Strukton Rail

Lifting the Load

Ergonomic Risk Assessment of Catenary Construction Work and the Development of an In-Situ Biomechanical Analysis Tool

Master Thesis Biomedical Engineering

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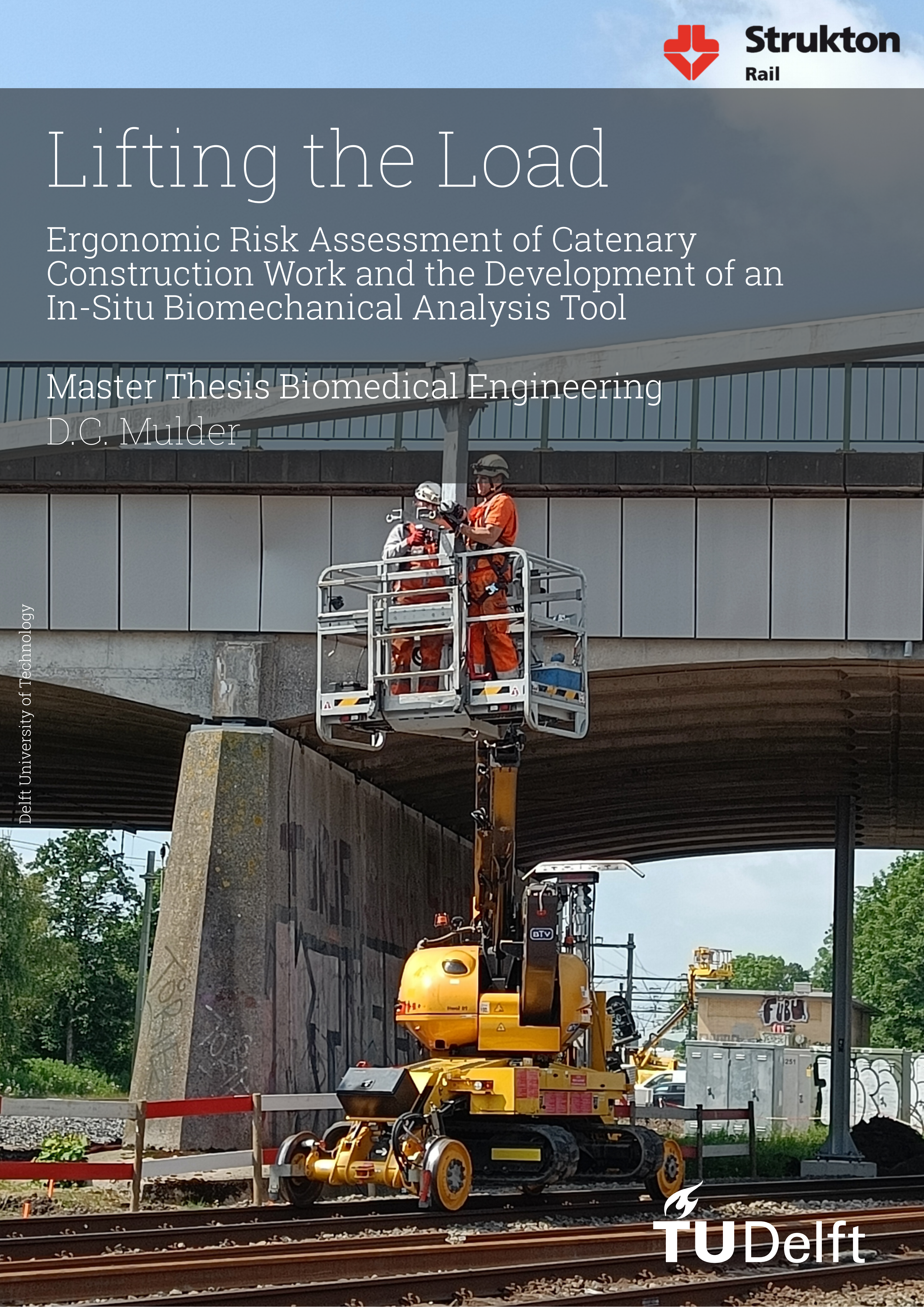

TU Delft

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by

D.C. Mulder

to obtain the degree of Master of Science
at the Delft University of Technology,
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Cover: Photo of rail catenary construction work performed by Strukton workers
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TU Delft

Preface

Over the past 7 months I have worked on this project in collaboration with the TU Delft and Strukton. It has been a journey of its own with all the challenges that are part of writing a master thesis at the TU Delft. Several experiences have motivated me to start this project, several people have motivated me to finish this project.
During my master's degree in BioMechanical Engineering, I discovered that combining engineering with the human body is something that both takes my interest and motivates me. During my internship at InteSpring, I delved into the interesting world of exoskeletons, learned several essential engineering skills, and made my first product design. Several other experiences during my time as a student in Delft showed me that helping people is what absolutely thrives me the most. Knowing this, I wanted to find a graduation project where I could help people with interesting technologies. When Arno suggested that I could design an exoskeleton for construction workers at Strukton, I was immediately enthusiastic. In the end, the project turned out a bit different, but not at all less relevant.
I would like to thank some people for their support in my project. At First my TU Delft supervisor Arno, who helped me out when I had no clue where to go next with my project and gave me the chance to start this very interesting project. Next, my company supervisor, Eddy, who encouraged and facilitated me to visit as many construction sites as possible, and helped me out with his extensive knowledge of catenary construction. These visits to construction sites were an exciting experience and made graduating much more fun. I also would like to thank all the other colleagues at Strukton: the ones in the office for helping me with specific rail topics and joining me for lunch; the ones working in the field for showing me how construction work is done and inviting me to watch a world cup football match at the site hut all in orange; and finally Jeroen and Jeffry for facilitating me to setup my measurement setup in their storage facility. Lastly, I would like to thank Chaja for Lifting the Load for me, my grandfather, mother and father for proofreading and all my friends and family who were involved in any way in proofreading or providing support.

D.C. Mulder
Delft, January 2025

Summary

Work-related musculoskeletal disorders (WRMSDs) are a leading cause of work leave in the construction industry. As Strukton experiences a shortage in workers for rail catenary construction, minimizing the occurance of WRMSDs is important. This is done by the implementation of new working methods or new worker aids, such as boom lifts and exoskeletons. Strukton has experienced that not all worker aids are, however, as helpful as expected. In order to find the right tools, a better understanding of the work and physical load is needed. This thesis aims to identify which parts of the catenary construction work are the most demanding by combining an ergonomic risk assessment (ERA) with the development of an in situ biomechanical analysis tool.

The research consists of two major components. First, a qualitative ergonomic risk assessment was conducted to identify the most physically demanding tasks in rail catenary construction. Methods included site visits to Strukton's rail construction projects, unstructured and semi-structured interviews with workers and experts, and a questionnaire administered to 12 workers. These data were used to develop a Work Breakdown Structure (WBS), categorize tasks based on their physical demand, duration, and frequency, and identify prevalent ergonomic risks. Tasks such as wire tensioning, removing wires, and task related to the support portal were identified as high-risk activities. Back, shoulder, and ankle complaints are the most commonly reported by workers and might be related to these tasks. Future research should expand the worker sample size, investigate the causes of WRMSDs further, and enhance the reliability of task scoring. Recommendations for Strukton include adding sidewalks on site, redesigning boom lift platforms, introducing ergonomic tool bags, and using electric tools for tasks that require high force.

The second component of the research involved designing and validating an in-situ biomechanical analysis tool. The tool leverages pose detection technology from widely available mobile devices and integrates it with musculoskeletal modeling software to capture and analyze joint kinematics and moments during construction tasks. This approach allows for task-specific quantification of physical loads experienced by workers, bridging the gap between qualitative insights and quantitative measurements. A pilot validation study demonstrated the feasibility of the tool in providing kinematic and joint moment data for biomechanical analysis, though further validation is needed to generalize its application. Potential uses of the tool include automating ERAs and validating conceptual worker aids. Future research should focus on deploying the tool in real-world working environments and refining the implementation of external force data in the modeling process.

The findings of this thesis highlight the critical need for task-specific ergonomic interventions in the construction of rail catenaries. The combination of qualitative ERA and biomechanical analysis offers a comprehensive framework to identify risks and design targeted solutions. This work provides a foundation for future research into ergonomic improvements in dynamic and physically intensive industries.

Contents

1 General introduction

In the Netherlands, the second largest reason for work leave is shoulder and back musculoskeletal diseases [1]. As there is a great shortage of workers in the Netherlands, this is highly undesirable [2]. Work-related musculoskeletal disorders (WRMSDs) are described as injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs that are caused by work conditions. WRMSDs are a major cause of discomfort for workers as they can cause functional impairments and even permanent disability [3]. Several factors are of influence on the development of WRMSDs. Often, they are caused by work tasks that include pushing, pulling, and lifting. In addition to the tasks performed, other factors such as the work environment, tools used and materials used are also influential for the development of WRMSDs [4].

Due to the physically demanding nature of construction work, WRMSDs are highly prevalent in the construction industry compared to other industries [5], [6]. In order to reduce the occurrence of WRMSD in construction work, an ergonomic risk assessment (ERA) can be used in combination with ergonomic interventions. An ERA focuses on identifying the aspects of work that introduce the highest risk of WRMSD [7]. Using ERA, ergonomic interventions can be introduced, focusing on reducing the risk of the work situations that pose the highest risk. These interventions can include changing the equipment and environment of the workplace, but also changing the work method or the rest schedule [8]. An accurate ERA is very important, as most ergonomic interventions cannot be used as universal solutions. Every construction job differs in the task that is performed, the materials that are handled, the tools that are used, and the work environment. Due to this high diversity in construction work, standard ERA methods have been reported to be challenging [9]. Methods that might be effective for manufacturing jobs have proven to be less effective for construction work.

This thesis focuses on the working activities of the rail catenary construction at Strukton. Strukton is a construction company in the Netherlands with a large rail construction department. Strukton Catenary Energy (SCE) is a part of this rail department that focuses specifically on the construction of rail catenary that supplies the train with electricity. Strukton faces a shortage of workers and is, therefore, interested in reducing the occurrence of WRMSDs for their workers. Currently, several measures have already been taken to reduce the physical load on their workers. For example, a new type of lorry boom lift has been introduced to perform work at height during rail catenary construction. This boom lift replaces the lorry ladder which required the workers to climb the ladder many times a day. New working methods such as prefabrication of parts have also been shown to be effective in reducing the physical load on the worker. In order to further reduce the physical load for their workers, Strukton is constantly implementing new innovations. Recently, several upper arm exoskeletons were tested by rail caternary workers. Here, it was shown that while these devices should help workers relieve the strain on their arms during construction tasks performed, this was not always the case. During certain tasks, such as bending over and picking up tools, the exoskeleton provides more resistance than support. During other tasks, the exoskeleton imposes new dangers to the workers from protruding parts of the exoskeleton. Only during very specific tasks did the exoskeleton prove to be helpful.

Given these findings, it is necessary to take a step back and consider the problem. Developing effective solutions requires a deeper understanding of the work and the factors that make it physically demanding. Priority should be given to reducing the physical load on the body parts that experience the most strain. Different tasks may require customized worker aids to meet their unique physical demands.

To address these challenges, this thesis focuses on identifying which parts of the rail catenary construction at Strukton make the work most physically demanding. This is done by performing two mostly independent researches. Firstly, a qualitative risk assessment of the rail catenary construction work is performed. For this assessment, multiple methods are used to gather information such as interviews, questionnaires, and site visit observations. From this information, an overview of all work tasks is made, the amount of physical demand required for every construction task is determined, experienced physical complaints are identified, and other ergonomic risks are identified. Secondly, a tool is developed to perform in situ biomechanical analysis of workers, focusing on the tasks seen in the construction of the rail catenary. This tool uses pose detection software to capture kinematics with widely available mobile equipment. With modeling software, joint moments are calculated during performed construction tasks. In this way, both expert opinions and quantitative measurements can be taken into account to identify risks related to the construction of a rail catenary. In the future, these results might help develop new worker aids that will further relieve the physical demand for rail caternary workers.

The qualitative ERA presented in the first part has several aspects. In chapter 2, several different existing methods for risk assessment used for construction work are presented. In chapter 3, a basic overview of rail caternary is given. In chapter 4, the method used for the risk assessment performed here is presented. In chapter 5, the results of this assessment are shown. In chapter 6, the results from the ERA are discussed, the limitations of the study are presented, and recommendations for Strukton are made. Finally, in chapter 7 the conclusions from the ERA are given.

In the second part, the development of a tool for In-Situ biomechanical analysis is presented. In chapter 8, several known methods for biomechanical analysis are presented. In chapter 9, the problem statement, the requirements, and the pilot validation tests performed are presented. In chapter 10, several potential solutions are presented and evaluated based on the requirements, and a design of choice is selected. In chapter 11, the two subsystems of the final design are presented. In chapter 12, the results of the pilot validation tests are presented. In chapter 13, the test results are discussed, the requirements are evaluated, and a potential application of the tool is presented. In chapter 14, conclusions are drawn on the usability of the tool, and potential future improvements are suggested.
In Chapter 15, a general conclusion is given on how the results from this thesis could be used for future research focused on improving ergonomics in construction work.

Part I
Ergonomic Risk Assessment

2 Introduction

Ergonomic risk assessment (ERA) identifies tasks that pose a high risk of work-related musculoskeletal disorders (WRMSDs). By analyzing job tasks, these assessments pinpoint critical areas that could lead to WRMSDs in the short or long term [7]. Information for such assessments can be collected through worker questionnaires, observational methods, and technical tools.

ERAs are widely used in industries such as manufacturing, healthcare, and office work [10]. Office jobs, often involve minimal physical activity and a consistent environment, making assessments relatively straightforward. A simple observational study might reveal that an incorrect chair height contributes to back pain. Validation studies have evaluated such assessments [11]. Similarly, in manufacturing, where tasks are more physical, but environments are relatively static, combining technology with ergonomic indices has yielded successful assessments, such as for assembly line tasks [12][13]. However, construction work presents unique challenges: tasks are less repetitive, environments are variable, and work is often dynamic. These factors complicate the application of standard ERA methods [10][14][15].

