approach aimed to investigate that the tool is suitable for extreme scenarios, assuring that it will function effectively for individuals within the range of these extremes.

Table 3.3: Height of the percentiles [14]

Percentile	90%	10%
Men	≥188	≤170
Women	≥174	≤158

The chosen participants consented to being photographed and to taking part in the analysis anonymously. Thereafter, the candidates recreated the postures for each position to be used when performing the RULA. The researchers provided instructions on each posture, explaining the most common body alignment observed and illustrated it.

After documenting each position, the project group collaborated with ergonomists at Volvo to conduct the analysis. Each image was discussed and analyzed to assign a score to each position based on ergonomic criteria. The values were then summarized in a table, and the results were analyzed to identify ergonomic challenges.

Reference product

A systematic approach, inspired by reverse engineering [15], was employed to analyze the reference tool with the objective of understanding its functionality. While the primary function of the tool was not to be altered, certain aspects of the methodology were utilized to identify any modifications that could be made without affecting the primary function. Reverse engineering typically involves finding new ways to enhance the primary function in terms of performance, durability, or similar factors [15]. However, in this case, the focus was on retaining the mechanical performance and investigating how the reference tool could be reshaped to enhance ergonomic factors, such as shape and weight.

The process started with testing the tool and creating a black box diagram [15]. The diagram was used to understand the primary function of the tool and to visualize the inputs and outputs of material flow, energy flow, and signals needed to perform this function.

Thereafter, the reference tool was systematically disassembled to understand its components and identify which ones could constrain the design of a new tool. Photos were taken during the disassembly to document the assembly order of the parts. The bill of materials (BOM) listed the components of the tool's assembly in the order of their arrangement [15]. Each component's name, material, description, quantity, and weight were included in the list.

A function analysis was created after examining the black box and the disassembly of the reference tool. Functional analysis involves breaking down a product into its functional components and understanding how each element contributes to the main function [15]. It focuses on what a product does rather than how it does it. The first step to conduct a function analysis is to create an energy flow to clarify how the energy moves through the product's components [15]. The second step is to break down the primary function into sub-functions. Creating a function analysis diagram gave clarity of what functions that the reference tool must have to maintain its primary function.

3.1.3 Identification of Stakeholder Needs

The process of identifying the ergonomist and operators needs was carried out by gathering information and knowledge described in Sections 3.1.1 and 3.1.2. The outcomes have been compiled into a stakeholder needs list and a product specification.

Stakeholder Needs List

From the interviews and observations, the ergonomists' and operators' statements were transformed into needs. To organize the collected data, a spreadsheet was created. The spreadsheet includes the stakeholder, their statements, and the translation to a need. When transforming a statement to a need it is important to specify the need in terms of its functionalities, rather than detailing the specific methods of achieving them [12]. In the spreadsheet, not all stakeholder statements were added, as many expressed the same needs in similar expressions.

After completing the spreadsheet of statements, the needs were sorted, duplicates were deleted, and then ranked by weight of importance. The need could get a ranking of importance between one and five, depending on what the stakeholder had expressed as their most significant issues. Value one is considered the lowest and five the highest. The reason for ranking the needs is to create a guideline when redesigning the reference tool and ensure that the stakeholders are in focus [12].

Product Specification

A product specification is a spreadsheet that displays what the tool has to achieve to satisfy the stakeholder's needs [12]. It consists of criteria, target value, classification, rank, verification method, and which stakeholder the criteria are associated with.

The criteria in the product specification are based on the data obtained from the stakeholder needs list, Volvo's ergonomic guidelines, and theory. Each criterion was assigned a target value and classified as either a requirement (R) or a desire (D), where a requirement indicates a criterion that must be fulfilled. The target values and classifications were set by discussing with the ergonomists. After that, the level of importance for each criterion classified as a desire was set in collaboration with the stakeholders. The ranking of importance was significant in understanding how to prioritize when facing trade-offs. Moreover, the criteria were assigned a verification method to investigate if the prototype achieves the target value.

3.2 Concept Development

The concept development phase consisted of two stages, as shown in Figure 3.4. This phase followed the *Product Design and Development* methodology [12] stages for concept generation, concept selection, testing, and evaluation. The concept generation employed an iterative approach that begins with broad exploration and progressively narrows down, similar to a funnel. Additionally, the methodology allows for the integration of new ideas and improvements to existing concepts as new insights are gained.

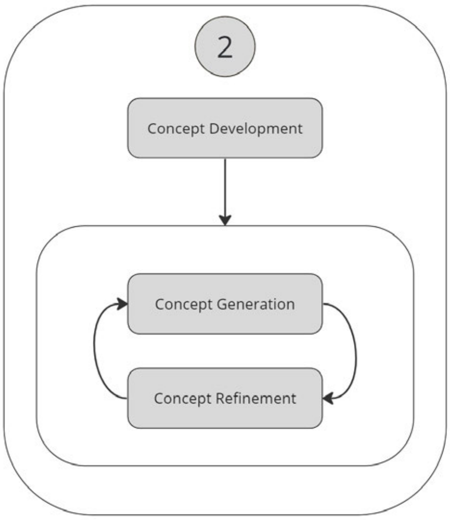

Figure 3.4: Overview of phase two of the project

3.2.1 Concept Generation

To solve complex problems, the five-step method [12] is employed, as demonstrated in Figure 3.5. The five-step approach involves breaking down the problem into smaller, more manageable sub-problems, which are solved through external and internal searches. Once solutions for each sub-problem are found, they are systematically combined to generate an overall solution. The process and solutions are then evaluated [12]. The goal of utilizing this method was to generate concepts systematically, eventually leading to innovative and unexpected solutions.

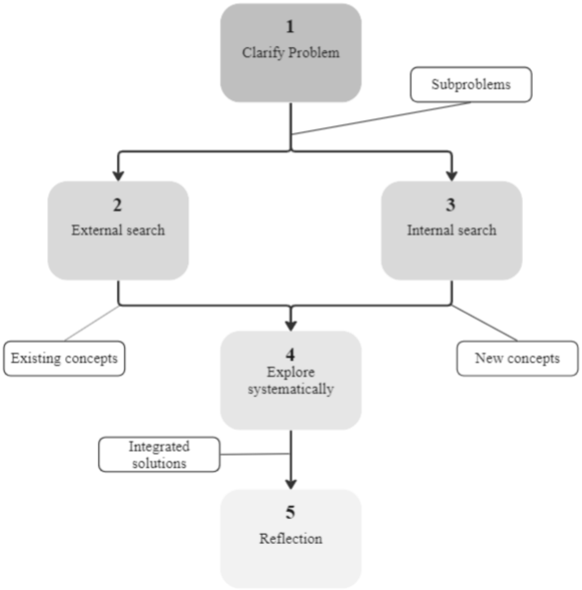

Figure 3.5: Five Step method inspired by Ulrich et al. [12]

Clarification of the Problem

According to Ulrich et al. [12], it is essential to understand the problem comprehensively by breaking it down into sub-problems. The sub-problems were formulated based on the black box, current state analysis, and product specification. The aim was to clarify the problem by dissecting the primary function to facilitate the development of solutions to solve the main issue.

External Search

External searching involves strategically using external solutions and gathering relevant information. One practical approach to external searching is the expand-and-focus strategy [12]. This method involves gathering broad information that could be relevant to the problem, followed by a more detailed exploration focused on the issue at hand.

The expand-and-focus strategy was used in a patent landscape analysis [12] to identify external solutions for the main problem and its sub-problems. The aim was to gather knowledge and inspiration of technical knowledge and information. The analysis was conducted for each of the identified sub-problems, allowing for a comprehensive range of technical solutions across relevant areas.

The patent analysis involved conducting patent searches via Espacenet and Google Patents, both widely recognized databases for patent information. The search process involved keywords to obtain technical information about the patents of interest. Keywords used in the search was ”handle”, ”ergonomic electric handle”, ”ergonomic hand tool”, ”hand-held tool”, and ”ergonomic aid”. After finding interesting patents, their patent classifications were used to find other relevant patents. The selected patents were then documented and subjected to further analysis.

Internal Search

The internal search process involved leveraging internal knowledge and creatively generating solutions and ideas. A method for this is brainstorming, a creative technique used to solve problems and generate new ideas [16]. One effective technique within brainstorming is known as ”stop and go” [17]. This method entails producing ideas within a limited time frame, followed by a period of reflection before proceeding to the next round of brainstorming. Another technique is interactive brainwriting, wherein team members collaborate to develop ideas and produce innovative solutions by contributing to each other’s ideas [18].

During each ”stop and go” session, individual sub-problems were addressed, with separate stages for idea generation and reflection lasting five minutes each. These sessions were conducted by the project team, and outcomes were noted on Post-it notes and sorted into categories such as function and shape. The aim was to brainstorm as many potential solutions as possible for each sub-problem.

The brainwriting session was divided into two five-minute sessions: one for individual brainwriting, followed by an inspirational idea generation session based on members’ solutions. This approach was specifically used for sub-problems related to ergonomic grip and trigger mechanisms, as these functions were central to the ergonomics of the reference tool. The results were summarized on Post-it notes with images and text.

After the brainwriting session, a feedback session with ergonomists and tool designers was conducted to gather additional ideas for sub-solutions. The outcomes from the previous brainstorming sessions were presented to the participants, and advantages and disadvantages of the solutions were discussed. The ergonomists and the tool designers were then tasked with generating new solutions for the various sub-problems and enhancing solutions from previous idea generating session. The results were summarized on paper and on Post-it notes.

Explore Systematically

The generated sub-solutions were merged into concepts using a morphological matrix [19]. A morphological matrix is a systematic approach to combining sub-solutions into conceptual designs. Each sub-problem represents a row, and each column represents a potential way to solve the problem. By pairing one sub-solution from each row, an overall solution can be derived.

Many of the concepts were anticipated to be similar, distinguished only by minor details. Therefore, the feasible course of action was to generate a limited number of potential combinations of solutions from the morphological matrix.

Concept Evaluation and Screening

To evaluate the generated concepts, it was necessary to seek the opinions and knowledge of the operators and the ergonomists to assist in making a decision. A list of pros and cons [12] was utilized to screen and select concepts based on the advantages and disadvantages identified. The outcome from the list assisted in determining which concepts to further development.

Initial prototypes were 3D-printed to evaluate the shape of the concepts. These prototypes were simple and constructed on a one-to-one scale, following the dimensions requirements outlined in the product specification. The shape of the prototypes was evaluated in two different ways: one user test with the operators and another with the ergonomists. The findings from the user tests were compiled, resulting in a pros and cons list for each concept.

The first user test was conducted with a group of five operators at the BML. During the test, operators could evaluate how the shape impacted accessibility, grip position, and suitability for the working environment by testing the prototypes. The objective of the test was to gather data on the advantages and disadvantages of the concepts' shape.

Furthermore, a user test was carried out with the ergonomists to gain valuable insights into the ergonomic aspects of the designs. Within this test, the ergonomists could assess the prototype's grip position and examine the shapes of the concepts.

Following the completion of user tests, a screening process was implemented to evaluate the advantages and disadvantages of the proposed concepts. The information gathered from the user test served as the foundation for decision-making about which concepts to further develop.

3.2.2 Concept Refinement

After evaluating the concepts, new designs were created by combining advantages from the previous concepts with new ideas based on feedback from user tests. The goal was to improve and enhance the first generated concepts.

To evaluate the new concepts, detailed prototypes were created through 3D-printing. The aim was to assess the impact of weight distribution and battery placement on the design, as the concept's weight plays a crucial role in applicable ergonomics. Likewise, the evaluation aimed to evaluate the shape and the handle of the concept.

User tests were conducted once more with the operators and the ergonomists. During these sessions, users engaged with the prototypes and offered insights, contributing to the iterative refinement of the design. The feedback was used as a decision basis for which concept would be chosen as the final concept for detailed development.

3.3 Detailed Development

The third phase of the methodology, detailed development, is composed of three steps, illustrated in Figure 3.6. The initial is focused on refining the final concept in detail. The second step involves developing a detailed 3D-model of the final concept, and the concluding step entails creating a physical prototype.

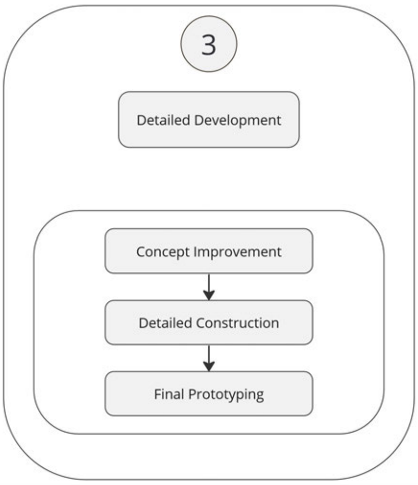

Figure 3.6: Overview of phase three of the project

The design of the final concept underwent iterative improvements based on feedback collected from operators and ergonomists . Feedback was obtained through meetings, where discussions focused on enhancing the comfort of the handle, ease of use, and alignment with ergonomic principles. Iterative design cycles were then employed to implement suggested improvements, with Computer Aided Design (CAD) models and prototypes to test the revised designs.

Following the collection of feedback, iterative cycles were used to implement and evaluate proposed improvements. The CAD models were adjusted to integrate suggested changes, and the model was 3D-printed to test the modified design. Operators and ergonomists were involved throughout this process, providing input on the implemented improvements.

This iterative approach allowed for continuous refinement of the final concept, ensuring that it met the ergonomic requirements and desires of users. Feedback loops were closed by reviewing the concept with stakeholders to validate improvements and identify any remaining areas for enhancement.

After detailed construction, a physical prototype was produced featuring 3D-printed parts, a contact, extended cables for the electrical components, and the mechanism from the reference tool. All parts were assembled, resulting in a final prototype.

3.4 Verification and Evaluation

The final phase consists of two main parts, as shown in Figure 3.7. In the first part, the working position when using the prototype was evaluated and compared to the existing tool's work positions. In the second part, the product specifications were analyzed to verify which criteria and desires had been fulfilled.

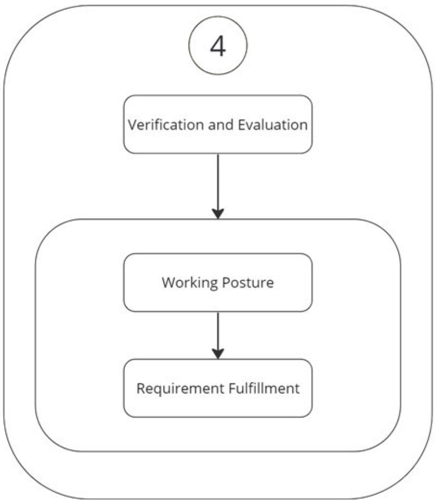

Figure 3.7: Overview of phase four of the project

To evaluate the prototype's work posture, RULA [13] was applied to the four selected work positions using the prototype. The method was previously explained in Section 3.1.2. The results of the RULA evaluations conducted during the current state analysis were compared with those obtained from the prototype evaluation.