Some established methods for construction work assessment are the Rapid Entire Body Assessment (REBA), Rapid Upper Limb Assessment (RULA), Ovako Working Posture Analysis System (OWAS), and the Posture, Activity, Tools, Handling (PATH) method. REBA and RULA evaluate specific postures, while OWAS and PATH employ sampling techniques to score tasks holistically. Despite their utility, these methods require trained observers, are time-consuming, and involve some level of subjectivity [16]. Questionnaires, such as the Nordic Musculoskeletal Questionnaire, offer an alternative by assessing worker-reported body complaints to identify risks indirectly. Though cost-efficient and less time-consuming, they introduce subjectivity [17]. Recent advances in sensors and computer vision, including IMUs (Inertial Measurement Units) and body detection algorithms, offer promising alternatives to collect postural data [18][19]. However, these technologies face challenges such as sensor intrusiveness and camera occlusion [16].

The goal of this thesis part is to identify high-priority tasks for improvement and suggest potential ergonomic improvements for rail catenary construction. This is done with a qualitative and time-efficient ergonomic risk assessment. The assessment involves several components identified in the literature, including creating a work breakdown structure (WBS) inspired by the PATH method, scoring identified tasks based on ergonomic risk, conducting site visits to observe work and identify ergonomic risks, and issuing an Questionnaire containing the Nordic questionnaire to pinpoint areas of the body with the highest complaints and other questions to identify ergonomic risks.

The subsequent chapters outline the background of rail catenary work (Chapter 3), the methodology for the work-breakdown structure and ERA (Chapter 4), the results from the WBS and ERA (Chapter 5), discussion on the results (Chapter 6), and a conclusion (Chapter 7).

3
Background

In this chapter, background information on rail catenary is presented. This information helps to understand the ergonomic risk assessment that is presented in this research. First, the rail caternary system is presented in section 3.1, followed by the working conditions during the construction of the rail catenary in section 3.2.

3.1. Rail catenary system

The objective of the rail catenary is to supply electricity to the vehicle below while minimizing obstruction to the vehicle. For conducting electricity, enough copper is needed and the rest of the system aims to minimize obstruction. The rail catenary system, as shown in figure 3.1, consists of two subsystems: the support structure and the overhead wires.

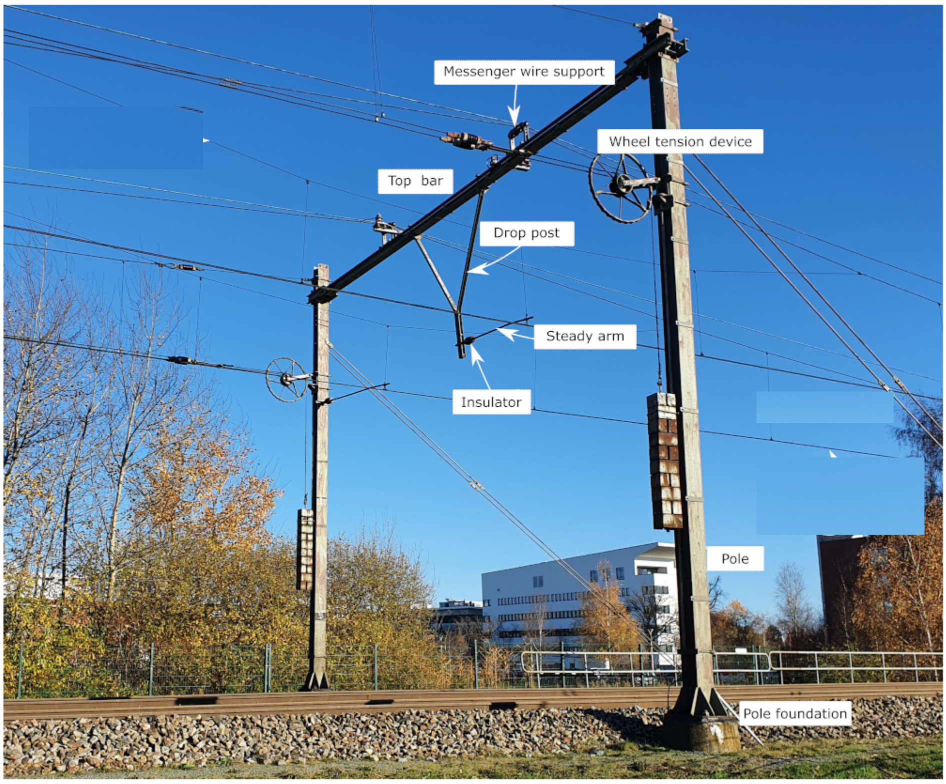


Figure 3.1: An example of a Dutch catenary support portal. The relevant construction parts of the support portal are labeled [20].

The support structure is there to hold the overhead wires and isolate the wires from the environment. The overhead wires are there to transport electricity to where it is needed at any given time. Minimizing vehicle obstruction is achieved by suspending the wires in a perfectly horizontal manner. The more perfectly horizontal the overhead wires are suspended, the less friction they have with the vehicle below. Having less friction increases the possible driving speed of the vehicle and reduces maintenance. There are many different types of systems for overhead catenary and in the Netherlands alone there are already eight different systems present.

The support structure for the overhead catenary consists of a row of portals, each consisting of a pole foundation, a pole, a top bar, drop columns/posts, horizontal arms, steady arms, insulators, wheel tension devices, and messenger wire supports. In figure 3.1 most of these parts are shown in a picture of a support portal. The pole and the top bar make up the portal that is used to support all other parts. Horizontal arms or drop posts combined with a steady arm are used to connect the contact wire to the portal. The messenger wire support is used to connect the messenger wire to the portal and carries the weight of both the messenger wire and the contact wire.

A system as shown in figure 3.1 has three overhead wires: the contact wire, the messenger wire, and the feeder. In figure 3.2 these wires are shown in a schematic drawing of a piece of rail catenary. The contact wire makes direct contact with the vehicle below through a pantograph, supplying the required current. The messenger wire acts to suspend the contact wire horizontally with the droppers. The feeder and messenger wire also act as supports to deliver the required current, as the three wires are all electrically connected. This reduces the electrical resistance of the system, increasing the maximum amount of current that can be transported. The connection between the portal and the wires is always done with the help of insulators to electrically isolate the wires from the portal.

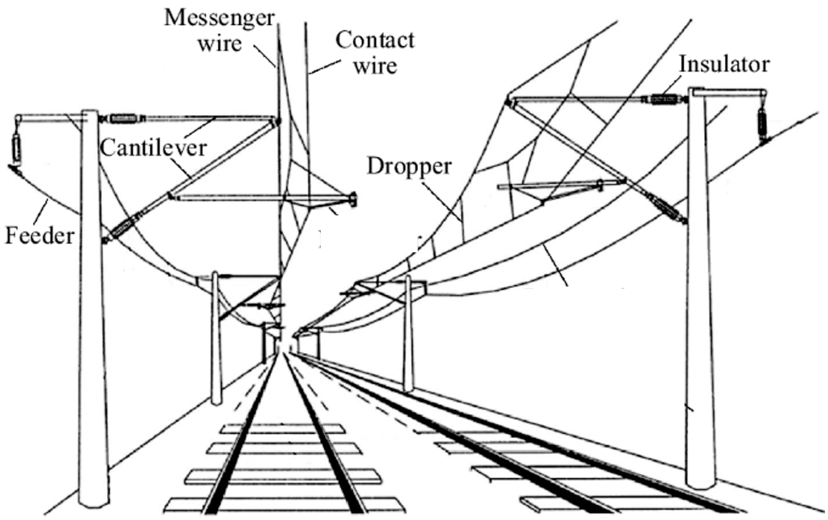


Figure 3.2: A drawing of a catenary system used for high speed trains. The different types of wires used are clearly shown [21].

3.2. Working conditions

Understanding the working conditions during the construction of a railway cadenary is essential to analyze the profession.
When constructing a new railway system, the rail tracks are traditionally constructed first. This means that the rail track is already in place before the construction of the rail catenary begins. Although the tracks provide support for construction vehicles, they also create uneven walking surfaces.
Since the contact wire is suspended at a standard height of 5.5 meters, most tasks cannot be performed from the ground. Catenary construction activities are typically carried out at heights between 4 and 8 meters, making the use of specialized lifting equipment necessary. Several specially designed vehicles on rails are used to lift workers to the right working heights. Boom lifts, see figure 3.3, are the most frequently used lifting machines. Trucks equipped with lifting platforms can also be used, particularly when larger work areas are required. For some specific tasks, specialized vehicles are used like

the GEMMA, designed for placing contact wires under mechanical tension. The choice of equipment depends on the specific task and circumstances.
A team of workers that is deployed for regular tasks often consists six people, four catenary workers, one crane operator, and one person in charge of the operation. The catenary workers operate a boom lift in pairs of two and the crane operator operates an excavator.
On railway construction sites certain personal protective equipment (PPE) is mandatory. This includes a helmet, safety shoes, reflective vest or jacket, and a safety harness when workers are standing in a boom lift. Some vehicles such as trucks do not require a safety harness, depending on the height of the fence and the type of vehicle.

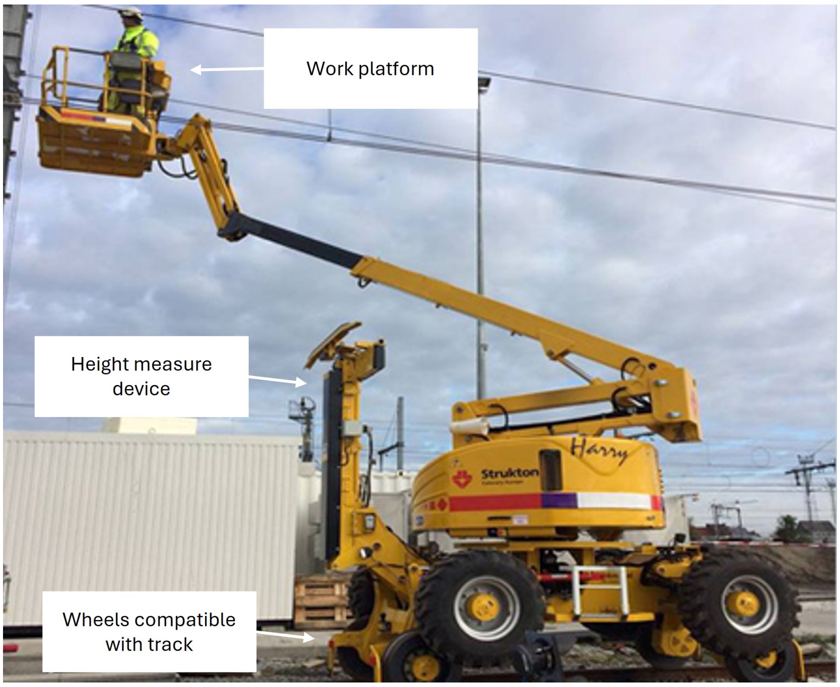


Figure 3.3: A boom lift on rail from Strukton. [22]

4 Methodology

In this chapter, the methodology for the work-breakdown structure (WBS) and ergonomic risk assessment (ERA) performed in this study are presented. In Figure 4.1 the different methods used, are shown. Some methods are used for both the WBS and ERA. The WBS is also used as an input for the ERA.

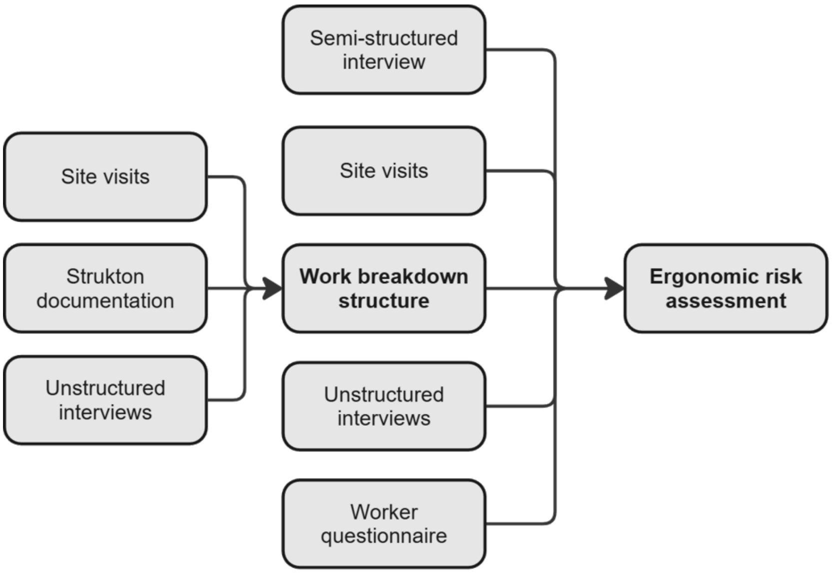


Figure 4.1: Overview of methods used for WBS and ergonomic risk assessment.

To understand why the methods presented in this chapter are used, it is useful to define the definitions of a WBS and ERA.

A WBS organizes a project into task groups, each composed of several specific tasks containing a limited set of operations. A WBS can be used to effectively represent different construction tasks, as suggested by Globerson et al [23]. The use of a WBS is not new and is often done in the construction industry and for ergonomic studies. The WBS presented in the results section is shown as a taxonomy flow chart, accompanied by descriptions of the individual tasks through text and images.

An ergonomic risk assessment is a systematic process of evaluating and identifying potential ergonomic hazards in the workplace that may affect the health and well-being of employees. [24] As mentioned in the introduction, such an assessment can be made in a number of ways. In this thesis, the assessment will include scoring different work tasks based on physical demand, identifying body complaints experienced by workers, and identifying risks of work tasks and the working environment.

4.1. Methods

The WBS and ergonomic risk assessment presented in this thesis are acquired using several methods, shown in figure 4.1. In this section, the different methods used and what data are gathered with these methods are explained.