The requirements and desires were evaluated and verified according to the verification method outlined in the product specification, see Appendix A.4. The verification process involved systematically reviewing each requirement and desire specified in the product specification document to ensure compliance and fulfillment.

4

Current Situation

This chapter provides an in-depth explanation of the existing ergonomic situation at the BML and the reference tool. The chapter sets the baseline for understanding the ergonomic challenges the new tool aims to address.

4.1 Identified Ergonomic Situation

The assembly operators working at the BML are all of different heights, ages, and genders. Unfortunately, many of them experience discomfort from tightening and cutting cable ties. Assembly operators at the BML have reported work-related injuries over the past six years. The most common injuries is in the back, shoulder, hand, and wrist, see Figure 4.1. Out of these, wrists and hands are the most frequently reported, according to Volvo Tuve's internal database [20]. The wrist and hand injuries are most often related to assembling and using hand tools.

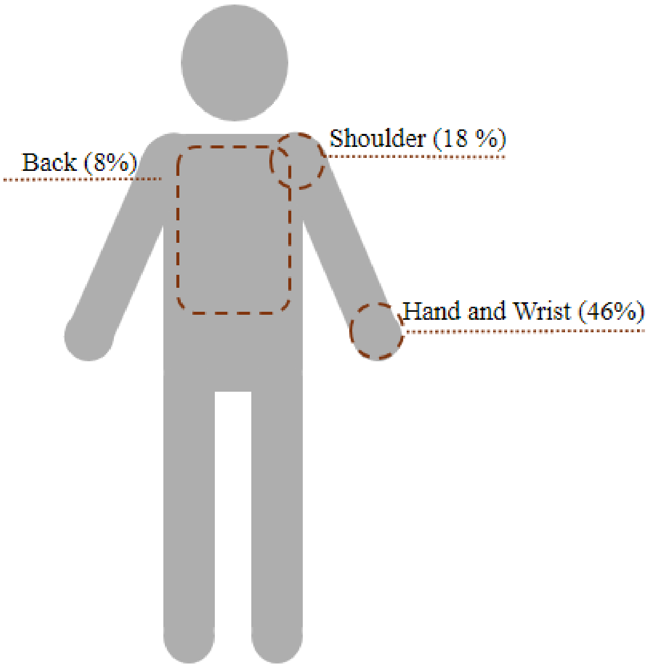

Figure 4.1: The most commonly injured body parts at the BML

At BML, operators have two tool options for tightening and cutting cable ties. The preferred option is a manual tool, see Figure 4.2, that requires operators to squeeze the trigger multiple times until the predetermined torque is reached, at which point a final squeeze cuts the cable tie close to the lock. This manual tool is favored for its perceived effectiveness and lightweight design, which facilitates task performance. Every operator carries this tool, contributing to its frequent use. Despite its advantages, ergonomists highlight that it is unergonomic, relying on manual force that causes constant stress and strain on the hands and wrists.

Figure 4.2: Manual tool

The existing electric tool, see Figure 4.3, activates by pushing the trigger and holding it down to tighten and cut the cable tie. The electric tool is placed at home stations, which requires the operators to walk a few steps to retrieve it, leading to its limited use. Moreover, the high frequency of cable ties tends to break the mechanism over time, requiring frequent repairs. Assembly operators also find that the tool's mechanism is overly tightening cable ties that are attached around soft tubes that certain cables is protected by, which contributes to its limited use.

Figure 4.3: Existing electric tool

Both tool options contribute to unergonomic work postures due to their design. The pistol grip on both tools forces operators to bend and twist their wrists, rotate their shoulders, and compromise their backs.

Based on observations and discussions with ergonomists, four positions were selected where the ergonomic situation is compromised at BML. These positions are located on the chassis's top, middle, and inside, as illustrated in Figure 4.4. The number of cable ties that need to be tightened and cut in these positions varies depending on the truck model. Approximately 30 cable ties are positioned at the top, six in the second position, two to three in the third position, and between 20 to 30 in the fourth position.

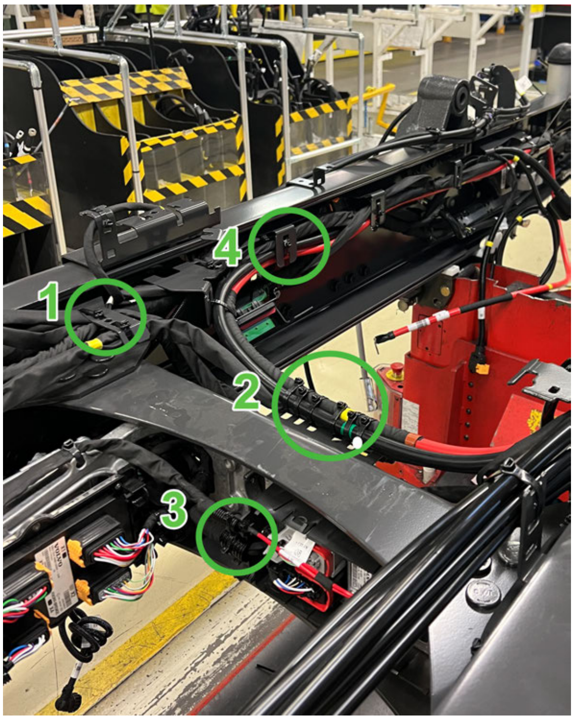

Figure 4.4: The four selected positions

The first position involves cable ties secured on the top of the chassis, requiring operators to raise their shoulders and elbows to cut them. The second and third positions are in the middle of the chassis, where operators need to straighten their arms to reach the cable ties. Additionally, in the second position, operators must raise their elbows to tighten the cable ties. The fourth position is inside the frame, where operators must lean forward and twist their shoulders, arms, and elbows to access the cable ties. The position when an operator is working is shown in Figure 4.5.

(a) Position 1 (b) Position 2 (c) Position 3 (d) Position 4

Figure 4.5: Work posture of the existing tool

4.1.1 Task Analysis

Based on observations and interviews with operators, and in collaboration with ergonomists, a Hierarchical Task Analysis was formulated for the process of tightening and cutting cable ties. This analysis identified the ergonomic critical points in the usage of the existing electrical tightening tool, as illustrated in Figure 4.6.

Figure 4.6 highlights that the most crucial aspect of the tool's tightening and cutting process is positioning the tool against the cable tie, particularly when placing it in cutting mode. This indicates that this stage of the process poses the highest risk for potential work-related injuries caused by bad ergonomics. Furthermore, grabbing the cable tie before placing the tool in cutting mode have been observed as a potential risks, depending on the tie's placement. This forces the assembly operator to put their wrists in unergonomic positions, such as flexion or extension. Additionally, the trigger's design, which fits only one or two fingers, poses a slight risk of injury when used.

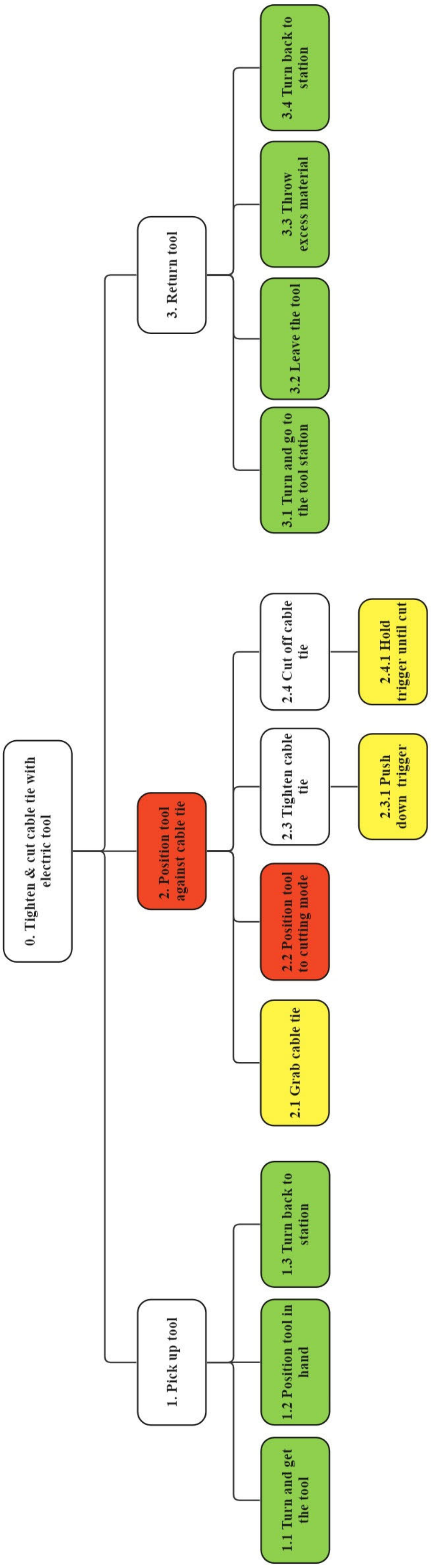

Figure 4.6: The HE-diagram describes the work tasks and critical aspects of tightening and cutting cable ties at the BML with the electric tool, where red indicates the most critical task.

4.1.2 RULA

The RULA analysis was conducted for each position. Table 4.1, 4.2, 4.3 and 4.4 display a summarized result of the analysis. The complete analysis is shown in Appendix A.6.

Table 4.1: RULA of the existing tool for position 1

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	3	3	4	4
Table B	3	3	3	3
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	4	4	5	5
Value D	4	4	4	4
RULA result	**4**	**4**	**5**	**5**

Table 4.2: RULA of the existing tool for position 2

Position: 2	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	4	5	4	5
Table B	2	3	4	3
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	5	6	5	6
Value D	3	4	5	4
RULA result	**4**	**6**	**5**	**6**

Table 4.3: RULA of the existing tool for position 3

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	5	5	5	4
Table B	4	4	4	4
Load frequency	0	0	0	0
Load	0	0	0	0
Value C	5	5	5	4
Value D	4	4	4	4
RULA result	**5**	**5**	**5**	**4**

Table 4.4: RULA of the existing tool for position 4

Position: 4	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	5	5	5	5
Table B	7	5	7	5
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	6	6	6	6
Value D	8	6	8	6
RULA result	**7**	**7**	**7**	**7**

As shown in the tables, the action levels for the work positions vary. The most critical scenario is in position four, where immediate action is required for all ranges. Positions two and three are at action level three for all except one range for each position, indicating that fast improvement is needed. Another interesting insight is that for all positions except position four, the analysis of hand and wrist is more critical or equivalent to the analysis of neck, back, and legs.

4.2 Reference Tool

The reference tool consists of two main parts: one battery and the hand tool, shown in Figure 4.7. The tool operates by electrically tightening and cutting the cable tie by pressing a button. The operator must manually apply the cable tie, but the tool facilitates pulling it to the desired tension and cuts off the excess material.

Figure 4.7: The reference tool and the battery

The reference tool features two different grips that can be used in three ways, as shown in Figure 4.8. However, its design presents several ergonomic issues, similar to the existing tool. The grip options shown in Figures 4.8b and 4.8c have a small grip area, making it uncomfortable and challenging to hold for extended periods. Secondly, the battery's weight unbalances the tool, creating torque that makes it difficult to maintain a straight wrist position. Lastly, the grip used in Figure 4.8b requires operators to change their grip to reach the activation button, increasing the risk of dropping the tool and making it uncomfortable for prolonged use.

(a) Pistol grip

(b) Straight grip tool from body

(c) Straight grip tool close to body

Figure 4.8: The reference tool three grips

4.2.1 Black Box Diagram

The first step of examining the reference tool functionality involved creating a black box diagram, which is visualized in Figure 4.9. To function, the tool necessitates three primary inputs. Initially, the assembly operator applies a cable tie to the tool, forming the material flow input. Afterward, the operator activates the mechanism by applying a force to the trigger, initiating the flow of electrical energy. The electric energy then executes the tightening and cutting functions within the tool where it is converts to mechanical energy.

As a result of these actions, several outputs are produced. Firstly, the cable tie is tightly fastened around the intended object, representing a material flow output. Additionally, waste material from the cable tie appears, such as cut-off ends of the cable tie. Finally, a signal indicating the completion of the process, providing feedback to the assembly operator.

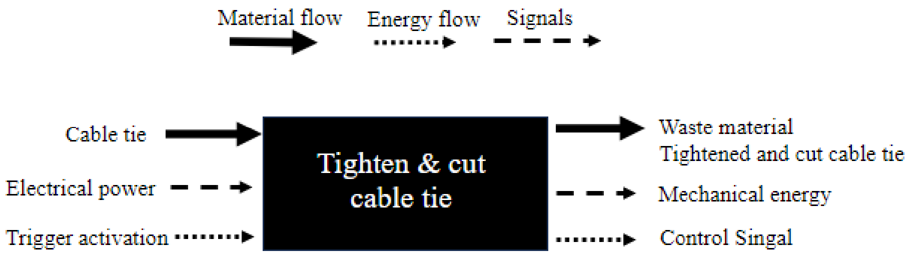

Figure 4.9: Black box of reference tool

4.2.2 Disassembly of Reference Tool

The disassembly of the reference tool resulted in a BOM, see Table 4.5. The BOM is based on an overview of the components, illustrated in Figure 4.10.