4.1.1. Work-breakdown structure

As shown in figure 4.1 site visits are performed, company documentation is consulted, and unstructured interviews are performed with Strukton employees for the WBS. During a site visit, a construction site is visited where the rail caternary construction is performed. Information is gathered by talking with workers and filming workers while performing work tasks. Strukton has extensive worker manuals on how to perform certain tasks, from these manuals tasks are identified, and a full description of the tasks is obtained. In addition, a template planning is consulted that is normally used by planners. From this planning, different working tasks can be identified. Lastly, several unstructured interviews with planners and an experienced ex-worker are conducted. From these interviews, information about different tasks is obtained on a descriptive level. All of these methods are existing methods that are frequently used to make a WBS.

4.1.2. Ergonomic risk assessment

The methods used for ergonomic risk assessment in this thesis are site visits, unstructured interviews, a semi-structured interview, and a worker questionnaire, as shown in figure 4.1. The WBS is used as a template for all tasks that need to be scored. During site visits, the different tasks are obsevered and potential ergonomic risks from the tasks and work environment are identified. Unstructured interviews with different workers are focused on identifying the different risks involved in the work tasks and environment. A semi-structured interview is done to score the different tasks. Lastly, a worker questionnaire is used to identify body complaints experienced by workers, rank different work environments, and rank work tasks. All of these methods are already often used for ergonomic risk assessment.

4.2. Study site and subjects

This study took place at two different construction sites of Strukton. The first construction site was in Leeuwarden, where a piece of rail was newly electrified. The second construction site was in Rotterdam, where the rail catenary was partly renovated and partly rebuilt. The focus of this study was specifically on the construction of rail catenary and everything involved in this. Other rail construction tasks are excluded.

The ergonomic risk assessment focuses on the permanent and temporary agency worker crew of the Strukton catenary energy group. The permanent worker crew has 25 workers. The crew of temporary agency workers alternates, but often the same workers are deployed on regular basis. No specific selection of the workforce was made for site visit observations or the questionnaire. During site visits, a total of 20 different workers are seen. For each site visit, a single pair of workers is selected for filming. A total of eight different workers are filmed. Unstructured interviews are conducted with current workers, former workers, and a project planner. For the semi-structured interview, a rail caternary expert with 20 plus years experience in the field was consulted. For the gathering of visuals from the work sites, the workers were asked for permission and the privacy regulations from Strukton were applied. For the questionnaire, the workers agreed that the test results can be used for the writing of this thesis, and information was again collected under Strukton's privacy regulations.

4.3. Design of methods

Here the design of the different methods used is presented, this includes a more detailed description of the method and how the desired results are obtained with the methods.

4.3.1. Work-breakdown structure

First a site visit is made to understand the type of work carried out at the specific construction sites. This gives a feeling of the time and space scale of the projects. Then an unstructured interview is conducted with a planner. This interview focuses on discovering what types of work are present during construction jobs. During these interviews, it is also investigated whether documentation exists on the performed tasks during construction. Project planning offers a complete overview of what different tasks need to be performed and in what order. Strukton has several worker manuals that describe different tasks. This helps in describing all the tasks included in the WBS. When an overview of all tasks is created, more site visits are conducted to gather more footage specifically of the identified tasks. This footage is used as an aid to describe the different tasks.

4.3.2. Ergonomic risk assessment

From the WBS a list of all the present construction tasks is made. During the semi-structured interview with an expert, the different tasks are scored on several criteria. This is done by discussing every separate task and giving a score on three different criteria. The criteria used for this method are the physical load, frequency, and duration of the tasks. These criteria are often seen in the PATH methods as well; see 2. The criteria are described below.

- Physical load: This criterion considers the amount of physical load applied to a worker during a certain task. Lifting a heavy object will result in a high score.
- Frequency: This criterion considers how often this task is performed by the worker. Tasks that are performed relatively frequently compared to other tasks receive a higher score.
- Duration: This criterion considers the duration of a certain task. A task that requires the worker to lift something for an extended amount of time during the same task would result in a high score.

The worker questionnaire has four different sections, as represented in figure 4.2. These sections are determined on the basis of observations during site visits and the unstructured interviews with the workers.
The Nordic questionnaire focuses on complaints experienced in different parts of the body. For every body part, four questions can be asked. First, it is asked whether the subject ever experiences any complaints from the specified body part. If the answer is yes, it is asked how often the subject experiences the complaint: almost never, once or twice a week, three of four times a week, every day, or multiple times a day; how severe the complaint is: light pain, moderate pain, severe pain, or very severe pain; and if the subject thinks the complaint is related to work: yes, no, or maybe.
In the second section, the work environment questions ask whether the subject experiences discomfort from wearing certain protection gear and what work circumstance they find most demanding. The first two questions are focused on the safety harness. The subject is asked whether the subject experiences the safety harness as uncomfortable, and if yes, why? In the following question, the subject is asked if they find working on the ground or in a boom lift or any other vehicle more physically demanding.
In the third section of the questionnaire, the subjects have to rate several task groups on a scale of 1 to 7. A low score means that tasks in the task group are experienced as tasks that require low physical demand, and a high score means the opposite.
The final section of the questionnaire consists of a single open question that gives workers the opportunity to present any aspects of their work that are not discussed but pose ergonomic risks to the workers. The whole questionnaire is shown in Appendix C.
The questionnaire was administered to the workers by visiting the work sites and asking the workers to complete the questionnaire during the coffee break.

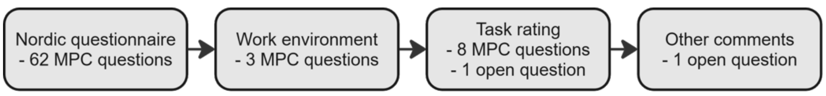


Figure 4.2: Overview of the four sections present in the worker questionnaire.

The ergonomic risks that were identified unrelated to the task ranking or questionnaire where mostly identified by performing unstructured interviews, asking workers what they found most physically demanding. An unstructured interview with a rail catenary expert also helped to identify some of these ergonomic risks.

4.4. Method testing

The site visits method was tested by conducting multiple site visits. By performing multiple site visits, the observer becomes more experienced in what to pay attention to. After multiple visits, it also becomes easier what can be effectively filmed. The WBS that was created is discussed with the rail catenary expert, mainly focusing on whether most tasks are included and if the right terminology is used. The task scoring is mainly based on the semi-structured interview, but the footage from the site visits can be used to verify whether a task is rightfully scored with a certain score. The method of scoring tasks was not tested in any other way. The worker questionnaire was tested by the rail catenary expert; this did not lead to any major adjustments.

4.5. Data management and analysis

The video footage captured during site visits is stored locally on the researcher's laptop and Google Drive. The questionnaire is sent with google forms and the answers are anonymous when the participant do not voluntary share their name. The answers of the Google form are saved on the google account of the researcher.

The scores for each task on the three different criteria are averaged to find which tasks receive the highest overall physical demand score. This can be used to determine what tasks are the most physically demanding for workers, thus posing the biggest risks. The tasks with the highest and lowest score for each criterion are shown as well. The scores of the individual criteria tell something about the nature of the task. This information can be used to identify what makes a task physically demanding.

The results of the worker questionnaire are used to show the most common physical complaints in a figure. The results on the frequency and severity of the complaints are presented in pie charts. This gives more insight into how workers are experiencing these complaints. The answers to the questions on the working environment are also shown in a pie chart. The resulting scores for the different task groups are compared to each other in a bar graph, and with a Wilcoxon-rank test, they are tested on significant difference.

5
Results

In this chapter the results from the WBS and ERA are presented. In section 5.1 the WBS is shown and all tasks included in the WBS are explained. In section 5.2, the results from the ERA are presented. Finally a visualization of the WBS combined with the task scoring is shown in section 5.3.

5.1. Work Breakdown Structure

In figure 5.1, the five main task groups for rail catenary construction are outlined in the WBS. In chronological order, the tasks in the first four task groups are performed when building a new rail catenary. The task groups are defined as follows.

Disassembly tasks include all disassembly of the already present catenary that needs to be removed first. Support structure tasks include all tasks that are needed to construct the support structure for the wires. Wire placing tasks include all tasks related to suspending the three different wires on the support structure. The wire finalization tasks include all the tasks that prepare the wires for operational use. Other tasks are several construction tasks that are performed to modify the already present catenary. In Appendix A the whole WBS can be seen.

In the following sections, the tasks within each task groups are explained in greater detail.

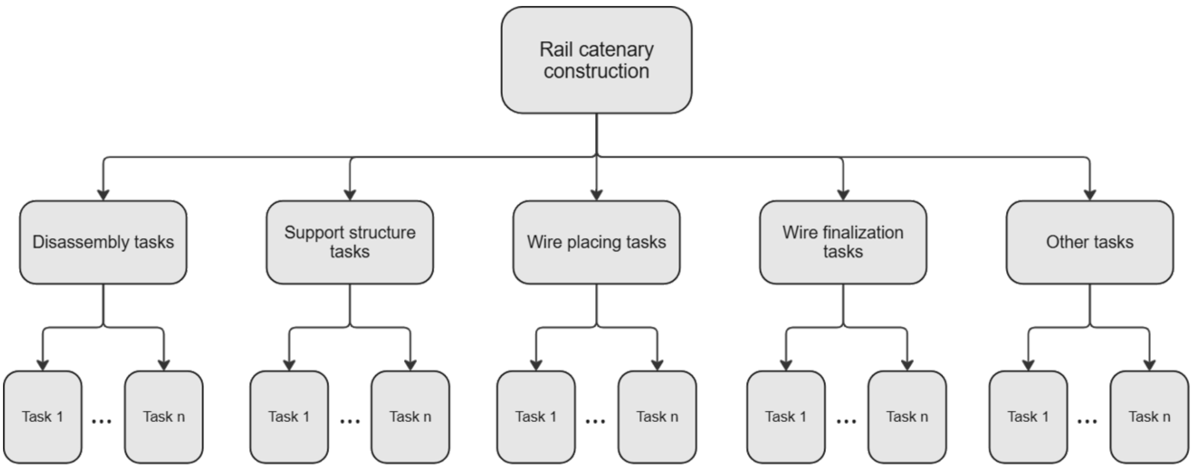


Figure 5.1: The work breakdown structure (WBS) for the working activities at Strukton catenary energy. The construction of rail catenary is divided into five different task groups. Every task group contains a couple of tasks that are shown here as empty boxes.

5.1.1. Disassembly tasks

When a rail catenary system is already in place on the construction site, it must be disassembled before any further work can proceed. Figure 5.2 illustrates the disassembly steps in chronological order from left to right.

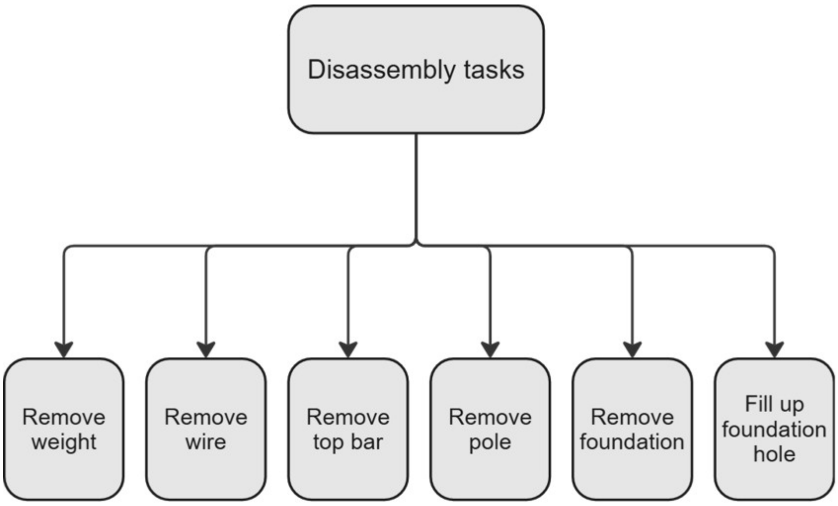


Figure 5.2: The disassembly tasks involved in the construction of rail catenary are shown in this figure in chronological order from left to right.

The process begins with the removal of the weight used to tension the contact wires. The weight, which totals approximately 500 kg, is lifted using an excavator. Once the tension is released, the wire is disconnected from the wheel tension device. The contact wires are first cut into smaller sections, typically using large handheld wire cutters. This is a demanding task as the contact wire is a solid wire with a $100mm^2$ cross-sectional area, which requires a large force to cut through. In figure 5.3 a worker can be seen cutting a contact wire. The cut wire sections are then collected and loaded onto trailers for transport. For the messenger wire and feeder, the same process follows.

Figure 5.3: A worker cutting a contact wire with a bolt cutter.

When all wires are removed, the top bar is detached from the supporting structure. While the clamps are manually removed by loosening the bolts with a power tool, an excavator is used to lift the top bar itself. To dismantle the poles, the bolts securing them to the foundation blocks are manually loosened, and the poles are lifted using the excavator. Finally, the excavator removes the foundation blocks from the ground and the resulting holes are filled to restore the ground. During these tasks, the workers' main job is connecting the lifted objects to the excavator.

5.1.2. Support structure tasks

In Figure 5.4, the construction tasks related to the construction of the support portals are shown chronologically.