Table 4.5: The bill of material table

Nr.	Name of part	Material	Description	Quantity	Weight [g]
1	Tighten and cut mechanism	-	The mechanism consists of multiple components that together perform the main function	1	696
2	Solenoid	Metal	A magnet coil	1	56
3	Circuit Board	Insulating material	Connects and control the electrical components	2	24
4	Battery connection	Metal and Plastic	Interface to fasten battery	1	29
5	Torque Adjuster	Plastic	Decides the tightening torque	1	7
6	Trigger	Plastic	Front trigger to activate tool	1	9
7	Button	Plastic	Back button is an alternative to activate tool	1	7
8	Shell	Plastic	Holds components at place	2	280
9	Battery	-	Provides electric power to the tool	1	393

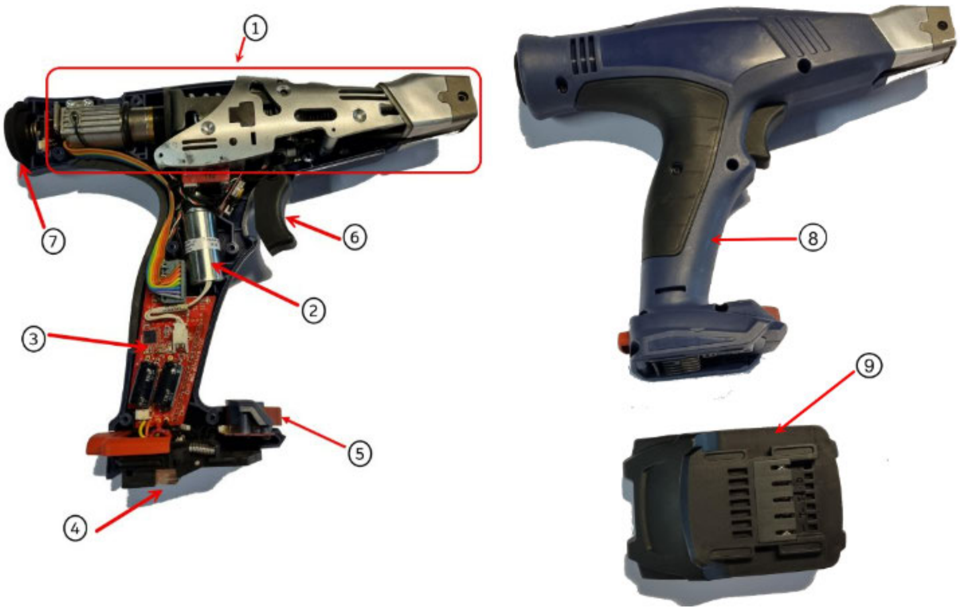

Figure 4.10: Overview of Reference Tool

The disassembly process provided insights into the functions and properties of the tool's components. It became clear that all nine parts are necessary for the tool to function, but certain parts can be redesigned or replaced without affecting mechanical performance. The trigger, button, tightening adjuster, and shell fall into this category.

Furthermore, it became clear that part one and two need to be oriented as shown in Figure 4.10, due to the function of the solenoid. The solenoid is responsible for releasing the mechanism once the set tightening torque is reached, signaling the tool to cut the cable tie. This action is crucial for the primary function of the tool.

Part three is a programmed circuit board that connects all electrical components. Although the circuit board will not be modified due to the project's scope, it can be placed in any position that allows it to connect all electrical components. Similarly, the battery's function and properties must be maintained to ensure the mechanism's proper functioning. However, it can be positioned differently.

4.2.3 Function Analysis

The knowledge gained from the disassembly was utilized to generate a function analysis. The results of creating a function analysis diagram are presented in Figure 4.11. The left side of the diagram illustrates the inputs, while the right side describes the outputs during the operation of the reference tool. Between the input and output flows are the sub-functions: storing energy, tightening and cutting mechanism, indicating power, and triggering the tool.

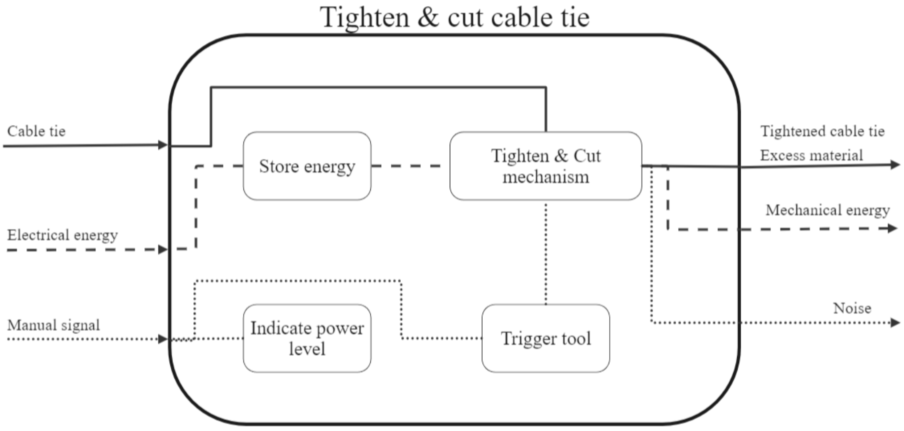

Figure 4.11: Function Analysis Diagram

The sub-functions are crucial for the proper functioning of the reference tool and must remain when redesigning it. The sub-functions ”tighten and cut” and ”indicate power level” do not require a new solution as they are part of the mechanism and circuit board.

5

Results

The results chapter presents the outcomes from the stakeholders' need identification and the phases: Concept development, Detail development, and Evaluation and Verification. It showcases the iterative process from concept generation to the final prototype. The chapter includes detailed findings from the ergonomic assessments, feedback from stakeholders, and performance evaluations of the prototype.

5.1 Identified Stakeholder Needs

Table 5.1 presents the stakeholder needs identified through a combination of observational studies and stakeholder interviews. The needs range cover practical aspects like battery life and portability to ergonomic concerns such as ease of use and comfort. All needs are weighted based on importance, where a five is the highest value. The needs are translated and formulated based on the operators and ergonomists statements in Appendix A.3.

Table 5.1: Stakeholder needs with weight of importance

Nr	**Identified Need**		**Imp.**
1	The battery	is easy to replace	2
2	The battery	has to have a minimum usage duration of two hours	2
3	The battery	is lightweight	4
4	The tool	is portable	5
5	The tool	can be used in different directions	3
6	The tool	is fast to use	3
7	The tool	is easy to use	3
8	The tool	is lightweight	5
9	The tool	is adapted for different positions	3
10	The tool	is usable for both right- and left-handed users	3
11	The tool	is usable by several different hand sizes	4
12	The tool	is easy to activate	5
13	The tool	is designed based on ergonomics standards	4
14	The tool	is comfortable to use	4
15	The tool	is easy to grip	3

16	The tool	has to have the center of gravity adapted to the working position	3
17	The tool	has to access hard-to-reach areas	3
18	The tool	can adjust torque	2
19	The tool	can resist vibrations	1
20	The tool	can resist recoil	1

While most needs received medium to high importance ratings, there were variations in stakeholder priorities. For instance, while lightweight design (Imp. 5) and ergonomic activation (Imp. 4) were rated highly, preferences varied regarding technical features such as torque adjustment (Imp. 2). Both operators and ergonomists prioritized lightweight design and easy activation as critical factors influencing tool usability and ergonomics.

Operators and ergonomists mentioned certain needs related to the mechanism's performance. For example, operators expressed the need for the tool to be ”fast to use”, referring to the time it takes to tighten and cut a single cable tie. Although these performance-related needs are not included in the scope of this project, it is important to document them to inform future product improvements.

5.1.1 Product Specification

The identified needs and requirements outlined in the Volvo Trucks ergonomic guidelines [9] were listed in a detailed product specification, see Appendix A.4. The criteria in the product specification is explained in Table 5.2.

Table 5.2: Explanation of the criteria

R/D	Criteria	Description
R	Tightening cable ties	The mechanism function for tensioning cable ties.
R	Cut cable ties	The mechanism function for cutting cable ties.
R	Adjust tension	The mechanism needs to be able to adjust to eight different tightening settings.
R	Chargeable	It is important the tool is chargeable for reusability.
D	Handle shape	The design of the tool should fit the hand of the user and not force the operator to work in an unergonomic posture.
R	The battery operating time	The battery needs to last for a single session before changing.
D	Tension and cut time	The time it takes for the tool to tension and cut cable ties.

R	Changing battery	The battery should be easy and smooth to change if needed.
D	Activate trigger with one finger or thumb	The trigger should be operable with minimal effort from one finger or thumb.
R	Activate trigger with more than one finger	The trigger should allow for operation with multiple fingers to ease the strain on the hand.
R	The position of the wrist	The tool should allow for a comfortable and natural wrist position during operation.
D	The tool is within forearm distance	The distance between the forearm and the center of the body should fall within the green zone, see Figure. 2.4
D	The position of the hand	The height from the floor to the hand should be within the green zone, see Figure 2.4.
D	The tool is portable	The tool should be designed to be easily transportable, allowing for quick and convenient access.
D	The shape of the handle	The tool should be adapted for both right and left-handed people.
R	The shape of the handle	The cross-section of the handle should follow ergonomic guidelines.
D	The trigger size	The trigger size should be larger than the size of a fingertip.
R	The largest diagonal of the handle	The longest diagonal of the trigger for design and ergonomic considerations.
D	The length of the handle	The handle should be of a suitable length for comfortable operation and fit the width of the hand.
R	Total weight	The maximum weight allowed for a handheld tool used at the BML without any additional support.
R/D	Weight in hand	The tool’s weight held in the hand should be manageable for extended use.

To summarize the product specifications, all stated requirements must be met. However, three criteria categorized as desires carry the highest weight and are therefore the highest priority for fulfillment among the desires.”Handle shape”, ”Trigger size”, and ”Weight in hand”.

5.2 Generated Concepts

The primary function of the cable tie tool was identified as ergonomically tightening and cutting cable ties. Five sub-problems were identified during examining the reference tool and discussing with ergonomists.

1. **Store battery** - This sub-problem involves providing a placement of the battery either within or outside the tool, ensuring it is safely stored and easily accessible for maintenance or replacement.
2. **Handle shape** - This sub-problem focuses on designing the tool so users can hold it comfortably and securely, minimizing strain and discomfort during use. It includes considerations such as the shape and placement of a handle to enhance ergonomic usability.
3. **Adjust tension** - This sub-problem involves the ability to adjust settings of tightness to achieve desired performance outcomes.
4. **Activate mechanism** - This sub-problem relates to the action of activating the tool's primary functionality. It involves designing user-friendly triggers that enable users to activate the tool and perform intended the task easily.
5. **Ergonomic aid** - This sub-problem involves incorporating features or design elements into the tool that provide ergonomic support to users. These elements aim to reduce strain on the wrist, arm, and shoulder, as these areas have the highest reported injuries at the BML.

5.2.1 Patent Landscape Analysis

The patent landscape resulted in a total of fifteen patents, see Appendix A.5. All patents have relevant features that can inspire the development of a new design for the reference tool. The majority of the selected patents focus on improving ergonomic conditions, such as the handle shape. For instance, patent number 5, 7 11 and 14 have a function to change the angle or direction of tool. The selected patents and their relevance to the project's purpose are outlined in Table 5.3.

Table 5.3: The selected patents and what is interesting about the respective solution within the sub-problem.

Patent	Sub-problem	Relevance of Prior Art
1	Handle shape	The shape and design of the handle
2	Ergonomic aid	An ergonomic attachment to enhance ergonomic use
3	Handle shape	The multiple grip styles
4	Ergonomic aid	The shape and design indicate how it should be held

5	Ergonomic aid	The adjustment mechanism that allows different angles
6	Handle shape	The design of the handle with the ergonomic properties
7	Ergonomic aid	The possibility to adjust the angle of the handle while still reaching the trigger easily
8	Store battery	The alternative battery design for a handheld tool
9	Store battery	The placement of the battery inside of the tool
10	Ergonomic aid	The strap's ability to relieve stress on the hand
11	Ergonomic aid and handle shape	The adjustment functionality for the handle, making the device adaptable to different needs and preferences
12	Ergonomic aid	Adding an attachment to reduce strain on the forearm
13	Handle shape and store battery	The shape of the handle and placement of the battery
14	Handle shape and activate mechanism	Change the angle of the handle, depending on the work position and the placement of the trigger
15	Activate mechanism	Having multiple triggers depending on grip option

5.2.2 Brainstorming

In the brainstorming session, multiple potential solutions were suggested for each sub-problem. However, not every idea was viable. Some sub-solutions were considered unfeasible or fell outside the project's scope. Others were refined or combined to create a new sub-solution. After the screening process, the sub-solutions for each sub-problem remained as follows:

Ideas that remained for storing battery:

- A battery in placed on the operator's body.
- A battery is placed inside the tool.
- A battery is placed on the outside the tool.

Ideas that remained for handle shape:

- A handle is shaped as a half square, that can enable multiple grip functions
- A handle shaped similar to the reference tool.

- A straight handle that allows a natural position of the wrist.
- A handle with a radial shape to facilitate hard to reach areas without putting strain on the upper body.
- A cross shape that can be used in different positions by changing grip.

Ideas that remained for adjusting the tightening:

- The tightness level is set by rotating a wheel.
- The tightness level is decided by clicking on different buttons.
- The tightness level is set by clicking on the same button until wanted tightness is achieved.
- The tightness level is changed with a lever, similar to a manual gear lever.

Ideas that remained for activate mechanism:

- The tool is activated by rotating a wheel, using one or two fingers.
- The tool is activated by punching in a longer lever with multiple fingers.
- The tool is activated with a push of a button, either with one or multiple fingers.

Ideas that remained for ergonomical aid:

- An elastic band placed on the hand to reduce the strain.
- An adjustable hand support to reduce strain on the hand.
- A solid support bracket to support the hand.

5.2.3 Morphological Matrix

Five complete concepts have been created using the morphological matrix. The combination of the various sub-solutions can be viewed in Figure 5.1, where each color in the matrix represents a complete concept. Among the sub-solutions, the ”handle shape” has a significant effect on the concept’s ergonomic design. The shape of the handle will influence the operator’s hand, wrist, and arm positioning, thereby affecting the ergonomic posture. As a result, one concept has been generated for each handle shape in the matrix.