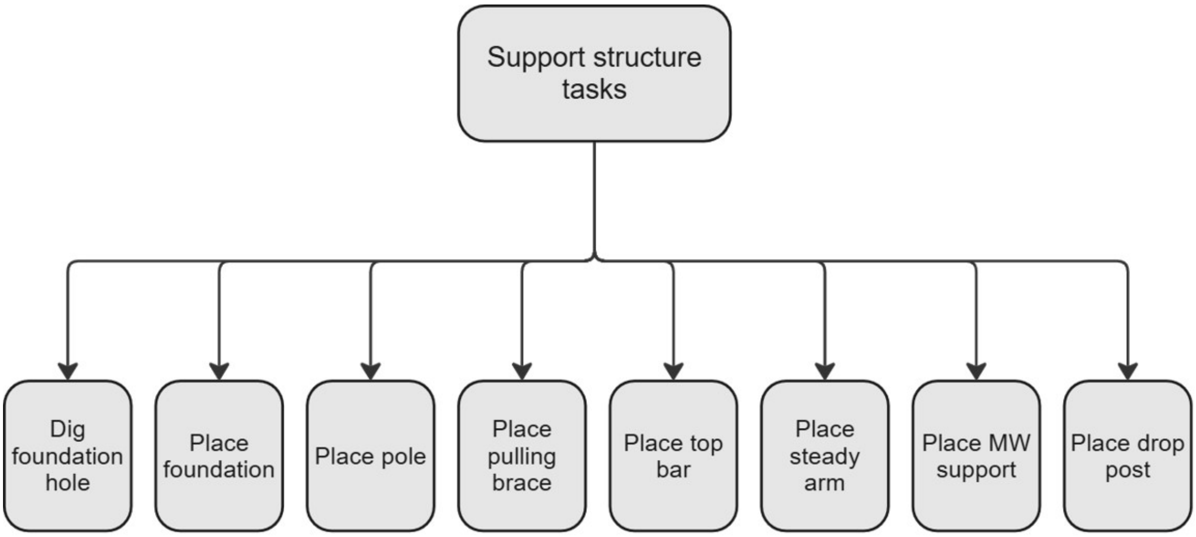


Figure 5.4: The support structure construction tasks involved in the construction of rail catenary are shown in this figure in chronological order from left to right.

The process begins with the digging of holes for the foundations, a task primarily carried out with an excavator. However, workers must perform some manual digging to make fine adjustments to the hole, as the excavator lacks the precision required for these refinements. Depending on the foundation type, the foundation is either poured as concrete directly into the hole or placed as a pre-fabricated unit. When using a pre-fabricated foundation, the excavator lifts it in position, as illustrated in figure 5.5a. After the foundations are in place, the poles are lifted on top of the foundations, see figure 5.5b). Workers manually tighten the nuts that secure the poles to the foundation, see figure 5.6. For poles positioned at the beginning and end of a section of contact wire, a pulling brace is installed between the pole and a foundation anchor. This brace gives contra weight for when the contact wire is put on mechanical tension. This brace is manually secured to the pole and foundation and also has to be tensioned manually, see figure 5.7.

Next, the top bar is positioned on top of the poles, here again the excavator handles the lifting and the workers guide the bar to the precise position on top of the pole, see figure 5.8a. The top bar is manually secured to the poles using metal clamps, as shown in Figure 5.8b. In some systems, fixed arms are used instead of the top bar. These arms connect to a single column rather than spanning two and are also lifted by the excavator and are installed in a similar fashion.

Following this, the messenger wire support is installed onto top bar. This heavy component is lifted manually from the working platform of the boom lift onto the top bar. Two workers are typically assigned to this task to effectively manage the load, see figure 5.9. Finally, hangers or drop posts suspended from the top bar are installed. These are lifted into position by the excavator and manually secured, see figure 5.10.

(a) (b)

Figure 5.5: a) The process of putting a prefabricated foundation in a hole. The workers coordinate the foundation and the excavator does the lifting b) The process of putting a pole on a foundation. The workers coordinate the pole and the excavator does the lifting.

Figure 5.6: The process of securing the pole on the foundation. The bolts are secured manually with a wrench.

Figure 5.7: The process of manually tensioning a pulling brace.

(a) . **(b)**

Figure 5.8: a) The process of putting a top bar on the two poles. The bar is lifted by the excavator and coordinated by the worker in the boom lift. b) The process of securing the top bar on the pole. The worker uses power tools to tighten the clamp.

Figure 5.9: The process of installing a messenger wire support on the top bar. The two workers work together to lift the messenger wire support onto the top bar.

Figure 5.10: The process of installing a drop post onto the top bar. The excavator lifts the drop post and the workers coordinates the drop bar to the right position and secures it to the top bar with a power tool.

5.1.3. Wire placing tasks

Once the support structure is fully assembled, the wires are put in place. In figure 5.11 all tasks involved in the wire placing process are shown in chronological order from left to right.

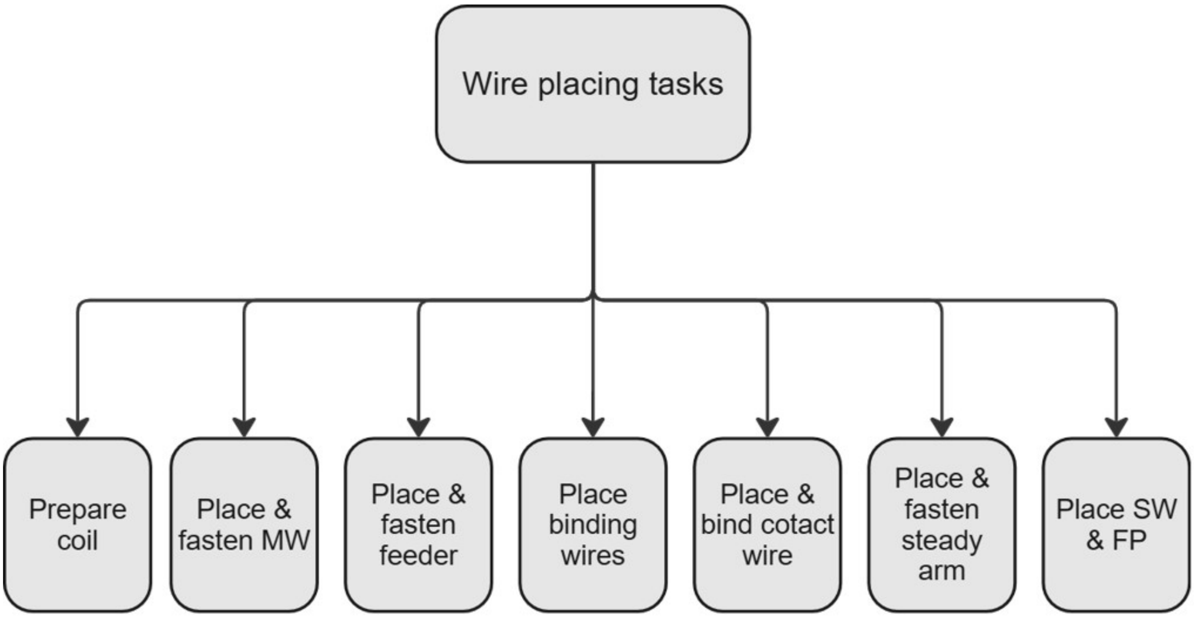


Figure 5.11: The wire placing tasks involved in the construction of rail catenary are shown in this figure in chronological order from left to right. MW stands for messenger wire; SW stands for stich wire; and FP stands for fixed point.

The first step of this process for wire placing is preparation: coils of the required wire are loaded onto a lorry, which is then transported to the starting point of the wire installation. A worker pulls the wire from the coil, enters a boom lift, and, as the lift moves forward, the wire gradually unwinds.

The messenger wire is placed on the messenger wire support at each portal and at the end connected to the last portal of the section with an insulator. To suspend the messenger wire at the correct height, it is reeled in from the beginning of a section using a chain hoist. The chain hoist with its 100:1 mechanical advantage enables significant manual force to be applied. Figure 5.12 shows such a chain hoist. This large force is needed, as the wires are suspended over sections up to 800 meters long, with each meter weighing close to one kilogram. To ensure that the wire is suspended at the appropriate height, measurements are taken at multiple positions along the section.
The placing and fastening process for the feeder wire follows a similar method to that of the messenger wire.

Before the contact wire is installed, lightweight copper binding wires are suspended from the messenger wire, which can later be attached to the contact wire. At the start of the section the contact wire is connected to a pole with isolators; see figure 5.13a. As the boom lift moves forward, the binding wires are wrapped around the contact wire to hold up the wire along the length of the section, see figure 5.13b. The binding wires are twisted around themselves to secure the contact wire and can be easily detached when necessary.
A second worker group attaches the steady arms to the contact wire with binding wires, which are later used to give the contact wire the correct horizontal offset relative to the track. When the contact wire reaches the end of the section, it is connected to a wheel with a counterweight, the wheel tension device. The chain hoist is then used to apply the correct mechanical tension. The wire must be tensioned to approximately 2000 kg with the chain hoist, see Figure 5.14.

The stitch wires (SW) are then mounted on the messenger wire to reduce the difference in the sagging effect happening at different points in the contact wire. The stitch wires consist of a copper wire with a clamp on both sides. Each clamp is attached on a different side of the support portal. Later, drop wires are installed from this stitch wire to the contact wire. Fixed points (FP) are installed in the middle of a section to connect the messenger wire to the contact wire with a diagonal connection; these are used to reduce the effective section length of a contact wire. This enables sections to be 800 meters in length on both sides of the fixed point. A fixed point is made with similar cable to the stich wire cable. The fixation of these cables to the wires with clamps is done with power tools.

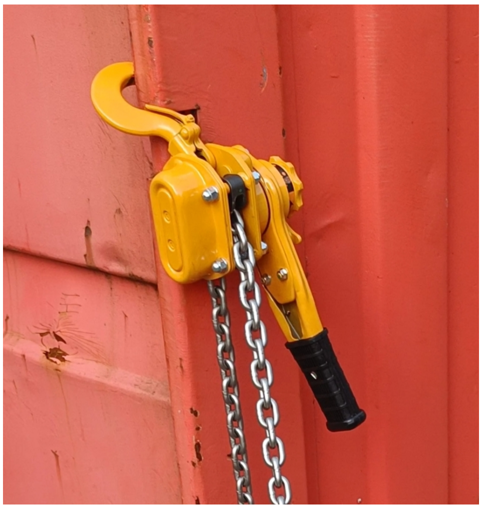


Figure 5.12: A chain host used to reel in messenger wire or tension the contact wire.

(a) .

(b)

Figure 5.13: a) The process of connecting the contact wire to one of the poles. Clamps are installed on the binding wire and the binding wire is connected to the insulator, that is attached to the pole. b) The process of putting the binding wires on the contact wire. As the boom lift moves , the worker wraps the binding wires around the contact wire to hold the contact wire up.

Figure 5.14: The process of tensioning the contact wire with the chain hoist. The worker connects the end of the chain hoist to the isolators and to the contact wire. By pulling the chain hoist the wire is brought to the desired mechanical tension.

5.1.4. Wire finalization tasks

Now that the wires are in place, modifications to the wires and additions to the wires are needed to make the system operable. In figure 5.15 all tasks in the wire finalization process are shown in chronological order from left to right.

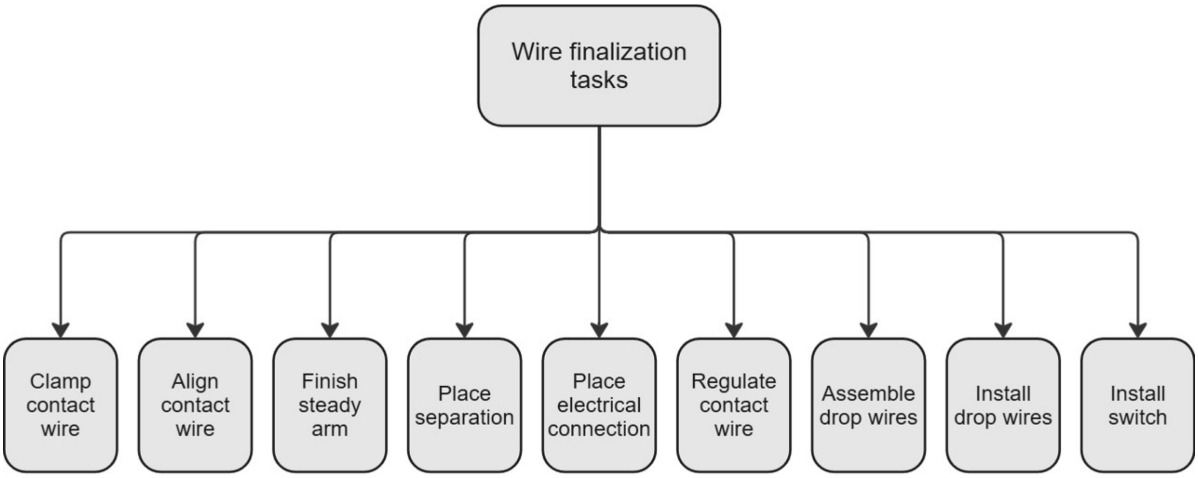


Figure 5.15: The wire finalization tasks involved in the construction of rail catenary are shown in this figure in chronological order from left to right.

The process begins with the installation of clamps on the contact wire. These clamps are secured with bolts that grip the contact wire from above while leaving the underside unobstructed.
Next, the contact wire is aligned. Proper alignment of the contact wire is crucial to ensure that the offset from the rail's center is accurate, which is critical for consistent contact with the pantograph. This is achieved by using a chain hoist to pull the wire to the side. The contact wire is then temporarily held in place with the binding wires. Often smaller chain hoists are used for this task compared to the tensioning of the contact wire because the forces are smaller.

In the next step, steady arms are attached to the clamps on the contact wire, locking the offset position of the wire. The electrical separators are then installed to isolate sections of the wire. This involves bringing the wires together using a chain hoist, cutting the wire at the midpoint, and inserting an insulating piece at the gap. Following this, electrical connections between the messenger wire, contact wire and feeder are established to ensure adequate conductivity in the wire section. These connections are secured with specialized clamps that are tightened using a power tool.

To position the contact wire at the correct height, workers measure its position and adjust it as needed by either pulling the contact wire up or loosening the bindings to let the contact wire down. This process is referred to as ”regulating the contact wire”.

Once the contact wire is positioned at the correct height, droppers are fabricated and installed. The process begins with measuring the distance between the messenger wire and the contact wire. The droppers are then custom-fabricated in a specialized tool container to ensure precise lengths. After fabrication, the droppers are installed by attaching them to the messenger wire and the clamps on the contact wire, replacing the temporary binding wires, see figure 5.16.

Finally, the switches are installed. Switches include a part on top of the support portal and a switch box at ground height. This switch enables it to mechanically interrupt the electrical circuit for a section of catenary wires. Both the switch itself and the switch box are heavy parts that require some manual lifting to install.

Figure 5.16: The process of installing drop wires between the messenger wire and the contact wire. The drop wire is manually secured to the messenger wire and contact wire.