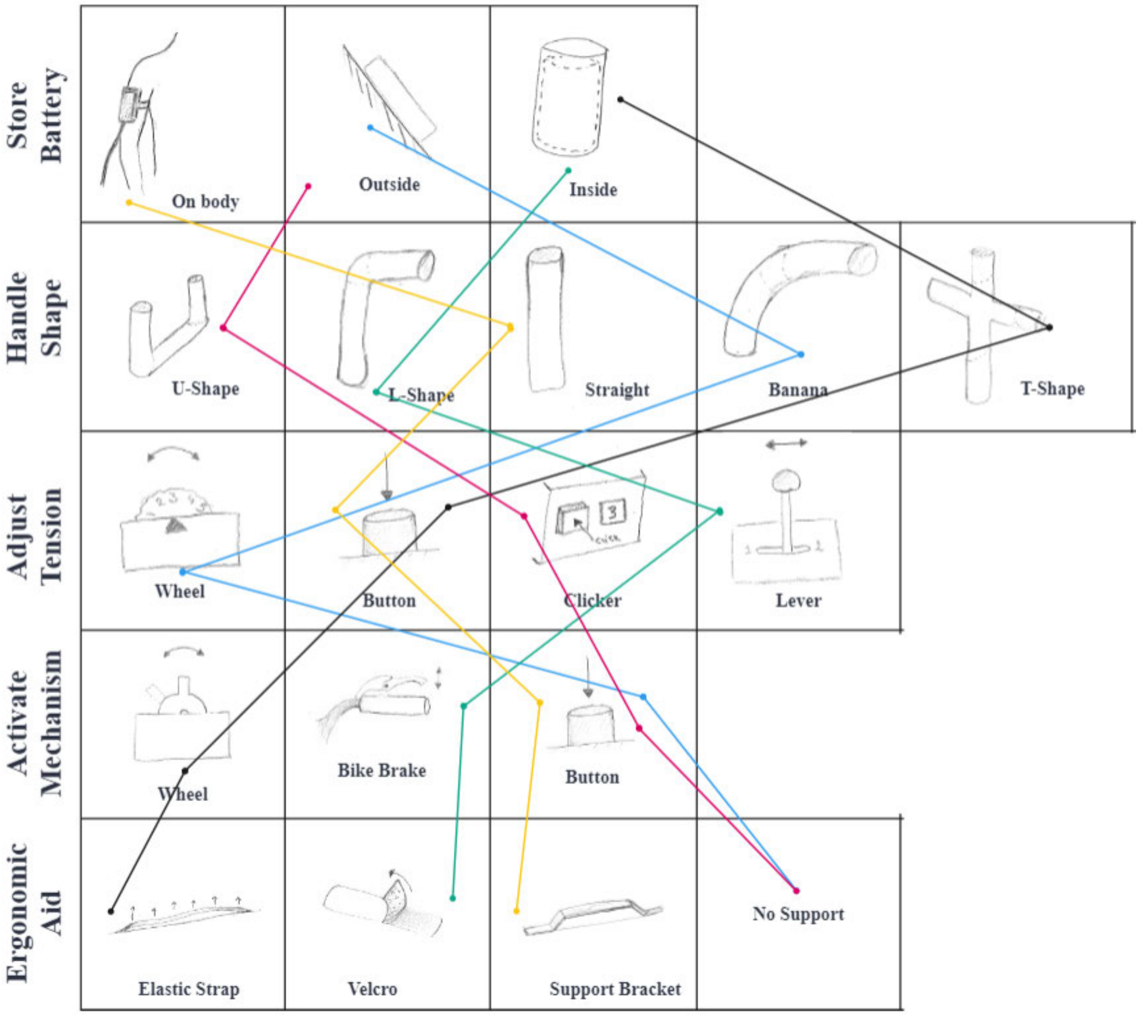

Figure 5.1: Morphological Matrix

5.2.4 Concepts

The first generated concept is named Leaf Blower, shown in Figure 5.2. As the name reveals, this concept is inspired by a leaf blower. The tool's battery is attached to the back portion of the tool. A large button is positioned on the handle to allow activation of the mechanism from different grips. Additionally, a wheel on the shell allows adjustment of tightness level.

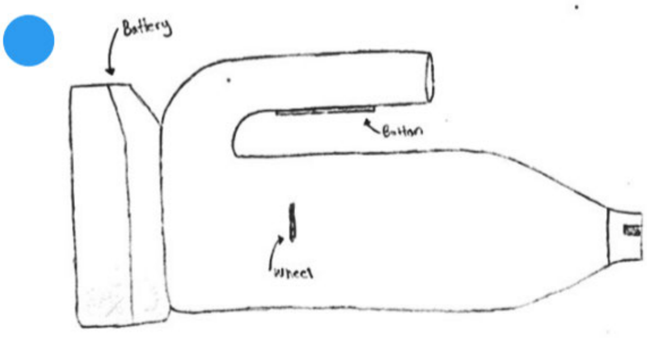

Figure 5.2: Concept Leaf Blower

The second concept is called T-shape handle. The concept has two different grip positions, which are designed to relieve the hand from strain. The first grip is a straight handle with an ergonomic aid to support the wrist and has a long button to activate the mechanism. The second grip option is a pistol grip with a wheel to activate the tool. To decide the tightness level different buttons are pushed. Lastly, the battery is placed in the tool's handle.

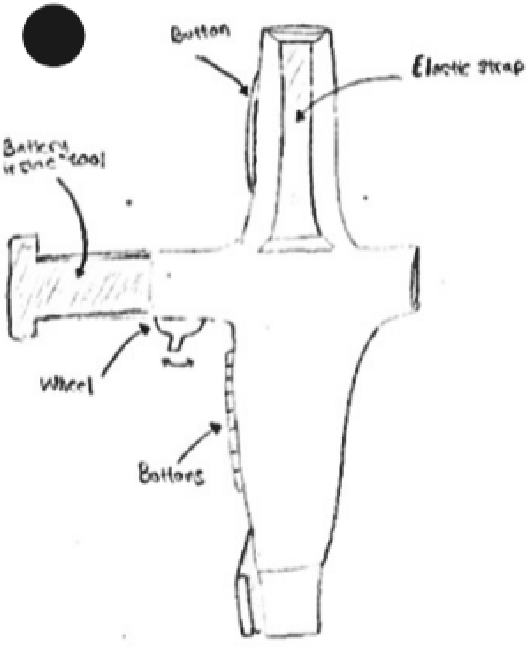

Figure 5.3: Concept T-shape

The third generated concept is called Hairdryer, featuring a built-in battery in the handle to maintain a balanced weight distribution. The handle has a Velcro strap to relieve the wrist and improved grip stability. A bike brake lever is placed on the handle, which enables the user to use one or more fingers to activate the tool. A lever has been placed on the shell to adjust the tightness level, which functions similarly to the gear lever in a car. The concept is shown in Figure 5.4.

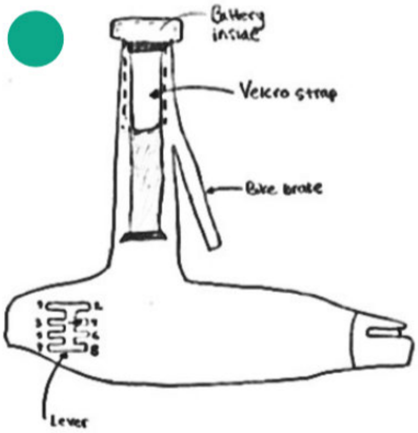

Figure 5.4: Concept Hairdryer

The fourth concept is called Mug. It has a square handle with multiple grip options. The handle is equipped with two long buttons to make tool activation user-friendly and accessible. The battery is placed on the upper side of the tool. To adjust the tightness level, the user can click several times on a button and view the tightness level on a screen.

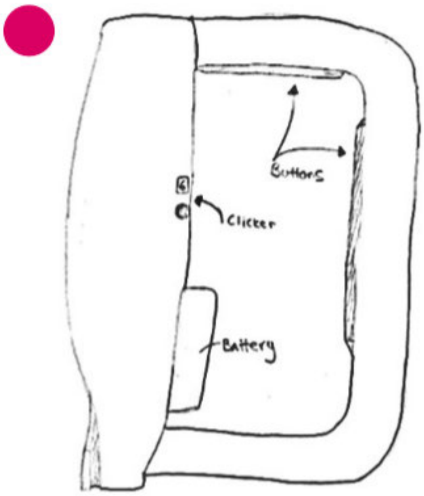

Figure 5.5: Concept Mug

The fifth concept is called Hand Blender. It has a straight handle and a support bracket on the handle to relieve wrist strain and enhance grip stability. The battery is located on the operator's body and connected to the tool via cable to reduce weight in the hand. The concept features two buttons, allowing for comfortable grip adjustment while maintaining the ability to activate the tool. Furthermore, a clicker is used to change the tightness level. Figure 5.6 visualizes the Hand Blender concept.

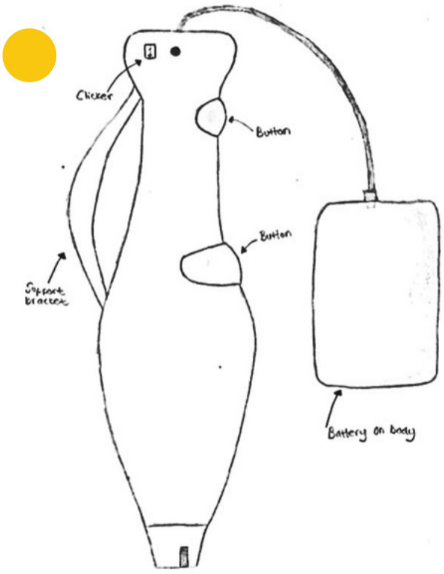

Figure 5.6: Concept Hand Blender

5.2.5 Evaluation of Concepts

The findings obtained from the user tests and feedback sessions with initial prototypes have been compiled in a summarized evaluation for each concept.

Leaf Blower

The operators and the ergonomists thought that the Leaf concept had promising potential due to its shape and multi-grip handle. The placement of the tool's battery was beneficial in positions one and two. However, in the other positions, the battery placement caused strain on the wrist. Table 5.4 shows the pros and cons of the Leaf Blower concept.

Table 5.4: Pros and cons for the Leaf Blower

+ Pros	**- Cons**
• The multi-grip option allows the operator to change the grip • The shape of the handle is slim and does not disturb users while performing the task.	• The weight of the battery and mechanism causes strain on the wrist in certain work postures • Bulky to carry on body • The center of gravity is far away from the hand

T-shape

The T-shape concept received positive feedback from the operators and the ergonomists regarding its ability to use different grip positions and for the balanced weight distribution of the handle. However, the tool was found to be uncomfortable in the working environment due to its size. Table 5.5 shows the pros and cons list for the T-shape concept.

Table 5.5: Pros and cons for the T-shape

+ Pros	- Cons
• The weight distribution is balanced • The multi-grip option allows the operator to change the grip • The handle has an extra support to allow grip	• Bulky to carry on body • The shape is perceived as inconvenient as it extrudes in multiple directions • In positions four and three, the tool caused bending in the wrist.

Hairdryer:

According to feedback from the operators and the ergonomists, the Hairdryer's shape allowed easy access in position four, not in others. The weight distribution of the tool has been positively noted. On the downside, its similarity to the reference tool poses risks of encountering the same issues previously identified in Section 4.1.2. Table 5.6 lists the pros and cons of the Hairdryer concept based on the user tests.

Table 5.6: Pros and cons list for the Hairdryer

+ Pros	- Cons
• The handle has an extra support to allow grip • The weight distribution is balanced • Center of gravity close to the hand	• The shape does not access some areas without having to stand in an unergonomic working position • Heavy to carry on body • Bending of wrist in position one, two and three

Mug:

This concept received negative feedback from the operators and the ergonomists due to its unbalanced handle and large size. However, they appreciated its multiple activation options. The pros and cons of the Mug concept are listed in Table 5.7.

Table 5.7: Pros and cons list for the Mug

+ Pros	- Cons
• The multi-grip option allows the operator to change the grip • The handle has an extra support to allow grip	• The positioning of the battery is causing some difficulties in regard to ease of attachment and detachment • Difficult to carry around, needs to be put away when working with other tasks • The weight distribution is unbalanced • The shape is perceived as cumbersome due to the size of the handle

Hand Blender:

The Hand Blender concept received positive feedback from the operators and the ergonomists for its straight design and the potential for a multi-grip handle in a smaller format compared to other concepts. However, it was noted that the cable could pose a safety risk, depending on how the battery is attached to the body, given the constant movement of the production line. The pros and cons of the Hand Blender are shown in Table 5.8.

Table 5.8: Pros and cons list for the Hand Blender

+ Pros	- Cons
• The weight is distributed across different parts of the body • The handle has an extra support to allow grip • The grip enables a straight wrist position while still accessing the work area	• Working with a cable could be a safety risk • Wearing the battery on the body can be uncomfortable.

5.2.6 Concept Screening

In the concept screening process, five concepts were evaluated. Two concepts were selected for further development, while three were eliminated. The Hairdryer concept was excluded due to ergonomic concerns; its shape did not allow the operator to maintain an ergonomic posture while working with the different cable tie cases. Similarly, the Mug concept was not chosen because its handle shape was perceived as cumbersome, resulting in an unbalanced weight distribution. Additionally, the

Leaf Blower concept was considered unsuitable due to balance issues caused by the battery and handle design in some working postures. This imbalance poses a risk for MSD in the wrist, leading to the elimination of the concepts Leaf Blower, Hairdryer and Mug as feasible options.

5.2.7 Refinements of Concepts

After consulting with an expert on tool batteries, the decision was made to keep the current battery. This decision was based on two main reasons: the battery is programmed to be compatible with the circuit board, making it complex to change, and building a new battery is not feasible due to the requirement for CE marking, which is beyond the project's time limit. Moreover, the decision was made to keep the tightening level adjuster due to the lack of knowledge about how the mechanism and the connected parts are integrated with each other.

The refinement of concepts resulted in two new designs based on previous concepts and the feedback from the user tests and feedback sessions. An improved version of the T-shape design has been developed, called T-rotation. In this version, the battery has been relocated from the inside of the handle to the outside of the shell. To balance the weight distribution, a wrist support with a Velcro strap has been added. The wrist support and battery holder are now rotatable, making the tool suitable for both left and right-handed users, and adaptable to various working positions. Instead of using multiple buttons for tightening adjustments, a wheel solution has been incorporated. The illustration presented in Figure 5.7 showcases the sub-solutions and parts of the concept on the left-hand side, and provides an illustration of the tool's grip on the right-hand side.

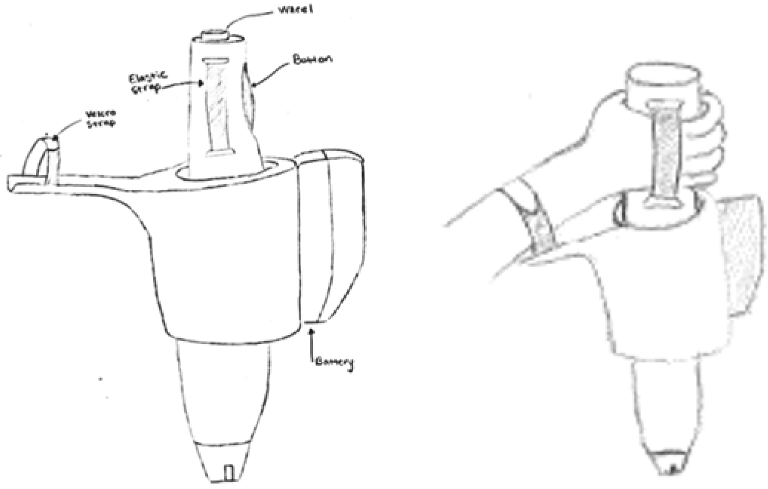

Figure 5.7: Concept T-rotation

The second concept is a further development of the Hand Blender concept, and is called Straight. The design aims to make the tool slimmer by using the mechanism as the handle, eliminating the need for a separate one. Additionally, the support bracket has been replaced with a Velcro strap to adapt for different hand sizes and reduce grip strain. The tool features two buttons, allowing users to employ different grip positions. Furthermore, the battery is situated on the operator's body to reduce the weight held in the hand. An illustration of the Straight concept and the grip is shown in Figure 5.8.