5.1.5. Other tasks

Although all tasks directly related to building a new section of rail catenary have been discussed, several other tasks are worth noting. In figure 5.17 six other tasks are shown. Three are construction related and the other three are performed at every job site but not directly related to construction.

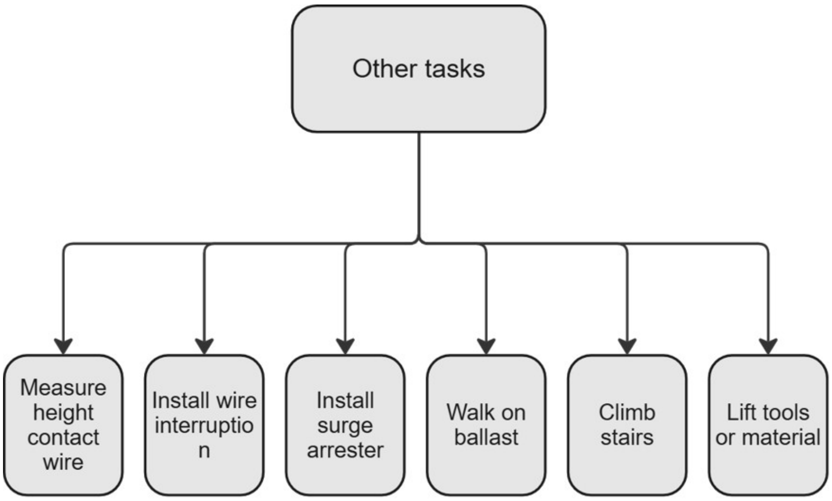


Figure 5.17: The other construction tasks involved in the construction of rail catenary are shown in this figure in no specific order.

Measuring the height of the contact wire is one of the tasks that is often performed during inspection of work, but also during construction. This is done with a laser measurement device that is put on the rail and measures the vertical distance to the wire. For this task, long distances are traveled on foot compared to other tasks.

Wire interrupters are often installed as standalone replacements for outdated components. Unlike separators, interrupters are designed to allow vehicles to pass underneath. Their installation process is similar to that of separators, with the main distinction being their weight: Each interrupter weighs about 20 kg. Often trucks are used instead of boom lifts for this task as they offer more freedom of movement on the work platform.

Installation of surge arresters is typically performed on already operational rail catenary systems that have outdated components. A surge arrester, which weighs approximately 10 kg, is mounted on top of the support portal and connected to the electrical circuit.

Walking on ballast is a task that is seen at every job site as workers have to move from one place to another.
Climbing stairs is often required as workers have to mount and dismount vehicles.
The lifting of tools and materials is also required for every construction task. The weight of the material and the tools differs greatly.

5.2. Ergonomic risk assessment

In this section, results as part of the ERA are presented. In subsection 5.2.1 the results from the task ranking are shown. In subsection 5.2.2 the results from the questionnaire are shown. In subsection 5.2.3 the other identified ergonomic risks are shown.

5.2.1. Task ranking with expert

In table 5.1, 5.2 and 5.3 the five tasks with the highest and lowest physical load, duration, and frequency score are shown, respectively. In table 5.4 all tasks with the average physical demand score are shown.

Table 5.1: The five highest and five lowest scored tasks ranked on their physical load score

Task	Physical load score (1-5)
Place and bind contact wire	5
Lift tools	5
Place MW support	4
Place and fasten feeder	4
Remove wires	4
Measure height contact wire	1
Remove pole	1
Place SW & FP	1
Finish steady arm	1
Install surge arrester	1

Table 5.2: The five highest and five lowest scored tasks ranked on their duration score

Task	Duration score (1-5)
Install switches	5
Remove wires	4
Walk on ballast	4
Place and bind contact wire	3
Remove foundations	3
Assemble drop wires	1
Install drop wires	1
Align contact wire	1
Measure height contact wire	1
Finish steady arm	1

Table 5.3: The five highest and five lowest scored tasks ranked on their frequency score

Task	Frequency score (1-5)
Remove wires	5
Walk on ballast	5
Place top bar	5
Dig foundation hole	5
Place and fasten MW	5
Install surge arrester	2
Lift tools	2
Install wire interruption	2
Place pulling brace	2
Place electrical connections	2

Table 5.4: All tasks identified in the WBS and site visits ranked on their average score for physical demand

Task	Average score	Task	Average score
Remove wires	4.3	Install wire interruption	2.7
Placing beams	3.7	Remove beams	2.7
Install switches	3.7	Fill up holes	2.7
Walk on ballast	3.7	Prepare work	2.7
Dig holes for foundations	3.3	Install drop wires	2.3
Place MW supports	3.3	Assemble drop wires	2.3
Place and fasten MW	3.3	Clamp contact wire	2.3
Place and fasten feeder	3.3	Place pulling braces	2.3
Place and bind contact wire	3.3	Place hanging columns	2.3
Place and fasten steady arms	3.3	Place binding wires	2.3
Remove foundations	3.3	Climb stairs	2.3
Place foundations	3.0	Remove columns	2.3
Place separations	3.0	Place electrical connections	2.0
Lift tools	3.0	Install surge arrester	2.0
Remove weights	3.0	Place SW and FP	2.0
Place columns	2.7	Align contact wire	2.0
Place cantilevers	2.7	Measure height contact wire	2.0
Regulate contact wire	2.7	Finish steady arms	1.7

Looking at the top ten tasks in table 5.4, three of them are wire pulling tasks, three are support structure tasks, two are disassembly tasks, one is a wire finalization task and one is in other tasks. In table 5.5 the top ten tasks are shown with task groups. This points out that wire placing and support structure tasks are generally the more demanding tasks for the workers in comparison to the tasks in the other task groups.

Table 5.5: Top 10 tasks ranked on the average score

Task	Task group	Average score
Remove wires	Disassembly	4.3
Walk on ballast	Other	3.7
Install switches	Wire finalization	3.7
Place top bar	Support structure	3.7
Dig foundation hole	Support structure	3.3
Place MW support	Support structure	3.3
Place and fasten MW	Wire placing	3.3
Place and fasten steady arms	Wire placing	3.3
Place and fasten feeder	Wire placing	3.3
Remove foundations	Disassembly	3.3

5.2.2. Results from questionnaire

The questionnaire was filled in by 12 respondents from the team of rail catenary workers. Results are presented below divided into the worker complaints, working conditions and task group physical demand scores.

Worker complaints

In figure 5.18 the body parts most affected by complaints are illustrated. Back complaints are the most prevalent, with nine out of twelve workers experiencing back complaints. One of these subjects reported to experience these complaints on a daily basis, while the other subjects experience these complaints only once or twice a week or less. Looking at the severity of the complaint, six out of nine reported that it was a minor complaint and three reported it to be a moderate complaint. In figure 5.19 these results on the back complaint qustions are shown. For shoulder complaints, three out of twelve reported to experience left shoulder complaints and four out of twelve right shoulder complaints. The results of the frequency and severity of the complaints are mixed. Ankle complaints were also observed, five out of twelve reported to experience left ankle complaints. For the left ankle four out of five people responded to experience ankle complaints once or twice a week, and the same amount reported to experience moderate level of complaints. For all complaints, it applies that most workers related their complaints to their work.

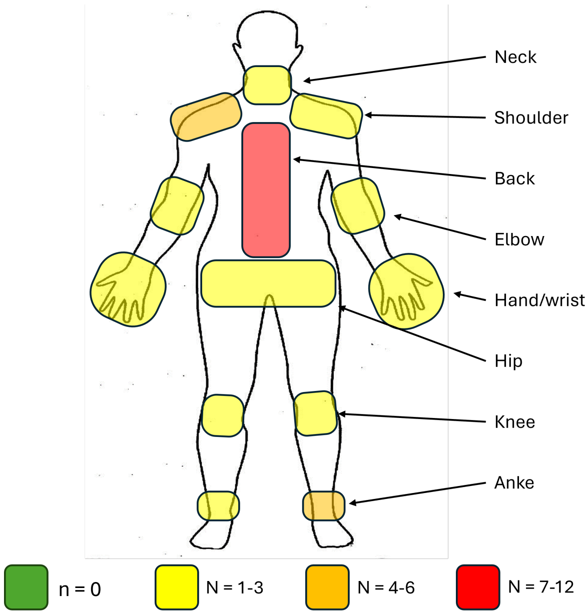


Figure 5.18: Map of the experienced worker complaints shown on the frontal view of the human body. Colors indicate the amount of complaints that were recorded for a specific body joint.

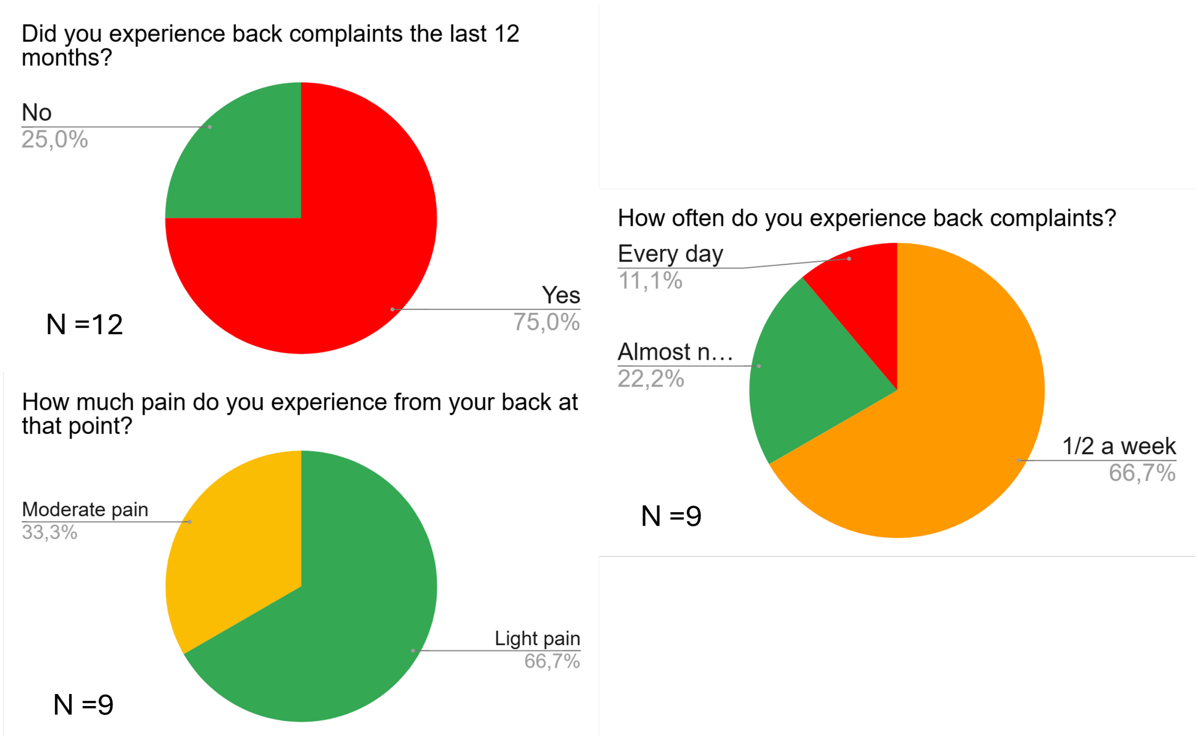


Figure 5.19: The results on the questioned from the nordic questionnaire about back complaints. It is also shown how many responses are gathered for each question.

Working conditions

The second part of the questionnaire is aimed at assessing the working conditions.

Seven out of twelve workers reported to experience the safety harness as uncomfortable. Among the reasons cited, four workers reported that it was because the harness limits their movements, two workers reported that the harness is too heavy, and one reported it to be both. This confirms the assumption that the safety harness is a source of discomfort for at least some workers. In figure 5.20

these results are shown. Regarding the most demanding working situation, walking on ballast was reported to be the most demanding working condition, receiving six votes. Standing on the working platform of a boom lift with a safety harness ranked second. These findings support the notion that walking on ballast is one of the most physically demanding parts of the job.

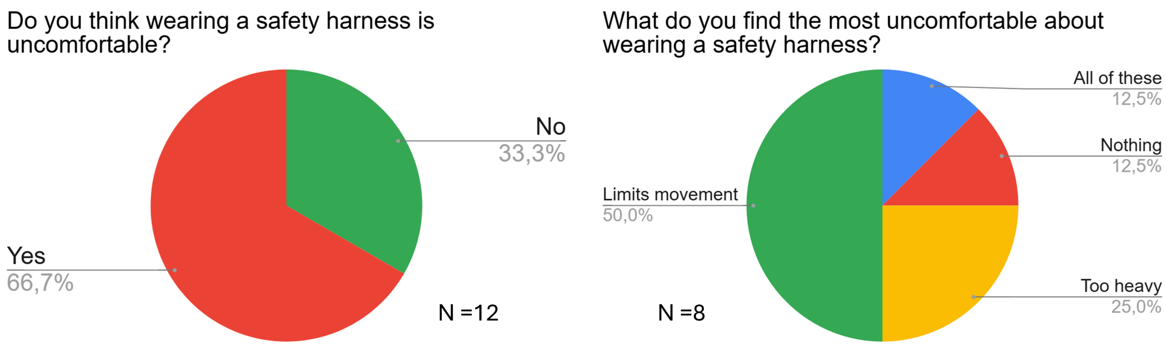


Figure 5.20: Map of the experienced worker complaints shown on the frontal view of the human body. Colors indicate the amount of complaints that were recorded for a specific body joint.

Physical demand score of task groups

The average scores for seven different tasks groups are shown in figure 5.21. The task groups ”Construct support portal”, ”install parts on the portal”, and ”place foundation” are part of the earlier specified support structure tasks. The place wire group equals the wire placing tasks. The ”place drop wires” and ” install parts of the contact wire” are part of the wire finalization tasks. The disassembly tasks and other tasks are not included in the questionnaire.

Table 5.6: Task descriptions with corresponding numbers.

Task Group	Task Group Description
1	Construct support portal
2	Install parts on the portal
3	Place foundation
4	Place wire
5	Place drop wires
6	Install parts on the contact wire

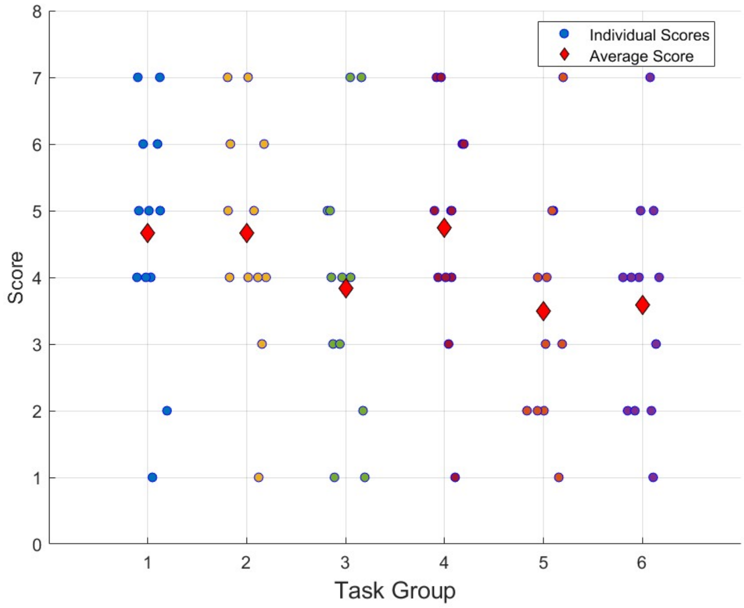


Figure 5.21: Task ratings for the six task groups that were used in the questionnaire. Every task group is rated by 12 subjects with a score between 1 and 7. The task groups were rated on the amount of physical demand occurring during the tasks in the task groups.

With a Wilcoxon Signed-Rank Test (n=12, α=0.05) the task groups are evaluated to determine significant differences between them. The results are shown in Table 5.7. This points out that the "construct support portal" tasks are rated significantly higher than the place foundation and install parts on the contact wire tasks. It also points out that the "install parts on the contact wire" tasks are rated significantly lower than three other task groups.

Table 5.7: A table showing if tasks are rated significantly different according to the Wilcoxon signed-rank test. A zero means that there is no significant difference between the distribution of the scores for the two different task groups. A one means that there is a difference in the distribution. The task groups are shown in table 5.6.

Task groups	1	2	3	4	5	6
1	-	0	1	0	0	1
2	0	-	0	0	0	1
3	1	0	-	0	0	0
4	0	0	0	-	0	1
5	0	0	0	0	-	0
6	1	1	0	1	0	-

5.2.3. Other observations and worker comments

During the site visits and worker interviews it became clear that some aspects of the construction work have a big impact on the amount of load experienced by the workers. In this sections some of these observations and comments from workers are presented.

Mechanization and tools

Much of the work done by the catenary workers is already partially mechanized. A team of workers is almost always accompanied by an excavator on rail. Almost all parts, especially the heavy ones, of the support structure are lifted in place by the excavators. Precision work like the fixation of a clamp on the support portal is then done manually. For as much tasks as possible an impact drill used but many times non-electrical tools, such as wire cutters, wrenches and hammers are still used as well. As there is no one tool that is compatible with every performed task.

Boom lift

Boom lifts greatly reduce the physical demand for the workers as they have to climb less stairs. The boom lifts also provide the big advantage of carrying most of the required tools wherever the workers go. Boom lifts are highly versatile due to their five degrees of freedom, enabling workers to position themselves in the desired stance relative to their work. Apart from the advantages of these boom lifts, they also pose some challenges. Five degrees of freedom make the control of the boom lift complex and slow. As a result workers are not always able or do not take the effort to put themselves in an ergonomic working position, see figure 5.22a. Additionally, the fence that is installed on the working platform for obvious safety reasons can also hinder ergonomic working positions. Most of the time workers are positioned on the working platform two at a time. This can result in discomfort as their movement is limited. Apart from working in the boom lift getting in and out of the boom lift is demanding for the workers as well, see figure 5.22b. The steps are often high and the body needs to be bend in awkward positions in order to enter the working platform.

(a) .   **(b)**

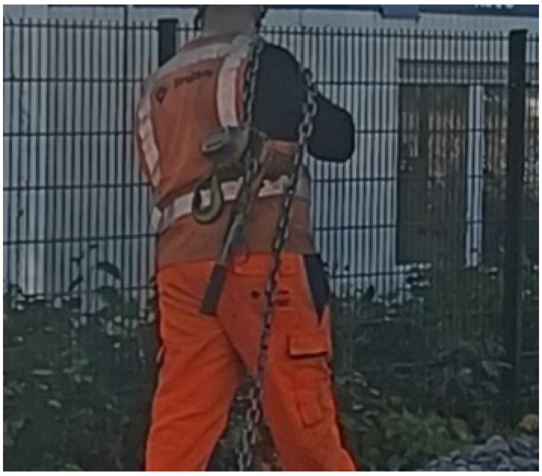
Figure 5.22: a) The worker secures the clamp on the top bar. The boom lift is not moved around the pole while doing this. b) A worker getting into the working platform on a boom lift.

Safety harness

When working in a boom lift, wearing a safety harness is required for safety reasons. The safety harness is attached to the work platform, which limits freedom of movement. The safety harness is often not comfortable to wear and sometimes must be worn eight hours a day. As a result, the harness is often not worn as tightly as intended and the harness is often taken off and on.

Walking on rail ballast

During work, workers have two modes of transportation. The first is to walk over the ballast or on the rail track, and the second is to ride on a boom lift that drives over the rail track. The rail track and ballast provide an awkward surface for walking, see figure 5.23. This causes the workers to take unnatural steps when walking on the rail track and strain their ankles and knees when walking on the ballast.



(a)

(b)

Figure 5.24: a) A worker carrying a chain hoist over his shoulder. b) A worker using a bucket with a hook attached to it, to transfer the load to the safety harness.

Figure 5.23: A worker walking on rail ballast.

Tool and material transport

When workers walk from one job site to another on the construction site, they often carry their tools and material with them. Typically, tools are carried in a bucket that is suspended on one arm, creating an asymmetric force on the body. These tool buckets can weigh up to 15 kg. Other tools are also often manually carried while being heavy pieces of equipment. The chain host is specifically heavy weighing up to 18 kg for the heaviest type, see figure 5.24a. Heavy materials like metal clamps and insulators often also have to be carried manually. Some workers find ways to reduce the physical load by, for example, distributing part of the weight of the tool bucket on their safety harness; see figure 5.24b.

Other comments from workers

Apart from the multiple choice questions, there was also one open question in the questionnaire on what the workers found physically demanding about their job. Two separate responses pointed out that their work is demanding due to different working shifts every week and often at night. One pointed out that entering and leaving the working platform is difficult due to tight spaces and stairs. Others noted that many of the materials and tools handled are still quite heavy.
These comments provide additional context and show that not only tasks determine how physically demanding the job is, but other factors as well.

5.3. WBS with ergonomic risk levels

In this section a visualization of the WBS with each tasked assigned to a different ergonomic risk level is shown.

By dividing the average physical demand scores from table 5.4 in four risk levels, every task can be colored according to its riks level. The risk categories are defined as in Table 5.8. The resulting visualization is shown in 5.25

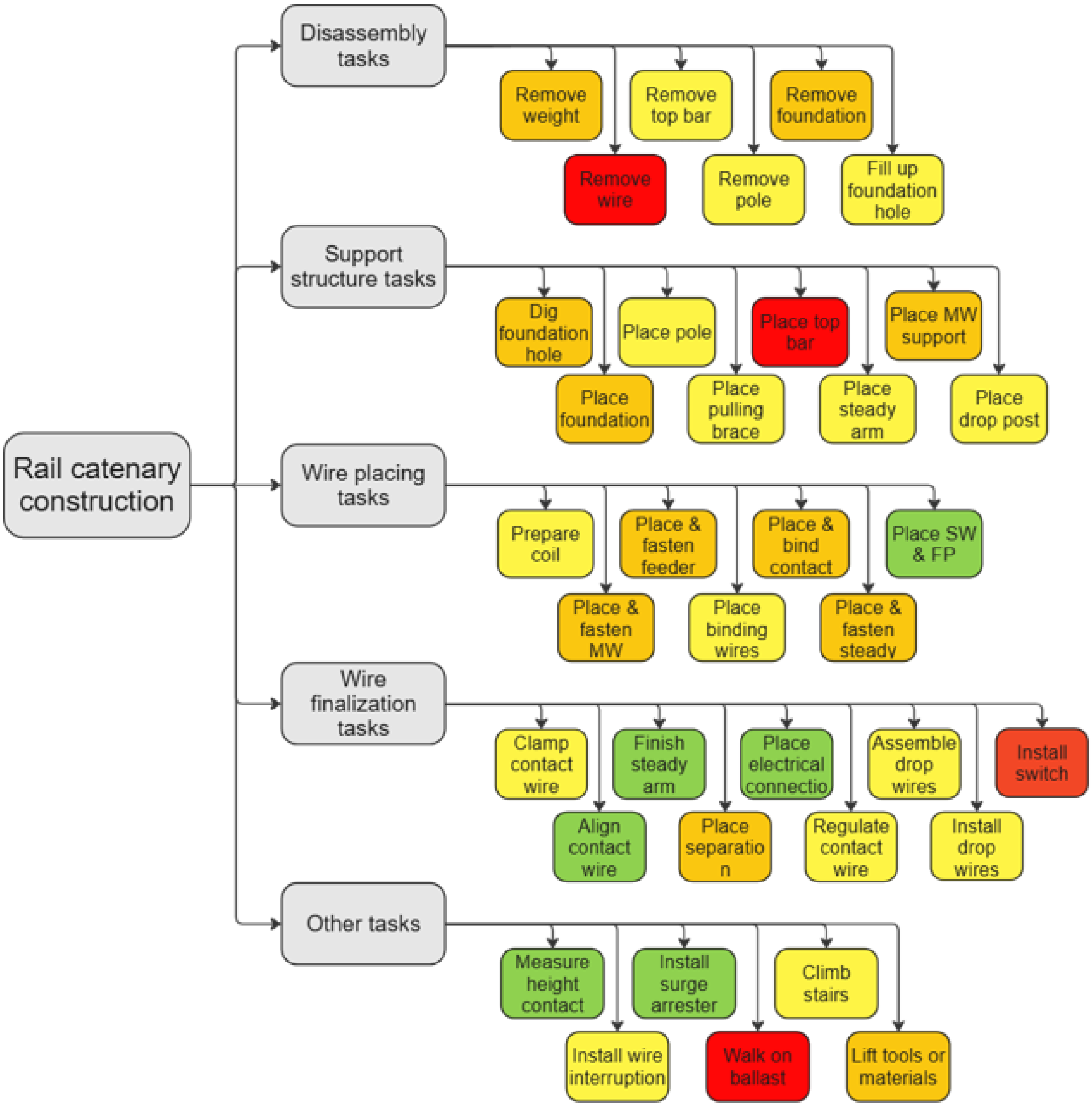


Figure 5.25: WBS with average physical demand score for every task

Table 5.8: The different risk levels and the physical demand score range and colors that they are represented by.

Risk level	Score range	Color
Low ergonomic risk	1.0 - 2.0	Green
Medium ergonomic risk	2.1 - 2.8	Yellow
High ergonomic risk	2.9 - 3.5	Orange
Very high ergonomic risk	3.6 - 5.0	Red

6
Discussion

The ERA performed in this research provided valuable insights into the physical demands of construction work during the construction of the rail catenary. This was done with the aim of identifying what makes this type of work physically demanding. In this chapter, the results of the WBS and ERA are discussed with this goal in mind. The assessment is compared to the literature with similar studies. Then, limitations of the assessment are noted along with recommendations for future research. Finally, some recommendations are made for Strukton to reduce the physical demand for their workers.

The WBS shows a close to complete overview of all tasks that are performed by rail catenary workers. During site visits, most of the performed tasks are seen and worker footage shows how exactly the tasks are performed. From the WBS it can be concluded that there are many different tasks that are performed by rail catenary workers, and it is also seen during the site visits that often workers perform multiple different tasks during a single work shift. The tasks in the disassembly task group were not seen during site visits. As a result, less attention was paid to these tasks for the rest of the ERA.

With a semi-structured interview, all tasks identified in the WBS are scored on their physical demand. The task ranking indicates that there is a difference in the amount of physical demand accompanying the different tasks seen in rail catenary construction. Only few tasks score very high on the physical load score, fewer tasks score very high on the duration score and many tasks score high on the frequency score. Only one task scores a 4 or higher on all criteria. In the top ten highest scoring tasks, there are tasks from all 5 task groups. Most of the tasks that had high scores were also reported to be physically demanding by the workers. From these results, it can be concluded that to reduce the overall physical load experienced by workers, separate solutions will be needed for different tasks. Most likely a single tool will not be able to reduce repetitiveness while also reducing the maximal physical load. The results could also be used to change the project planning, for example scheduling the more demanding tasks during day time.

The questionnaire sent to the workers pointed out several things. At first, shoulder, back, and ankle complaints are the most common. Back complaints often point to heavy lifting or poor posture. Shoulder complaints often point to above shoulder height work. Ankle complaints might be related to walking on the uneven ballast surface and mounting the boom lift. These results show that reducing the weight of the lifted loads and reducing the amount of walking on the ballast might be beneficial to workers. The workers also scored several task groups on their amount of physical demand. Although only 12 answers were collected, it could be shown that some task groups were significantly higher than other task groups. The tasks related to the construction of the support portals are scored as more demanding than the tasks related to the placement of the foundations and the installation of parts on the contact wire. This implies that more research on the construction of the support portal might be needed to make these tasks less physically demanding.