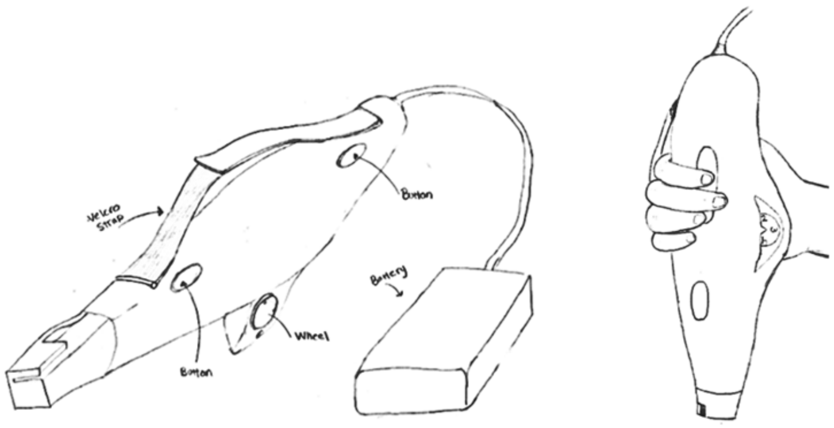

Figure 5.8: Concept Straight

Final Concept

Based on user tests of the two concepts, it was decided to place the battery on the body. This decision was made because the weight of the battery significantly increases the load that needs to be carried in the hand. By repositioning and reducing the weight from the hand and wrist, operators will have a lightweight tool that addresses a high-priority desire. This change mitigates the risk of MSDs in the hand and wrist area, which is the most common work-related injury at BML.

The final design of the concept is a combination of previously redefined concepts, T-rotation and Straight, which have been improved through user feedback. As illustrated in Figure 5.9, the design incorporates a battery attached to the upper arm using an adjustable Velcro strap that can be tailored to adapt for various arm sizes. This feature reduces the hand and wrist weight, resulting in a comfortable user experience.

The tool has a long button for easy activation with several fingers from multiple grip positions. The decision to incorporate a single button was driven by the need for a slim shell design without compromising on including all necessary mechanical and electrical components. This design feature also ensures that the tool can be held and gripped without the risk of accidental activation, enhancing user-friendliness.

Furthermore, the handle incorporates an adjustable Velcro strap, offering ergonomic relief for the hand and reducing reliance on grip strength. Responding to feedback from operators and ergonomists, the handle is designed to be straight and short, facilitating access to all areas without necessitating uncomfortable body positions such as wrist flexion. Additionally, the handle is designed to allow grip and comfort according to the Volvo Truck ergonomic guidelines, including a round shape and a specific handle diameter.

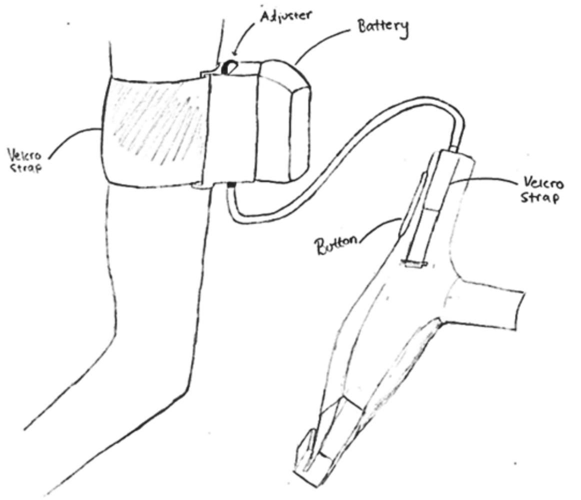

Figure 5.9: Concept design of the final concept

5.3 Detailed Development of Final Concept

After receiving feedback from the ergonomist, some modifications were made to the concept. One difference was relocating the battery from the upper arm to the back, using a harness to distribute the weight evenly and reduce weight on the arm. To allow the operator to easily adjust the tightness level while working, it was necessary to move the adjuster away from the battery. As a result, the decision was made to attach the adjuster to the upper arm and fasten it to the body with an adjustable Velcro strap, making it easily accessible and usable. This decision was made in conjunction with relocating the battery to the back. Additionally, the decision was made to not develop the Velcro strap at the tool's handle due to the project time constraints and the potential risk of limiting use for both left- and right-handed operators.

5.3.1 Final Prototype

The final prototype comprises six primary parts: tool housing, button, adjuster housing, battery box and a harness, which were developed alongside modifications to the electrical cables to adapt them to the concept. Figure 5.10 provides a visual representation of the final prototype.

Figure 5.10: Physical prototype

As previously mentioned, the battery is placed on the operator's back using a harness. A cable extends from the back to the handle of the tool, where the tool and battery connect via a contact. This contact allows the operator to easily disconnect the tool when not in use or to replace parts in case of damage. The adjuster housing is placed on a Velcro strap on the upper arm, where the cable is attached to stay along the arm, minimizing the risk of it getting stuck. Additionally, it is designed to stay out of the way during other tasks. When the tool is not in use, the operator places it in a bag carried on their body. Figure 5.11 illustrates the tool when used.

Figure 5.11: Prototype in action

Tool Housing

The tool's housing is designed to be slim and features a symmetrical cylinder-shaped handle that allows for both right- and left-handed users. The shell is created in two parts to facilitate the assembly of the prototype and ensure that the mechanism is correctly positioned, see Figure 5.12.

The handle of the tool has grooves to hold the button's circuit board. The solenoid is placed at the bottom of the extended part and secured by supports to keep it aligned with the mechanism. The extended part is designed specifically to fit the solenoid and is not an extra grip. The motor is placed beneath the button grooves and is secured with supports to fit against the mechanism. Additionally, guide grooves and mounting holes are integrated to make it easy to assemble the two sides.

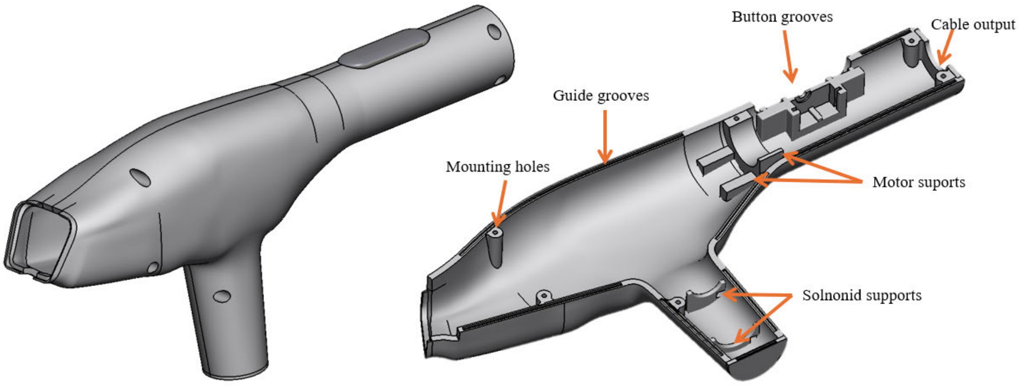

Figure 5.12: Tool Housing

Button

The button is designed with an elongated shape, enabling users to activate the mechanism with multiple fingers and from different grip positions. The button's top surface is slightly convex, promoting an integrated design that enhances user-friendliness by blending with the hand grip. The button is illustrated in Figure 5.13.

A feather is positioned between the button and the shell to ensure that it returns to its original position after activation. Additionally, the button is equipped with two wedges to prevent it from disengaging from the shell.

Moreover, a cross-shaped guide track is used to ensure reliable activation when pressing the button. This feature ensures that the button's pin hits the electrical button placed in the shell, triggering the mechanism. This design approach is inspired by a keyboard's space button, which utilizes a similar mechanism.

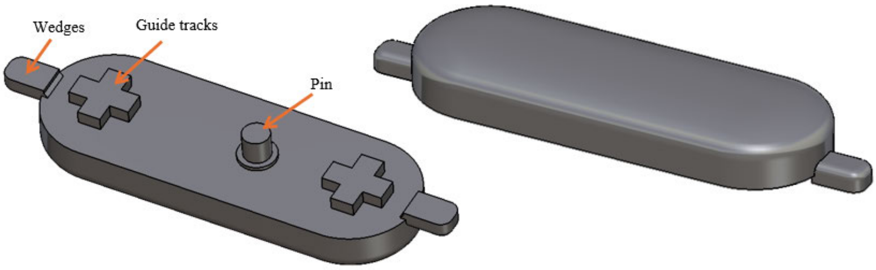

Figure 5.13: Button

Adjuster Housing

The adjuster is housed in a small box with an arrow indicating the set tightness level of the tool, allowing customization based on different sizes of cable ties. It is worn on the operator's arm and directly connected to the battery box via cables. The adjuster housing is displayed in Figure 5.14.

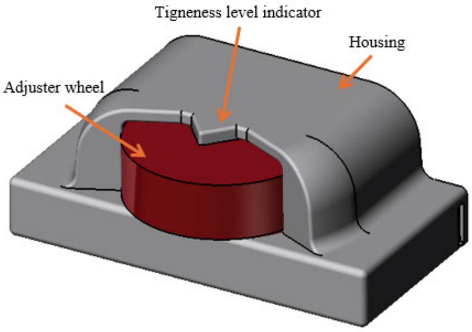

Figure 5.14: Adjuster Housing

Battery Box

The battery box, see Figure 5.15, comprises two halves, making it easier to install the battery connector and circuit board. The battery connection is secured in a track inside the box to enable a stable connection against the battery. The track also allows for easy detachment, replacement, and recharging of the battery.

Moreover, the circuit board is secured with two supports in the battery box. These supports prevent the circuit board from being damaged when the operator moves. The battery box also has two output holes for the cables running from the electrical components to the circuit board.

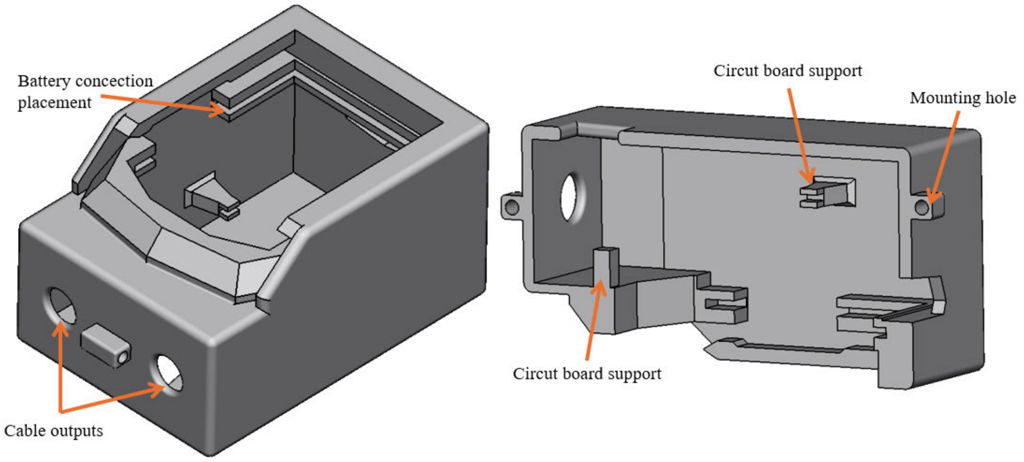

Figure 5.15: Battery Box

5.4 Verification and Evaluation

Operators' and egronomists' feedback on the prototype revealed both advantages and disadvantages. The handle design was found to be comfortable for different hand sizes due to its diameter and length. However, the operators desired a support at the top of the handle to prevent losing their grip and to provide additional support, as the mechanism remains heavy for long-term use.

The operators and the ergonomists liked the shape of the button and thought it was well-integrated with the shell and easy to press. However, they suggested that the button could be extended to allow more variation in grip options.

The cable running between the tool and the battery box received varied feedback. Operators appreciated moving the battery, as it reduced the weight on their hands. However, they expressed concerns about working with a cable, fearing it might cause disruptions when performing other tasks, even if it is attached to the body.

5.4.1 Evaluation of Work Postures

The evaluation the prototype work postures resulted in four analyses, one for each position. The summarize result is shown in Table 5.9, 5.10, 5.11 and 5.12. The detailed analysis for the prototype is displayed in Appendix A.7.

Table 5.9: RULA result of the prototype for position 1

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	2	1	2	2
Table B	2	2	2	3
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	3	2	3	3
Value D	3	3	3	4
RULA result	**3**	**3**	**3**	**4**

Table 5.10: RULA result of the prototype for position 2

Position: 2	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	3	3	4	3
Table B	2	2	2	2
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	4	4	5	4
Value D	3	3	3	3
RULA result	**3**	**3**	**4**	**3**

Table 5.11: RULA result of the prototype for position 3

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	4	4	5	2
Table B	3	4	2	4
Load frequency	0	0	0	0
Load	0	0	0	0
Value C	4	4	5	2
Value D	3	4	2	4
RULA result	**3**	**4**	**4**	**4**

Table 5.12: RULA result of the prototype for position 4

Position: 4	**Female**		**Male**	
	Low range	High range	Low range	High range
Table A	3	3	3	3
Table B	3	3	3	3
Load frequency	1	1	1	1
Load	0	0	0	0
Value C	4	4	4	4
Value D	4	4	4	4
RULA result	**4**	**4**	**4**	**4**

According to the tables, all four work positions reach action level two for all ranges when using the prototype. Although the work postures are not deemed acceptable, immediate action is not required. In position one, the load frequency significantly increases the action level across all ranges, except for high-range males, compared to a lower task frequency.

A comparison of the work postures between the existing electric tool and the prototype is displayed in Table 5.13. As shown in the table, the prototype has the same or lower values in comparison to the existing tool in all ranges. Additionally, work position four has shown the most improvements.

Table 5.13: RULA results for existing tool and prototype for all work positions

Tool Type	**Work Position**	**Female**		**Male**	
		Low range	High range	Low range	High range
Existing	*1*	4	4	5	5
Prototype	*1*	**3**	**3**	**3**	**4**
Existing	*2*	4	4	5	5
Prototype	*2*	**3**	**3**	**4**	**3**
Existing	*3*	5	5	5	4
Prototype	*3*	**3**	**4**	**4**	**4**
Existing	*4*	7	7	7	7
Prototype	*4*	**4**	**4**	**4**	**4**

5.4.2 Requirements Fulfillment

Table 5.14 displays which criteria have been fulfilled in the product specification. An ”X” indicates which requirements or desires are fulfilled according to the stated verification method.