During site visits, several observations are made and some other ergonomic risks are identified. In the construction industry mechanization of physically demanding tasks can alliviate the work load for workers. Conserning the mechanization of the work performed by the rail catenary workers, Strukton has already mechanized a large part of the rail catenary construction work. Tasks that, however, need some precision are most of the time still performed manually. There does not seem to be much room for extra mechanization. The boom lifts greatly support the workers and allow them to perform tasks in their preferred position. However, it was also seen some parts of the boom lifts might benefit from some ergonomic improvements. First, entering the boom lift is seen as a demanding task due to the high stairs and low fence. Secondly, the control of the boom lift is quite complex; if the control of the boom lift were more intuitive, this would most likely encourage workers to put the boom lift in positions that enable more ergonomic working postures. The safety harness worn by the workers was found to cause discomfort. Some workers do not properly wear the harness because the harness limits their movements. The workers walk long distances of the rail ballast during their working shifts, this causes high strain on their ankles and knees. Workers must carry many different tools around in buckets. These buckets are most practical when in the boom lift, but also cause nonergonomic lifting postures when transporting tools.

In comparison to other risk assessment studies like the PATH study performed by Paquet et al this study was not able to quantitatively define what are the most demanding tasks [25]. It was able to point out several aspects of the work and several tasks that are most likely to make the work demanding. In addition, this method was much less time consuming in comparison to a full PATH study.

Together, these results highlight that the work of a rail catenary construction worker is varying in nature and has many factors influencing how ergonomic the work can be performed. The different types of tasks that are seen and their different scoring points out that multiple aspects of the work are demanding, which might also be experienced differently by different workers. The different body complaints show that work most likely places a stress on the whole body, although the back is put under the most strain. The problems that are introduced by the boom lift show that even a complex and multifunctional tool can still have flaws and even introduce new challenges.

There are several limitations to the current study. Together with several recommendations, these are presented below. Firstly, very little information was available on the amount of WRMSD's that are reported by the Strukton workers. To effectively focus on the tasks that cause the most WRMSD it is needed to know what kind of WRMSD are experienced. Future studies should focus on collecting data on what exactly causes most workers to drop out in the long term. This might enable a more precise focus on the tasks that have to be improved ergonomically.
Secondly, the scoring of the different tasks is now still very sensitive to the opinion of the Strukton expert and the observer. To more objectively score the different tasks, it would be beneficial to determine how exactly the tasks can be scored in a more objective way. This could be done, for example, by developing a standardized scoring method with a detailed rubric or using one of the existing ergonomic risk assessment methods. Reliability could also be improved by asking more workers to score all tasks. This can be done by adjusting the questionnaire to include all the construction tasks performed.
Lastly, the current method mainly focuses on tasks that are physically demanding but does not go into the details of what makes tasks physically demanding. Identifying exactly what makes tasks physically demanding would also help finding ways to make tasks less physically demanding. A more technical measurement method could be used for this like using a motion capture system to measure what exact forces are present in the human body during certain movements.

Some recommendations can also be made for Strukton to reduce the physical demand for its workers. Starting with boom lifts, designing an additional part for the stairs would reduce the amount of force required to step onto the first step. In the long term it might also be beneficial to change the control of the boom lifts into something more intuitive to the workers, this should be done in cooperation with the workers. Regarding the safety harness, workers should be able to choose their own safety harness as long as it meets the safety standards. For ballast walking, an improvement could be to construct a type of sidewalk next to all pieces of rail. For tools transport, a new bag could be designed in collaboration with workers that satisfies their needs and could also be carried in a more ergonomic way. Looking at the tasks that were analyzed, several solutions could reduce the workload. Using more pre-fabrication for parts of the support portals could be a solution for the support portal construction tasks. This is already done frequently, but more could probably be gained here. Tasks like cutting the contact wire and tensioning the contact wire could be made easier by introducing specialized electrical tools. For example, an electrical chain hoist could be attached to the excavator. Another possibility would be tensioning the contact wire by lowering the weight package with the excavator. Looking at the physical health of the workers, it would be recommended for Strukton to keep a good unanimous record of the physical complaints their workers are experiencing. In the long term, this could point to certain tasks that cause the highest amount of WRMSD.

7 Conclusion

This study assessed the ergonomic risks associated with rail catenary construction work, identifying key factors that contribute to its physical demands. The analysis reveals that a combination of challenging working conditions, physically intensive tasks, and repetitive movements contribute to discomfort and musculoskeletal complaints among workers, particularly in the back, shoulders, and ankles.

The task analysis highlighted the physically demanding nature of the construction of support portals and tensioning wires, driven by heavy loads and high forces. Additionally, tasks like placing top bars, despite lower physical loads, were noted for their frequency, emphasizing the importance of addressing both intensity and repetition. Walking on ballast for extended periods also proved to be a significant ergonomic challenge, demonstrating how long task duration can strain workers despite lower immediate loads. These findings show the diverse nature of the tasks in this work, making it difficult to address all ergonomic issues with a single solution.

Physical complaints from workers further illustrate the toll of these tasks. Back pain can be linked to poor postures and heavy lifting, shoulder discomfort to overhead work and heavy weights, and ankle issues to uneven surfaces such as ballast.

Interviews and site visits identified additional risks, such as non-ergonomic tool lifting methods, long walking distances, and challenges posed by boom lifts, including constrained working postures and uncomfortable safety gear.

While this study provides valuable information, limitations include the reliance on subjective assessments, limited data on specific musculoskeletal disorders, and a lack of an objective method for scoring tasks. Future research should prioritize quantifying the tasks scores more objectively, broadening participant involvement, and exploring technological methods for more objective risk evaluation. These steps could support the design of targeted ergonomic interventions, such as improved equipment, task aids, and prefabrication strategies.

Compared to similar ergonomic risk assessments in construction, this study did not fully quantify risks but effectively evaluated a wide range of activities in a short time frame, providing a comprehensive overview of the physical demands of work.

Recommendations for Strukton include ergonomic improvements to safety harnesses, tool bags, and boom lifts, along with changes to work methods, such as adding rail-side walkways, expanding prefabrication, and introducing electric tools for tasks such as wire tensioning. Together, these measures aim to reduce physical strain, improve worker safety, and improve efficiency in rail catenary construction.

Part II

Preliminary Design of an In-Situ Tool for Biomechanical Analysis

8 Introduction

Technical methods now enable the measurement of worker posture during activities using cameras and sensors, facilitating biomechanical analysis to visualize joint forces during tasks. This section of the thesis focuses on developing a new method for in vivo biomechanical analysis and performing test measurements.

Motion capture technology has become increasingly accessible across industries such as military, film, gaming, and healthcare. Two primary systems are commonly used: camera-based systems employing markers or anatomical recognition points, and sensor-based systems worn by subjects. Recent advances in computer vision have enabled posture recognition using standard camera images, significantly reducing the required equipment. For example, the Xbox Kinect pioneered posture recognition at home, and similar systems are now applied to ergonomic risk assessments [26].

Motion capture improves ergonomic risk assessment in two ways. First, it automates posture observation. By recording worker postures during tasks and applying ergonomic indices like RULA or REBA, activities can be scored at every frame, offering a comprehensive overview. Second, motion capture data enable biomechanical analysis, evaluating not only postures but also movements and exerted forces.

Several studies have explored motion capture for ergonomic risk assessment in construction work. Wang et al. demonstrated how a single camera combined with pressure soles can automate ergonomic risk assessment and estimate joint torque. Using 3D pose estimation, 3D kinematics are determined, and the REBA method provides ergonomic risk scores. Concurrently, pressure soles estimate handled loads, and joint torque is calculated through static torque equilibrium equations [27]. Subedi et al. utilized a Kinect camera for input into OpenSim modeling, estimating forces in back muscles [28]. Chu et al. compare IMU-based methods with 3D pose estimation, finding that while 3D pose estimation has higher error, it remains effective for identifying awkward postures [29]. Brandt et al. used IMUs and EMG sensors for in vivo measurements of bricklayers, highlighting how posture and working height affect muscle activation [30].

These studies underscore the potential of computer vision due to its low intrusiveness and accessibility. However, challenges remain, such as occlusion issues and the lack of in vivo measurements—most studies occur in controlled environments. IMU sensors have demonstrated potential for in vivo assessments but can cause user discomfort. Marker-based motion capture has not been extensively studied in the literature, and the used methods for estimating external forces are limited to specific tasks. Often, dynamic forces are overlooked in biomechanical analysis.

This thesis aims to develop a tool for in vivo biomechanical analysis, focusing on the shoulder and elbow joints. The V-model for design will be used to compare various concepts from literature, selecting the optimal method. The final design will detail the entire process, from motion capture to biomechanical analysis. Selected rail catenary construction tasks will be analyzed using the tool, with validation measurements to evaluate its accuracy and usability. Finally, two potential use cases for the tool will be presented.

The subsequent chapters include an overview of the design process in Chapter 9; the evaluation of design concepts in Chapter 10; the final design of the biomechanical analysis tool in Chapter 11; pilot validation tests and results in Chapter 12; a discussion of design and validation in Chapter 13; and a conclusion in Chapter 14.

9

Design process

Building upon the challenges in biomechanical analysis identified in the chapter 8, the development of a new tool for in situ biomechanical analysis is proposed. Some of the problems identified for current biomechanical analysis tools are the lack of accessibility to a wide audience and the limited usability in different settings. To address these problems, the focus for the design of this tool is on finding a suitable solution for In-Situ motion capture.
The development of this tool is set according to the V model, shown in figure 9.1. The V model focuses on verification at every step of the design. This is useful for this design as the final design of the tool should be directly implementable in the rail catenary work case. Verification at every step will help making the tool more usable. Like this, the end user of the tool is taken into account as well.

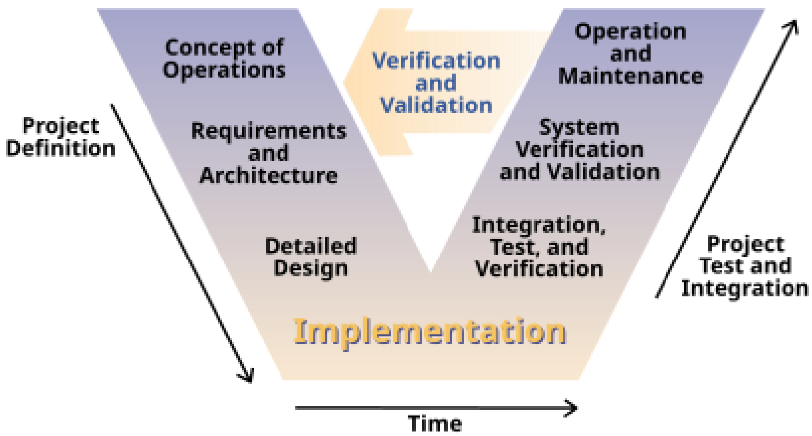


Figure 9.1: V-model for system development [31]

Beginning with the concepts of operations, the goal of the tool is defined and how it should accomplish this goal. The observations from site visits can be used to validate whether these concepts are applicable in practice.
In the requirements and architecture phase, it is presented what is specifically required from the tool and how these requirements could be met by different concept solutions. Here again, an understanding of the work sites for catenary workers helps defining the requirements and validation of the requirements. The concepts are evaluated on the requirements and criteria; this results in a design of choice. The design of choice is then split up into two different subsystems, and system requirements are set up.
A detailed design is presented covering all aspects of the different subsystems and how the system requirements are met.

A test environment is made for integration, testing, and verification. In the chapter on the preliminary validation, the results obtained with the newly designed tool are presented.
In the conclusion and discussion, it is discussed how the designed tool satisfies the requirements and criteria of the user and the system.
The design process in this thesis is limited to initial testing; user testing is not performed due to a lack of time.
In this chapter, the outline for the design of the biomechanical analysis tool is presented. This includes the problem statement in section 9.1, the initial requirements and criteria in 9.2 and 9.3 and lastly, the pilot validation tests performed on the final design in section 9.4.

9.1. Problem statement

The development of a tool for in situ biomechanical analysis is motivated by the need to effectively quantify the physical load on construction workers and the need to understand what might be needed to reduce this load. This support is required because the dropout of workers due to WRMSD is still too high and the workers are in high demand. Due to the non-repetitive nature of construction work, the identification of ergonomic problems is more challenging compared to other fields of work. Measurement of human joint angles and forces could greatly help identify ergonomic problems and determine what support forces are needed.
The maion problem for current methods for biomechanical analysis is that they are still laborious, expensive, inaccurate or usable only in a lab environment. Motion capture systems with markers are often very accurate but require a camera setup with several cameras. Because of this, measurements can only be made in the lab. Sensor measurements like with IMU's are more mobile, but the sensors are very inconvenient in use and calibration. EMG sensors provide more information about the muscles themselves, but are not reliable in determining the total joint moment and are also inconvenient. Implantable sensors seem to be the most accurate for determining joint moments, but are for obvious reasons not applicable in most cases. For modeling, it is required to accurately estimate the external forces. This is often very difficult to measure during real-life tasks.
The design proposed here aims to address these problems by enabling in situ measurements with accessible materials with ease of use. In situ means that this measurement should be possible in a setting similar to construction work conditions.

9.2. User requirements

The user requirements are the requirements that are set for the end user of the tool. Here these requirements mainly focus on what exactly the tool should be able to do, the accessibility of the tool, the usability of the tool and the safety of the tool.

9.2.1. Performance

For the performance requirements for the tool, the requirements can be split into the capabilities and the accuracy of the tool. The tool should be able to measure joint angles, joint angular accelerations and joint moments. In addition, it is required to measure these values during construction work activities. Lastly, it should be possible to incorporate the handling of construction objects like tools or material into the joint moments. These requirements are listed as follows:

- Joint angle: measure joint angle with at most 10 degrees of error margin
- Joint angular acceleration: measure joint angular acceleration with at most 100 deg/s^2 of error margin
- Joint moment: measure joint moments with at most 2Nm of error margin
- Construction work activities: measure subject while doing construction work activities
- Object handling: incorporate object handling into the measurements

9.2.2. Accessibility

For accessibility requirements for the tool, it is regarded what is needed in order to use the tool. Some methods might require expensive software or hardware. As this method should be accessible, the following requirements are set up:

- Hardware: in order to use the tool no expensive specialized equipment is needed
- Software: in order to use the tool no expensive software is needed

9.2.3. Usability

For the usability requirements for the tool, it is regarded how usable the method is in a variety of circumstances and how easy it is to use the method. The requirements following from this are the following:

- Portability: the hardware required for measurements should be movable by a single person
- Setup time: the setup time for doing a single measurement with the tool should take less than 15 minutes
- Complexity: the tool can be used by a new person with less than an hour of explanation
- Environment: the tool should be compatible with a construction site

9.2.4. Safety

Lastly, we have a single safety requirement.