Table 5.14: Product specifications and requirement fulfillment

PRODUCT SPECIFICATION

Product: Electric Cable Tie Gun

Created by:	*Stina Andersson Gejnäs & Saga Norin*	Weight 1 - 5, with 5 being highest
Created:	2024-01-29	R= Requirement, D= Desires
Modified:	2024-05-20	X= Fulfilment

Nr.	Criteria:	Target Value	R/D	Weight	Verification Method	Stakeholder	Fullfilment
1	**Functions**						
1,1	Tighten cable ties	= Reference tool	R		Tighten cable ties the same as reference tool	Volvo Trucks	
1,2	Cut cable ties	= Reference tool	R		Cuts off excess material the same as reference tool	Volvo Trucks	
1,3	Adjust tension	8 settings	R		Compare tightened cable ties for different settings between prototype and reference	Volvo Trucks	X
1,4	Chargeable	Yes	R		Battery test	Volvo Trucks	X
1,5	Handle shape	Perceived as good by 8 of 10 stakeholders	D	5	10 user test with the prototype at the BML	Ergonomist, Developer	X
2	**Performance**						
2,1	The battery operating time	≥ 510 cycles	R		Battery test	Ergonomist, Operators	X
2,3	Tension and cut time	≤ Reference tool	D	3	Test of tightening and cutting 10 cable ties with prototype and the reference tool	Operators, Volvo Trucks	
2,4	Changing battery	≤ 2 min	R		Time test of changing battery of the prototype	Operators, Developer	X
2,5	Changing battery	≤ 30 sec	D	1	Time test of changing battery of the prototype	Operators, Developer	X
3	**Ergonomics**						
3,1	Activate trigger with one finger or thumb	≤ 5 N	D	3	Measure the force with dynamometer	Volvo Guidelines	
3,2	Activate trigger with more than one finger	≤ 30 N	R		Measure the force with dynamometer	Volvo Guidelines	X
3,3	The position of the wrist	< 20° in Flexion < 30° in Extension < 20° in Radial deviation < 30° in Ulnar deviation	R		Compare before and after picture of the working position	Volvo Guidelines	X
3,4	The tool is within forearm distance	≤ 300 mm	D	2	Compare before and after picture of the working position	Volvo Guidelines	
3,5	The position of the hand	1000-1300 mm from the floor	D	3	Compare with before and after picture of the working position	Volvo Guidelines	X
4	**User environment**						
4,1	The tool is portable	Assembly operator can wear it on body	D	3	User test with prototype	Ergonomist, Operators	X
5	**Design**						
5,1	The shape of the handle	Symmetrical	D	4	10 users test with both right and left hand	Ergonomist	X
5,2	The shape of the handle	Cylindric or elliptic	R		User test of the prototype	Volvo Guidelines	X
5,3	The trigger size	> one finger	D	5	10 users test to activate the trigger with more than one finger	Ergonomist	X
6	**Dimensions**						
6,1	The largest diagonal of the handle	34-38 mm	R		Measure in CAD drawings	Volvo Guidelines	X
6,2	The length of the handle	≥ 125 mm	D	3	Measure in CAD drawings	Volvo Guidelines	
7	**Mass**						
7,1	Total weight	< 2 kg	R		Test by weighing with a scale	Ergonomist, Operators	X
7,2	Weight in hand	< 1.5 kg	R		Test by weighing with a scale	Ergonomist, Operators	X
7,3	Weight in hand	< 1 kg	D	5	Test by weighing with a scale	Operators	X

As seen in the table, not all requirements were fulfilled. Two performance-related requirements, criteria 1.1 and 1.2, for the mechanism were not fulfilled due to the prototype design incorporating cable extensions, which led to a loss of energy flow to the motor. Consequently , the motor did not receive enough power to perform the tightening and cutting functions effectively. Additionally, the desire to have the same tension and cut time as the reference tool was not fulfilled (criteria 2.3).

The criteria 3.1 for activating the trigger with one finger or thumb were not met, as the design of the tool only included one button that is pressed with more than one finger. The desire for this feature was formulated under the assumption that the tool would include more than one button. The handle, originally 125 units long, was considered too long and cumbersome. Therefore it was decided to make the handle shorter based on the operators and ergonomists feedback and not fulfill the desire based on the Volvo Trucks ergonomical guidelines.

The criteria 3.4 did not get fulfilled for all four work positions. In position two and three the operators still needs to straighten their arm to tighten and cut cables ties, which is due to the assembly process at the BML.

According to the Table 5.14, all criteria concerning mass have been met. The weight of the tool in the hand has been reduced from 1.5 kg in the reference tool to 960 grams indicating a reduction of approximately 36%. Additionally, all desires with an important weight of four or higher have been fulfilled.

6

Discussion

The chapter reflects on the methodology used, the challenges encountered, and the results. The discussion critically analyzes how well the prototype meets the ergonomic requirements and addresses the research questions posed in the Section 1.3. It also explores the broader ethical impacts of the Master thesis.

6.1 Methodology

The main methods used for collecting data included semi-structured interviews, observations, and continuous stakeholder engagement. These qualitative methods provided a detailed understanding of the ergonomic issues that operators encounter and the actual needs for a new tool. The interviews allowed for open and in-depth discussions, enabling participants to freely express their experiences and insights, which may not have been captured through structured surveys or quantitative measures.

Observations, both passive and active, provided direct insights into the operators' interactions with the existing tools, revealing ergonomic issues and potential areas for improvement. This method was effective in identifying specific postures and movements that contribute to discomfort and injuries.

However, no quantitative methods were employed, meaning some statistical data might have been overlooked. This decision was influenced by several factors. First, the research questions focused on understanding the internal experiences and ergonomic challenges at Volvo Trucks, which were best explored through qualitative methods. Additionally, the small number of ergonomists familiar with the BML situation limited the feasibility of gathering a large sample size required for quantitative analysis. Lastly, the operators' optimized time schedules constrained opportunities for extensive quantitative data collection, as disrupting their workflow to answer a survey could have impacted their productivity.

RULA was a valuable tool for assessing ergonomic risks, but it naturally involves subjectivity. The assessment relies on the evaluator's judgment to observe and rate workers' postures and movements, which can introduce inconsistency. Different evaluators may interpret the same postures differently, potentially affecting the reliability. To address this, multiple evaluators were used to evaluate the same tasks, and their ratings were discussed to identify and resolve any inconsistencies. This approach helped to minimize individual biases and improve the reliability of the assessments, leading to more objective conclusions.

The reference tool was investigated using the method Reverse Engineering. This method provided valuable insights into the tool's components and the constraints they imposed. By disassembling the tool and analyzing its parts, the project group better understood its design and functionality. However, additional datasheets explaining the components and their functions would have been helpful. This could have saved time and improved the redesign of the reference tool. Having access to specifications about the reference tool would have contributed to spending more time developing the prototype and focusing on its ergonomics attributes.

During the development process of redesigning the reference tool, it was valuable to create rapid prototypes of the concepts generated to give the users something tangible. Using physical models made it easier for the stakeholders to understand the concept, rather than having to interpret a 3D-model and make assumptions about how they could work at the BML. The feedback sessions with operators and ergonomists would not have been as insightful if rapid prototypes had not been used. The quickly developed prototypes had no details, only the shape of the handle, which could have influenced the users' opinion about its suitability at the BML. However, given the project's time limit, it was not possible to make five separate prototypes with detailed features.

6.2 Result

The prototype design has received positive and negative feedback regarding its fit at the BML. Users have expressed that the redesigned handle and overall shape of the tool promote a more natural and comfortable grip, reducing the strain on the hands and wrists. The shape of the prototype enables a more ergonomic posture, allowing operators to perform tasks without compromising their body as much as with the existing tool.

Despite efforts to make the concept as compact as possible, certain features still need to be included to fit the components within the shell. The solenoid feature on the shell was often mistaken for a handle, leading users to think it was a pistol grip. The extruded feature for the solenoid could have been designed differently to improve user-friendliness and make it clearer how the tool should be gripped. Furthermore, the users expressed a preference for the handle design to have a top support to prevent it from slipping out of their hand. However, it would have required additional time to develop this feature and incorporate it into the final prototype.

Moving the battery to the operator's back reduced the load on the hand and wrist by approximately 36%, which is a significant improvement for the hand and wrist work postures. However, the final prototype includes a cable running from the back of the operator to the arm, which may impact the operator's ability to perform other tasks. Despite weight reduction efforts, users still found the tool too heavy due to the weight of the mechanism, which the project group cannot change. Further investigation is needed to address these issues and improve the concept.

The RULA analysis showed that all work positions have been improved when using the prototype. Positions one, two, and three are still at the same action level for the prototype as they were for the existing tool at BML, but the prototype falls within the lower spectrum of these levels, indicating a small improvement in working positions. However, the results show significant improvements in the ergonomics of hands and wrists, which are the most critical area at BML. Additionally, better results could have been achieved if changes to the mechanism and its performance had been possible. This could have led to other interesting concepts that further improved ergonomics through design settings.

Another insight is that this Master's thesis does not explore process alternatives that deal with time in terms of frequency, which is one of the three factors affecting ergonomics according to the Cube model presented in Section 2.1.3. The high frequencies of tightening and cutting cable ties in three of four selected work positions have a negative impact on the ergonomic situation, and this could not be changed.

According to the results of this Master's thesis, the ergonomic improvements could potentially lead to positive health outcomes. The redesigned cable tie tool, with its ergonomic enhancements, is expected to improve operator comfort when tighten and cut cable ties. Implementing this tool in the assembly line could reduce injury-related absences and enhance efficiency, providing health benefits to the operators. However, this must be further investigated and evaluated by implementing the tool to BML. Additionally, the concept's development and evaluation were conducted only at the four selected work positions. This means that the thesis results do not cover the complete situation of the BML, and therefore, the outcomes might differ in other work positions.

The prototype, however, did not fulfill all the requirements in the product specification. The requirement that the redesigned tool should have the same functionality regarding the tightening and cutting of cable ties was not met. The loss of functionality was due to the extension of cables, and the lack of knowledge about the tool's components contributed to not meeting the requirement. If the Master's thesis had been in collaboration with the creators of the reference tool, it might would have been easier to understand the tool's capabilities.

If the tool had functioned, the goal would have been to test the prototype on operators over a period of time to gather their valuable feedback on the concept of working with a cable, as well as a deeper analysis of the tool's comfort and ability to tighten and cut cable ties at the BML. This feedback would have contributed to further improving the concept.

6.3 Ethics Aspects

Engaging with stakeholders throughout the project was crucial for the development of a concept for a new tool. This ensured that the project's scope was clearly understood and opportunities for improvement were recognized. Keeping stakeholders informed and actively seeking feedback ensured the project stayed on course, preventing misunderstandings and enabling informed decisions.

When conducting interviews and observations, it was vital to inform the participants about the purpose of the study and how their information will be used. All the participants needed to consent that the data could be used and published before each interview. This consent process protects participants' anonymity and ensures that their contributions are voluntary.

Moreover, the thesis included pictures of people using both the existing tool and the prototype. These pictures were necessary to visualize ergonomic issues with the reference tool and demonstrate the prototype's ergonomic performance. Ethical handling of visual data was ensured by informing participants about data usage and obtaining their permission. Faces were blurred, and names were excluded to ensure anonymity and respect participants' privacy.

A societal ethical aspect of developing a user-friendly, ergonomically designed tool is that it can decrease work-related injuries among operators. Such a tool not only reduces sick leave but also enables seamless performance of daily tasks, benefiting numerous operators and enhancing overall workplace well-being.

Although the implementation of the tool falls outside the project scope, providing clear guidelines for its usage remains crucial. Throughout the project, clear communication and instructions were provided to all involved parties to ensure correct usage. This commitment to ensuring all users understand the proper procedures for using the tool demonstrates ethical responsibility by prioritizing user safety.

While, the project did not focus on ecological aspects, sustainability must be considered in future iterations of the tool. Ethical product development involves assessing the environmental impact throughout the tool's life cycle. Future, designs should incorporate sustainable practices to align with Volvo Trucks, environmental goals.

7

Conclusion

The Master's thesis has developed a final concept and a prototype of an electric cable tie tool designed to tighten and cut cable ties at the BML while ensuring ergonomic interaction for the operators. This was achieved by redesigning the reference tool, leading to ergonomic improvements in the four selected work positions. However, the prototype is not fully functional and has not met all requirements regarding the mechanism. Additionally, the project has addressed the following research questions:

How can the ergonomics be improved in the reference tool?

Through an investigation of the current ergonomic situation and the reference tool, two main improvements were made. Firstly, the ergonomics of the reference tool were improved by changing its shape, allowing operators to perform tasks in an ergonomic work posture. Secondly, the ergonomics were enhanced by moving the battery from the tool to the operator's body, thereby decreasing the force applied to the hands and wrists and promoting a more ergonomic solution.

These changes are expected to reduce the risk of MSDs and improve comfort for the operators. Future work could focus on further refining these ergonomic improvements and conducting long-term studies to assess their impact on operator health.

How should the tool be designed to meet the stakeholders' requirements?

To ensure the tool met the stakeholders' requirements, the tool was designed with continuous involvement from all stakeholders throughout the redesign process. This collaborative approach ensured that the tool addressed ergonomic concerns and aligned with the practical needs and preferences of both the operators and ergonomists. Regular feedback sessions, prototype testing, and iterative improvements based on stakeholder input were essential to redesign the final concept. However, two requirements related to the mechanism's functionality were not fulfilled, as the project group did not succeed in maintaining the function after reorganizing the parts. Further work is required to ensure mechatronic feasibility. On the other hand, this unmet requirements did not affect the tool's design.

How can the tool be evaluated as an ergonomic hand tool?

The RULA analysis effectively evaluated the ergonomic qualities of the tool. The analysis demonstrated an improvement in all work postures when using the prototype, indicating that its design contributes to better ergonomic conditions compared to the reference tool. This improvement highlights the prototype's potential to reduce the risk of MSDs at the BML.

In conclusion, all of the research questions have been answered. The prototype has shown promising potential for implementation. The operators and the ergonomists have expressed various additional needs regarding the performance and design of the mechanism, but these were not addressed due to the project's scope. It is recommended that Volvo utilize the tool's straight handle, as it significantly contributes to ergonomic work positions compared to the current situation. However, the mechanisms should be replaced with a lighter and slimmer option to address all concerns raised by the operators and the ergonomists.

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A

Appendix 1

A.1 Interview Questions: Assembly Operator

(Translated from Swedish)

1. How long have you been working in production?
2. Do you consider your ergonomics when you work?
3. Do you feel that you can perform your work ergonomically?
4. Which tool do you prefer to use when tightening and cutting cable ties? Why?
5. Have you experienced any discomfort from tightening and cutting the cable ties?
6. How do you perceive the user-friendliness of the tools you use?
7. Are there any limitations with the tool?
8. What do you like about manual tools?
9. What do you like about existing electric tool?
10. What problems arise with manual tools?
11. What problems arise with existing electric tools?
12. **Improvements:**
    - How would you like the tool to be improved?
    - How can the design of the tool be adapted so that you can work more ergonomically in the future?
    - Is there any function missing in the existing tool?

A.2 Interview Questions: Ergonomist

(Translated from Swedish)

1. Has there been any feedback or complaints from workers regarding the usability or ergonomics of the tool?
2. Are there any industry standards or guidelines that the tool must adhere to in terms of ergonomics?
3. What are the advantages of the existing electric tool?
4. Why is the existing electric tool a problem?
5. What are the advantages of the existing manual tool?
6. Why is the existing manual tool a problem?
7. What are the advantages with the reference tool?
8. Why is the reference manual tool a problem?
9. What characteristics are important to prioritize for a hand tool to prevent work-related injuries?
10. What is preferable handle shape from an ergonomic perspective?
11. How should we verify that the requirements are met? Is there a method that is commonly used?
12. How does the design of the tool minimize the risk of strain or injury with repeated use?
13. How does the weight of the tool impact usability and worker fatigue?
14. What measures are in place to ensure proper training and education for workers on the correct usage of the tool to prevent injuries?

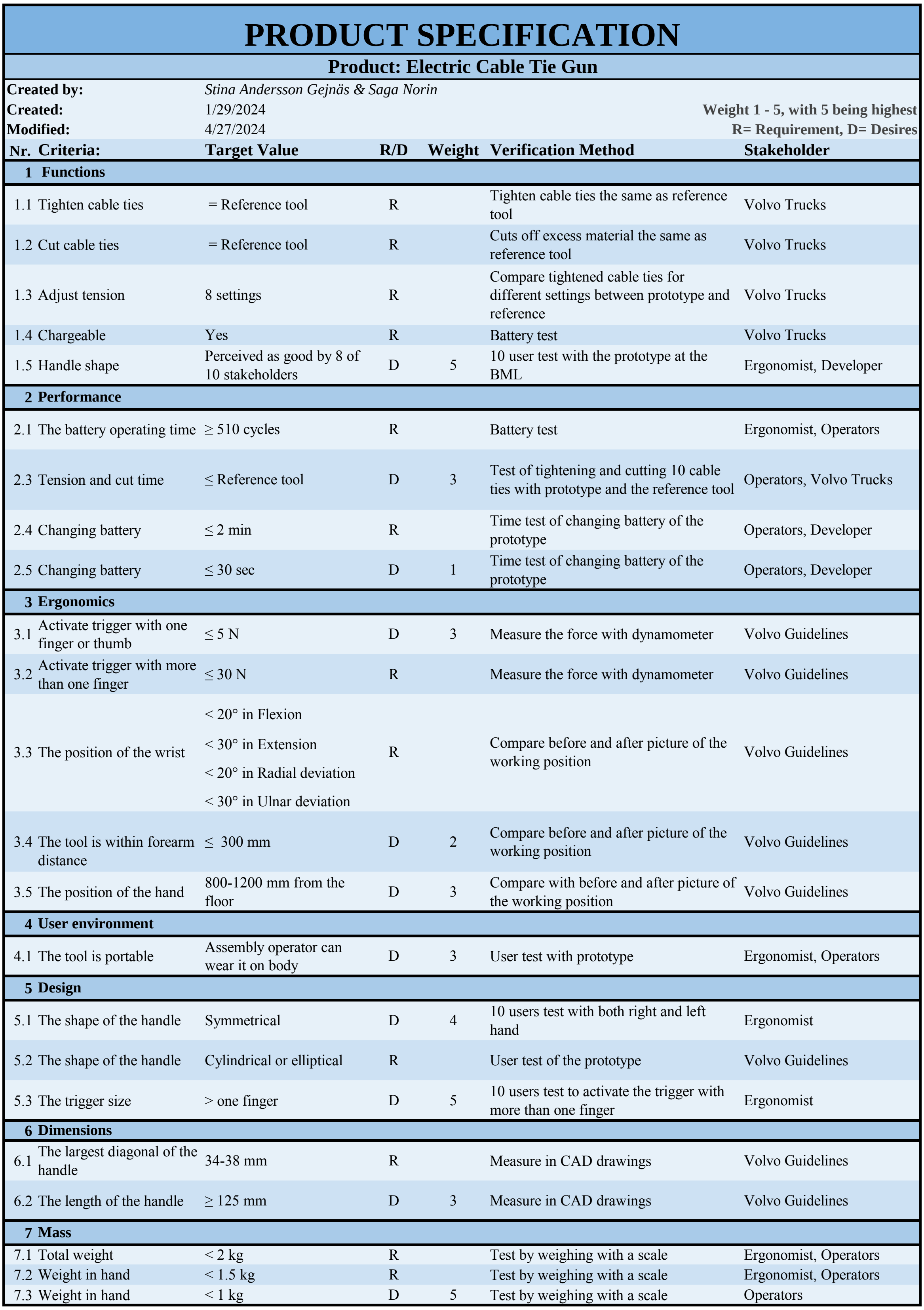
A.3 Stakeholder Needs Statement

(Translated from Swedish)

Stakeholder	Nr	Stakeholder Statement	Identified Need
Assembly Operators	1	I often use the manual tool, because I carry it with me wherever I go.	The tool has to be portable
	2	The existing electric tool has a slim nose which is good to reach confined spaces.	The tool can access confined spaces
	3	I like that the electric tool has a rotatable nose, it makes it possible to use it in different positions	The tool can be used in different direction
	4	I choose to use the manual because it is faster than the electric.	The tool is quick and efficient in its usage.
	5	I experience that the electric tool is clumpy to use	The tool has to be smooth and ergonomic to use.
	6	I feel that the tool is to heavy to use.	The tool is light-weighted
	7	It is not possible to use the tool for all types of cable ties	The tool is able to control the tightening torque
	8	I would like to hold the tool in different ways	The tool is adapted for different hand positions.
	9	I would like to use the tool with different hands	The tool is usable by both right- and left-handed people
	10	The electric tools is quite big to hold	The tool is usable by several different hand sizes.
	11	I would like it to be easy to change the battery if needed	The battery is easy to replace.
	12	I would prefer if it is easy to reach and push down the trigger	The tool is easy to activate.
	13	You should be able to use multiple fingers to trigger the tool	The tool is easy to activate
	14	You should be able to use the tool for at least two hours	The tool have a minimum usage duration of two hours

Ergonomist	15	It is preferable if you can grab the tool in different ways	The tool is adapted for different hand positions.
	16	It should be adapted for left handed and right handed users	The tool is usable by both right- and left-handed people
	17	" If the tool exceeds a weight of 2.5 kilograms, it needs to have a relieve function	The tool had to be lightweighted
	18	You should not have to adapt your hand to reach the trigger	The tool has to be ergonomic to activate
	19	The tool should be designed based on ergonomics standards	The tool is designed based on ergonomics standards
	20	It should be comfortable to hold the tool	The tool has to be comfortable to use
	21	It should be graspable	The tool has to be easy to grip
	22	The center of gravity should be positioned in a way that avoids putting strain on the wrist.	The tool have the center of gravity adapted to the working position
Assembly Operators from other areas	23	The reference tool tightening to lose some times	The tool have to be able to adapt the torque
	24	I use the different buttons to access all areas, the top one to access hard-to-reach areas	The tool have to accesses hard-to-reach areas
	25	The reference tool is a bit to heavy and clumsy	The tool had to be lightweighted
	26	The battery could be smaller	The battery has to be small
	27	I do the electrical parts and i would like a long nose to access all areas	The tool have to access hard-to-reach areas
	28	The tool should cut faster	The tool have to be quick and smooth to use
	29	The biggest problem i have with the manual tool is the vibration	The tool can resist vibrations
	30	The recoil from the manual tool is a big problem	The tool can resist the recoil when cut the cable ties

A.4 Product Specification



PRODUCT SPECIFICATION

Product: Electric Cable Tie Gun

Created by: *Stina Andersson Gejnäs & Saga Norin*
Created: 1/29/2024 **Weight 1 - 5, with 5 being highest**
Modified: 4/27/2024 **R= Requirement, D= Desires**

Nr.	**Criteria:**	**Target Value**	**R/D**	**Weight**	**Verification Method**	**Stakeholder**
1	**Functions**					
1.1	Tighten cable ties	= Reference tool	R		Tighten cable ties the same as reference tool	Volvo Trucks
1.2	Cut cable ties	= Reference tool	R		Cuts off excess material the same as reference tool	Volvo Trucks
1.3	Adjust tension	8 settings	R		Compare tightened cable ties for different settings between prototype and reference	Volvo Trucks
1.4	Chargeable	Yes	R		Battery test	Volvo Trucks
1.5	Handle shape	Perceived as good by 8 of 10 stakeholders	D	5	10 user test with the prototype at the BML	Ergonomist, Developer
2	**Performance**					
2.1	The battery operating time	≥ 510 cycles	R		Battery test	Ergonomist, Operators
2.3	Tension and cut time	≤ Reference tool	D	3	Test of tightening and cutting 10 cable ties with prototype and the reference tool	Operators, Volvo Trucks
2.4	Changing battery	≤ 2 min	R		Time test of changing battery of the prototype	Operators, Developer
2.5	Changing battery	≤ 30 sec	D	1	Time test of changing battery of the prototype	Operators, Developer
3	**Ergonomics**					
3.1	Activate trigger with one finger or thumb	≤ 5 N	D	3	Measure the force with dynamometer	Volvo Guidelines
3.2	Activate trigger with more than one finger	≤ 30 N	R		Measure the force with dynamometer	Volvo Guidelines
3.3	The position of the wrist	< 20° in Flexion < 30° in Extension < 20° in Radial deviation < 30° in Ulnar deviation	R		Compare before and after picture of the working position	Volvo Guidelines
3.4	The tool is within forearm distance	≤ 300 mm	D	2	Compare before and after picture of the working position	Volvo Guidelines
3.5	The position of the hand	800-1200 mm from the floor	D	3	Compare with before and after picture of the working position	Volvo Guidelines
4	**User environment**					
4.1	The tool is portable	Assembly operator can wear it on body	D	3	User test with prototype	Ergonomist, Operators
5	**Design**					
5.1	The shape of the handle	Symmetrical	D	4	10 users test with both right and left hand	Ergonomist
5.2	The shape of the handle	Cylindrical or elliptical	R		User test of the prototype	Volvo Guidelines
5.3	The trigger size	> one finger	D	5	10 users test to activate the trigger with more than one finger	Ergonomist
6	**Dimensions**					
6.1	The largest diagonal of the handle	34-38 mm	R		Measure in CAD drawings	Volvo Guidelines
6.2	The length of the handle	≥ 125 mm	D	3	Measure in CAD drawings	Volvo Guidelines
7	**Mass**					
7.1	Total weight	< 2 kg	R		Test by weighing with a scale	Ergonomist, Operators
7.2	Weight in hand	< 1.5 kg	R		Test by weighing with a scale	Ergonomist, Operators
7.3	Weight in hand	< 1 kg	D	5	Test by weighing with a scale	Operators

A.5 Patent Landscape analysis

1. **Ergonomic Tool Handle**
   The invention is a handle for a tool with a ratcheting mechanism at one end. The handle is ergonomically designed to fit comfortably in the palm of the user's hand. The handle has a frictional outer shell to enhance its ergonomic features. [21]

2. **Ergonomic handle device for holding tools**
   This device provides an ergonomic grip for tools, relieving hand strain and creating a natural hold. It has grip indentations that increase friction, making it easier for users to hold the tool with less force. [22]

3. **Balanced ergonomic surgical handle**
   This is an ergonomic laparoscopic device that reduces hand fatigue during prolonged usage. It can be used in multiple grip styles without compromising the reachability of the buttons. A ballast offsets the weight of the elongated shaft. [23]

4. **Electric head shaver with ergonomic handle**
   The invention is an ergonomic electric head and face shaver. It has a shape that provides a firm grip for the palm, as well as finger grooves for added comfort and control. [24]

5. **Adjustable holder assembly for painting tools**
   The invention is an holder for painting tools. The holder, together with the painting tool can be adjusted from 0 to 90 degrees. The angle of the holder are made with a button trigger that is connected to a spring pin that locks the holder in wanted angle. [25]

6. **Handheld welding torch for electric-arc welding**
   The related art is a handheld welding torch with ergonomic properties. The invention enables smaller handheld welding torch due to space savings of the wire feed unit, which contributes to a ergonomic and user-friendly usage. [26]

7. **Ergonomic gripping mechanisms of a handheld air movement apparatus**
   This invention is an ergonomic grip with a trigger and adjustable handle angle (0-45 degrees) that fits naturally in the palm while using a handheld air movement device. [27]

8. **Hand-held tool**
   The application offers a handheld tool to aid in battery pack installation and removal. The handheld tool has a built-in battery held by a slot with an opening and a way to push it out. A locking mechanism inside the slot connects to the battery to securely hold it in place when inserted. [28]

9. **Hand Held Scrubbing Tool**
   This invention is a handheld motorized cleaning device with housing, battery, motor, output drive shaft, rotating cleaning attachment, and flexible adapter. Handheld motorized cleaning device with housing, battery, motor, output drive shaft, rotating cleaning attachment, and flexible adapter. [29]

10. **Ergonomic handle-less hair dryer**
    The invention is an ergonomic hair dryer equipped with an adjustable strap that supports the hand and allows for a natural and relaxing grip. The strap can rotate 180 degrees around the housing of the dryer to enable both right and left-handed use. The buttons for adjusting the dryer's speed and heat are placed in an ergonomic position, making them easy to reach with the fingers. [30]

11. **Hair Dryer Apparatus**
    The invention is a hair dryer that features a rotatable handle. The handle is connected to the outer surface by a pivot, which allows for the angle of the handle to be adjusted. The handle is held securely in place by a locking mechanism once it is positioned. The power cord runs through the handle and is connected to the pivot point with a rotatable coupling that supplies power to the motor. [31]

12. **Ergonomic attachment for inline power tools**
    This invention is a patent for an ergonomic attachment for operators using power line tools. The main aim is to reduce strain and make the use of these tools more comfortable. The mechanism consists of a bracket and a U-shaped device that is placed on the operator's forearm. The bracket has a fastening device to attach the power tool. [32]

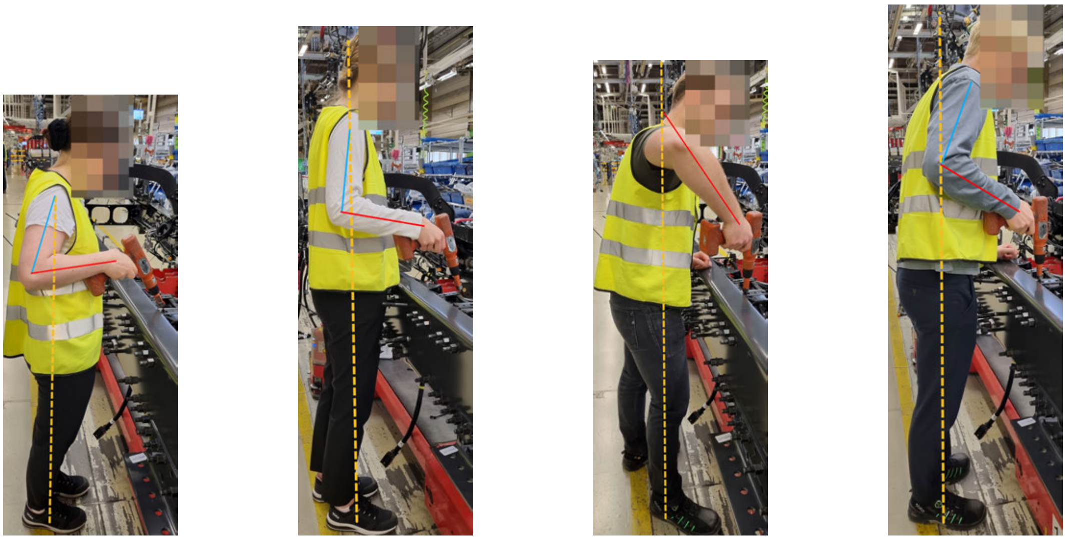
13. **Screwdriver**
    The invention is an electric screwdriver that, simply described, includes a motor, a handle, a battery housing, and a spindle. The handle is in the same axial direction as the gear housing. It extends vertically and has a grip-friendly surface. The battery is attached to the lower part of the handle. [33]

14. **Power tools**
    The invention is an power screwdriver consisting of a housing body and a grip portion. The grip portion can be used in a pistol grip or it can be held in position in the axial direction relative to the housing body. The trigger is placed on the housing body. [34]

15. **Ergonomic hand held paint spray gun.**
    The invention is a handheld liquid spray gun. It has been designed with multiple triggers and grip options to reduce fatigue and stress for operators based on their work position. [35]

A.6 RULA of existing electric tool

Position 1



(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.1: Postures for the first position with existing electric tool

Table A.2: Analysis of hand and wrist for existing tool

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	2	1	4	3
Forearm	1	1	2	1
Wrist flex	3	4	3	3
Wrist twist	1	1	1	1
Table A value	**3**	**3**	**4**	**4**

Table A.3: Analysis of neck, back, and legs for existing tool

Position: 1	Female		Male	
	Low range	High range	Low range	High range
Neck	3	3	2	3
Back	1	1	3	2
Legs	1	1	1	1
Table B value	**3**	**3**	**3**	**3**

Table A.4: Analysis of load frequency and load for existing tool

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

Position 2

(a) Low range female **(b)** High range female **(c)** Low range male **(d)** High range male

Figure A.2: Postures for the second position with existing electric tool

Table A.5: Analysis of hand and wrist for existing tool

Position: 2	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	4	4	4	3
Forearm	2	2	2	2
Wrist flex	4	4	4	4
Wrist twist	1	1	1	1
Table A value	**4**	**5**	**4**	**5**

Table A.6: Analysis of neck, back and legs for existing tool

Position: 2	**Female**		**Male**	
	Low range	High range	Low range	High range
Neck	2	3	2	3
Back	2	1	3	2
Legs	1	1	1	1
Table B value	**2**	**3**	**4**	**3**

Table A.7: Analysis of load frequency and load for existing tool

Position: 2	**Female**		**Male**	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

Position 3

(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.3: Postures for the third position with existing electric tool

Table A.8: Analysis of hand and wrist for existing tool

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	4	3	4	2
Forearm	2	1	2	1
Wrist flex	4	4	4	4
Wrist twist	1	1	1	1
Table A value	**5**	**5**	**5**	**4**

Table A.9: Analysis of neck, back, and legs for existing tool

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Neck	2	3	2	2
Back	4	3	3	3
Legs	1	1	1	1
Table B value	**4**	**4**	**4**	**4**

Table A.10: Analysis of load frequency and load for existing tool

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Load frequency	0	0	0	0
Load	0	0	0	0

Position 4

(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.4: Postures for the fourth position with existing electric tool

Table A.11: Analysis of hand and wrist for existing tool

Position: 4	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	4	4	4	4
Forearm	2	2	3	2
Wrist flex	4	4	4	4
Wrist twist	1	1	1	1
Table A value	**5**	**5**	**5**	**5**

Table A.12: Analysis of neck, back, and legs for existing tool

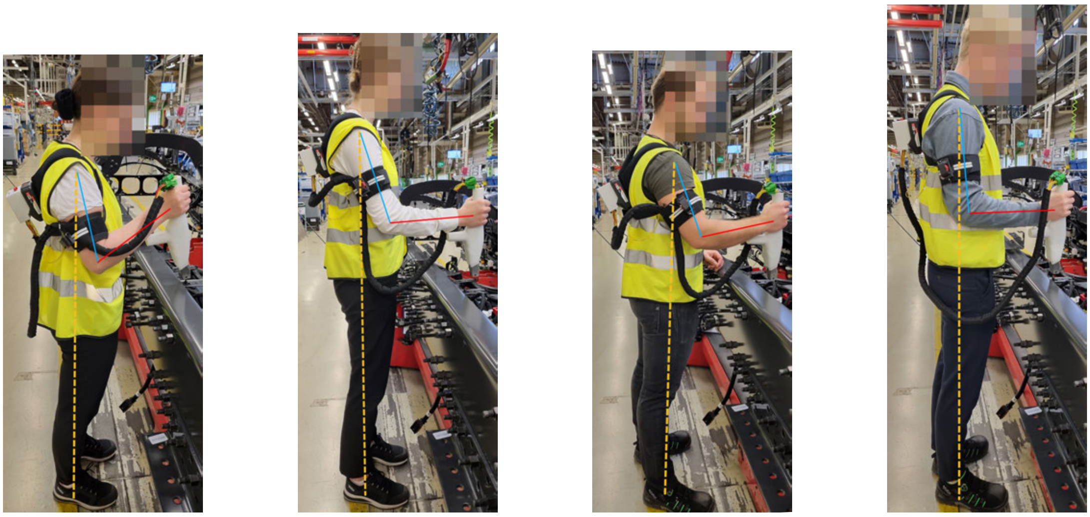
Position: 4	**Female**		**Male**	
	Low range	High range	Low range	High range
Neck	4	3	4	3
Back	4	4	4	4
Legs	1	1	1	1
Table B value	**7**	**5**	**7**	**5**

Table A.13: Analysis of load frequency and load for existing tool

Position: 4	**Female**		**Male**	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

A.7 RULA of Prototype

Position 1



(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.5: Postures for the first position with prototype

Table A.14: Analysis of hand and wrist for prototype

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	1	1	2	1
Forearm	2	1	1	1
Wrist flex	2	1	1	2
Wrist twist	1	1	1	1
Table A value	**2**	**1**	**2**	**2**

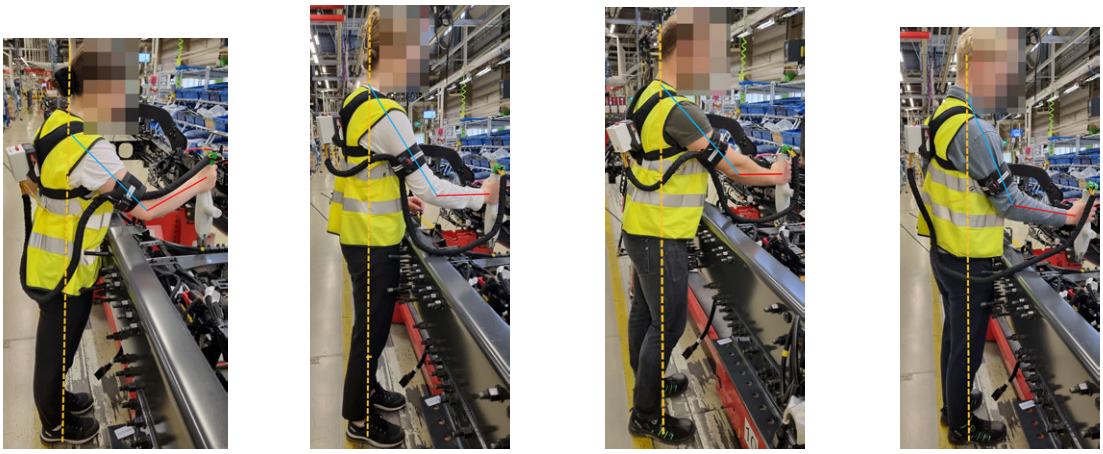
Table A.15: Analysis of neck, back, and legs for prototype

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Neck	2	2	2	3
Back	1	1	1	1
Legs	1	1	1	1
Table B value	**2**	**2**	**2**	**3**

Table A.16: Analysis of load frequency and load for prototype

Position: 1	**Female**		**Male**	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

Position 2



(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.6: Postures for the second position with prototype

Table A.17: Analysis of hand and wrist for prototype

Position: 2	Female		Male	
	Low range	High range	Low range	High range
Upper arm	3	2	3	2
Forearm	1	1	1	1
Wrist flex	1	2	2	2
Wrist twist	1	1	1	1
Table A value	**3**	**3**	**4**	**3**

Table A.18: Analysis of neck, back, and legs for prototype

Position: 2	Female		Male	
	Low range	High range	Low range	High range
Neck	1	2	1	2
Back	2	1	2	1
Legs	1	1	1	1
Table B value	**2**	**2**	**2**	**2**

Table A.19: Analysis of load frequency and load for prototype

Position: 2	Female		Male	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

Position 3

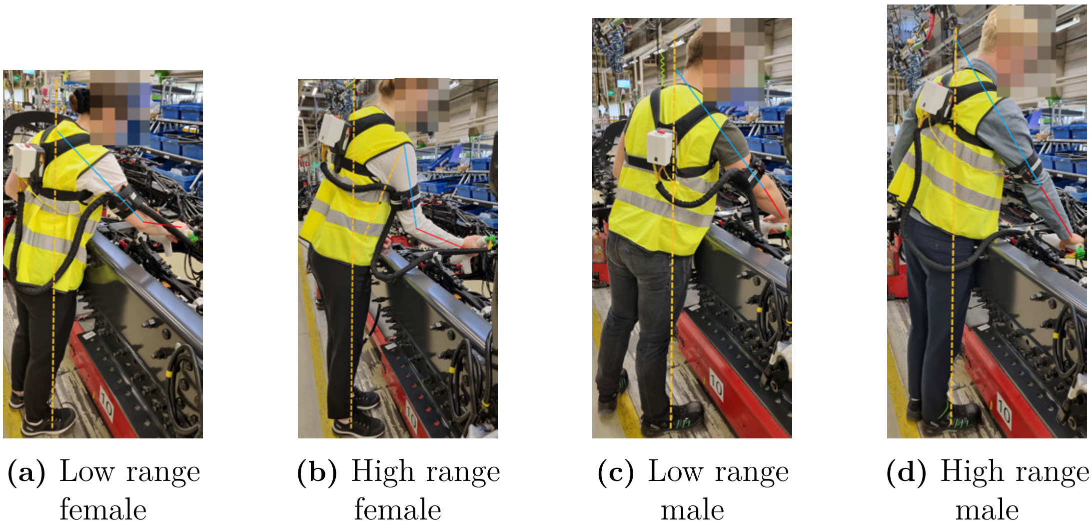

(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.7: Postures for the third position with prototype

Table A.20: Analysis of hand and wrist for prototype

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Upper arm	3	2	3	2
Forearm	1	1	1	2
Wrist flex	2	2	4	2
Wrist twist	1	1	1	1
Table A value	**4**	**3**	**5**	**3**

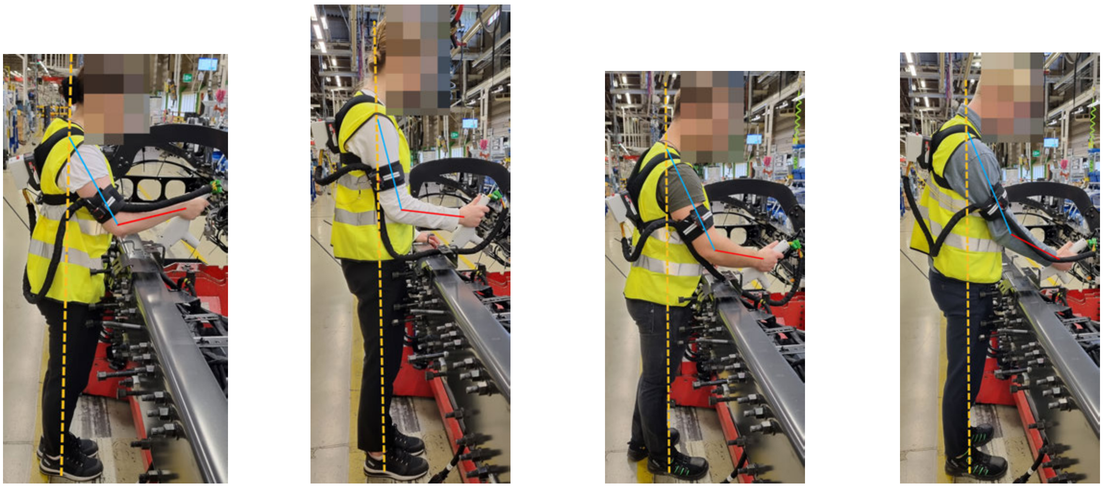
Table A.21: Analysis of neck, back, and legs for prototype

Position: 3	**Female**		**Male**	
	Low range	High range	Low range	High range
Neck	3	2	2	2
Back	2	3	2	3
Legs	1	1	1	1
Table B value	**3**	**4**	**2**	**4**

Table A.22: Analysis of load frequency and load prototype

Position: 3	Female		Male	
	Low range	High range	Low range	High range
Load frequency	0	0	0	0
Load	0	0	0	0

Position 4



(a) Low range female (b) High range female (c) Low range male (d) High range male

Figure A.8: Postures for the fourth position with prototype

Table A.23: Analysis of hand and wrist for prototype

Position: 4	Female		Male	
	Low range	High range	Low range	High range
Upper arm	2	2	2	2
Forearm	1	1	1	1
Wrist flex	2	2	2	2
Wrist twist	1	1	1	1
Table A value	**3**	**3**	**3**	**3**

Table A.24: Analysis of neck, back, and legs for prototype

Position: 4	Female		Male	
	Low range	High range	Low range	High range
Neck	3	3	3	3
Back	1	1	1	1
Legs	1	1	1	1
Table B value	**3**	**3**	**3**	**3**

Table A.25: Analysis of load frequency and load for prototype

Position: 4	Female		Male	
	Low range	High range	Low range	High range
Load frequency	1	1	1	1
Load	0	0	0	0

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