- Safety: the test subject does not pose any hazards from doing measurements with the tool

9.3. User criteria

In order to qualitatively compare different possible solutions, some criteria are also set. These criteria are shown in table 9.1

Table 9.1: Table with list of user criteria setup for comparing different concepts

Criteria	**Description**
1. Joint angle accuracy	Scores high for high accuracy in joint angle measurement. Being able to accurately measure joint angles helps with correctly estimating the body pose.
2. Joint angular acceleration accuracy	Scores high for high accuracy in angular acceleration measurement. Angular acceleration is often calculated from the joint angles but can still be highly inaccurate if there is a lot of noise in the measured data. An accurate value is needed for joint moment estimation.
3. Joint moment accuracy	Scores high for high accuracy in joint moment estimation/measurement. Accurate joint moment calculation/estimation is needed to effectively evaluate the body force for a certain movement.
4. Setup time	Scores high for low setup time. A higher setup time is very undesirable as the measurements will be performed in many different work environments.
5. Usability	Scores high for high ease of use. A tool that has higher ease of use makes it possible to use the tool for many different users.
6. Environment	Scores high if able to measure in many different kinds of environments. The tool should be usable in 'in situ' work environments. This includes different types of weather conditions and, for example, uneven underground.
7. Costs	Scores high if costs for equipment and software are low. For the tool to be used widely, low costs for equipment and software are beneficial.

9.4. Testing of the final design

Upon completing the design process, the final design of the biomechanical analysis tool undergoes some tests to validate its performance. These tests will be used to evaluate the tool according to the user requirements and criteria that are set up, as well as the system requirements specified later. The tests that are performed include the following:

- Control movements: during these tests the subjects will perform basic movements such as shoulder flexion, abduction, axial rotation and elbow flexion. Measurements are validated by video analysis with Kinovea.
- Construction task movements: during these tests the subject will perform several relevant construction tasks in a controlled environment in order to see if these movements can be effectively recorded with the designed tool. Five different tasks are performed and measured. For each task, the subject manipulates different tools and materials. Each task is performed twice, and one task is performed in three different body positions.

How exactly these tests are performed is presented in Chapter 12 on the pilot validation of the final design.

10

Concepts

In this chapter several concepts are proposed for the biomechanical analysis tool. The proposed concepts are evaluated on the setup requirements and criteria. Lastly a concept is chosen for the final design.
In the literature, mainly two possibilities are seen for in situ biomechanical analysis. The first is motion capture in combination with human modeling. The second is direct or indirect measurement of joint moments and muscles forces.
Motion capture in combination with modeling uses different types of measurements to model human joints and estimate joint moments. Direct and indirect force measurements use sensors such as implants or EMG sensors to measure joint moment or muscle activation. Five different concepts based on these two options are presented in table 10.1.

Table 10.1: The five proposed concepts for the biomechanical analysis tool.

Concept	**Description**
1. Human modeling with IMU sensor MC	With IMU sensors like the Xsens system, human motion is recorded. The movement data is used to create kinematics of a model in OpenSim. With kinematics, inverse dynamics can be used to estimate joint moments.
2. Human modeling with marker MC	With a marker motion capture system like OptiTrack, human motion is recorded. The movement data is used to create kinematics of a model in OpenSim. With these kinematics, inverse dynamics can be used to estimate joint moments.
3. Human modeling with markerless MC	With a markerless motion capture system like OpenCap, human motion is recorded. The movement data is used to create kinematics of a model in OpenSim. With this model, inverse dynamics can be used to estimate joint moments.
4. Implantable sensors	With prostheses that have embedded sensors, the joint moments are directly measured. This requires subjects that have an implant.
5. EMG sensors	EMG sensors on the body parts of interest measure the muscle activity directly. Joint moments can also be estimated if calibrated to EMG values.

10.1. Evaluation of concepts

Based on the literature and common sense, the proposed concepts are evaluated according to the requirements and criteria for the setup. This tells something about the suitability of the presented concepts.

10.1.1. Evaluation of requirements

In figure 10.1 it is shown how each concept satisfies the requirements.
Concept 1 satisfies most requirements, but not the hardware, software, and setup time requirements. This is because Xsens and similar IMU suits are generally quite expensive. Also, they require quite some time to put on a calibrate.
Concept 2 does not satisfy most of the practical requirements. MC systems that use markers are generally only used in controlled test environments, expensive, complex, and because of occlusion not all movements might be possible.
Concept 3 seems promising, as only two requirements are maybe not satisfied. Like marker MC, markerless MC might struggle with occlusion during certain tasks. Also, in all concepts where modeling is used, object handling will need to be added in the modeling program. This might affect the accuracy.
Concept 4 does not satisfy some of the practical requirements and is also not able to measure joint angles and angular acceleration on its own. Depending on the implant this might differ. However, the safety concern of using an implant for measurements like this is very problematic as such an implant is not used on healthy subjects.
Concept 5 also does not offer the possibility of measuring joint angles. Apart from this, some practical requirements like the hardware, software and complexity are not satisfied.

Figure 10.1: This table shows how the several proposed concepts score on the setup requirements. Green means the requirements are met, orange means it is not sure and red means the requirements are not met.

Requirements	Con. 1	Con. 2	Con. 3	Con. 4	Con. 5
Joint angle	1	1	1	0	0
Joint angular acceleration	1	1	1	0	0
Joint moment	1	1	1	1	1
Construction work activities	1	0.5	0.5	1	1
Object handeling	0.5	0.5	0.5	1	1
Hardware	0	0	1	0	0
Software	0	0	1	0	0
Portability	1	0	1	1	1
Setup time	0	0	1	1	0
Complexity	1	0	1	0	0
Environment	1	0	1	1	1
Safety	1	1	1	0	1

Concluding from the evaluation of requirements, only concept 3 seems to potentially meet all requirements. Some validation will be needed to see if the construction work activities and object handling can be done.

10.1.2. Evaluation of criteria

In table 10.2 the scoring of the five concepts is presented for the setup criteria. It can be seen that concept 1 scores the highest in all criteria. This is because of its average performance and high practicality. Concept 3 scores second best due to slightly worse performance scores. Concept 5 is third because it scores low for the joint angle and acceleration criteria as these cannot be measured.

Figure 10.2: This table shows how the proposed concepts are evaluated on the setup criteria. Each concepts has a total amount of points representing the potential of the concept solution.

Criteria	Con. 1	Con. 2	Con. 3	Con. 4	Con. 5	Weighting (1-5)
Joint angle accuracy	3	5	3	1	1	3
Joint angluar acceleration accuracy	3	5	3	1	1	2
Joint moment accuracy	3	4	2	5	4	5
Setup time	3	1	4	2	3	3
Usability	4	2	4	2	3	4
Environment	5	1	3	5	5	4
Cost	3	1	5	1	2	2
Total	81	62	75	66	70	

10.1.3. Design choice

From this evaluation of the requirements and criteria, concept 3 is chosen as the method for the final design. This is because this concept satisfies the most requirements and also scores relatively well for the criteria.
As this method uses both MC and modeling, these aspects will be regarded as subsystems for the rest of the design cycle. For MC, markerless MC will be used as this allows measurements to be made with minimal equipment and high accessibility. With respect to modeling, software that is capable of calculating the joint moments from human kinematics is required. Other data processing steps might be needed as well and will be regarded as part of the modeling. This data processing will be performed with the help of an arbitrary programming language.

10.2. Subsystem 1: Motion capture

In the previous section, markerless motion capture was chosen as the concept of choice. The system for motion capture should be accurate enough to accurately measure the kinematics during construction tasks and simple enough to be able to use it at different locations. Accurate measurement can be in conflict with simple and versatile measurement.

10.2.1. System requirements

Apart from the requirements that the chosen markerless motion capture system sets, several other requirements can be set for the system. The cameras that are used require a certain resolution in order to perform accurate posture detection. In this case, this is minimally 720P. Tripods are needed in order to position the camera's stably. A stable underground is also needed for positioning the cameras. Enough light is needed for the cameras to capture the subject. The subject needs to wear clothes that make it easy for the software to distinguish the arms from the body. Lastly, cameras need to be placed in a clear line of sight with the subjects.

10.3. Subsystem 2: Modeling

For the modeling subsystem, there are some requirements of the chosen modeling software, but also some other requirements set for the design. It should be possible to model a wide variety of circumstances and subjects, but at the same time the process should remain intuitive.

10.3.1. System requirements

At first the program should be able to run inverse dynamics with the data from the MC method. Data flow should be easy and relatively intuitive. Processing data in a desired manner should be possible and different kinds of output graphics should be possible to the users desire. The modeling software must be able to easily use different models so that different human subjects and different objects can be modeled. External forces must be easily inputted into the model. In addition, the programs used for modeling and data processing should be relatively understandable, so that a user with minimal experience can still operate the tool.

11
Final design

Resulting from the design evaluation in chapter 11, the markerless motion capture method in combination with human modeling is chosen as the tool for biomechanical analysis. Figure 11.1 shows an overview of the tool.

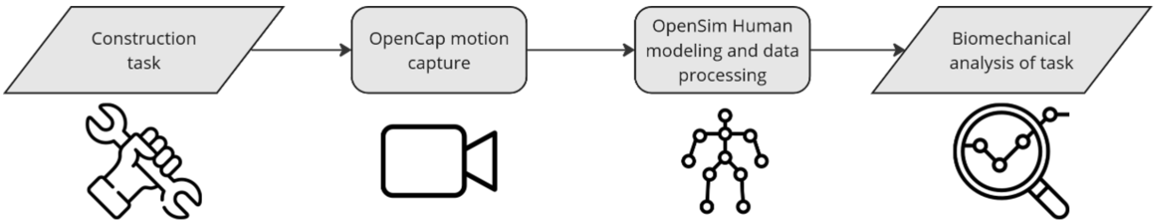


Figure 11.1: Overview of the method used by the biomechanical analysis tool. In figure 11.2 and 11.5 the processes in the two middle blocks are further visualized.

The goal of this chapter is to describe how this tool can perform biomechanical analysis on body movements. To describe this, the two subsystems need to be explained and the data flow from beginning to end needs to be explained. In section 11.1 it is explained how OpenCap works and what kinds of outputs are created by this software. In section 11.2 it is explained how OpenSim works and how the OpenCap data needs to be processed for the biomechanical analysis.

11.1. OpenCap Motion Capture

In this study, OpenCap software was selected for the motion capture system due to its accessibility, efficiency, and accuracy. OpenCap, is described by Ulrich et al., as follows
"OpenCap, an open-source, web-based software tool for computing the motion (e.g., joint angles) and the musculoskeletal forces underlying human movement (e.g., joint forces) from smartphone videos."[32]
OpenCap was developed by researchers from the university of Stanford in order to make human movement analysis more widely available to researchers. It was stated to be 25 times faster at only 1 % of the costs compared to laboratory based approaches. In figure 11.2 the process of motion analysis with OpenCap is shown.

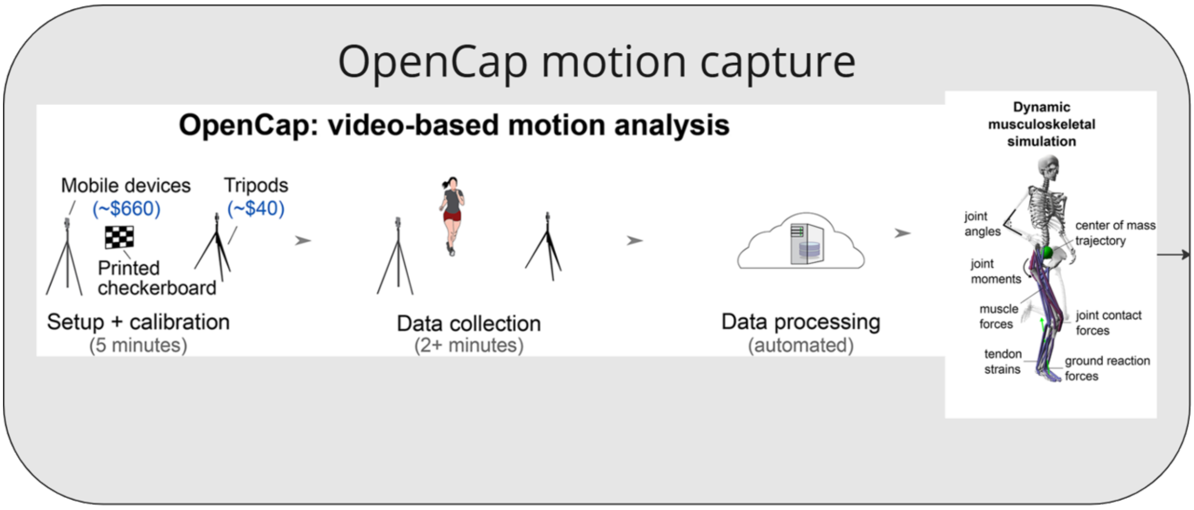


Figure 11.2: The process of gathering kinematic data with OpenCap. This represent the first process block in figure 11.1. [32]

The setup for OpenCap requires minimal equipment, including two smartphones, two tripods, a laptop, and a printed checkerboard. Initially, the measurement environment is calibrated by placing the checkerboard centrally within both camera views and recording a short video. This step ensures alignment of the cameras for accurate data collection. Once the setup is calibrated, the human subject is positioned in the center of the camera views and recorded while standing still. Alongside this recording, details such as the subject's weight, height, gender, and age are input into the software, enabling the creation of a subject-specific musculoskeletal model scaled to individual proportions.
Following successful calibration, videos of the subject performing the targeted movements are recorded. The cameras remain stationary throughout the session to maintain consistent alignment. The videos are then uploaded to cloud storage, where OpenCap processes them to generate 3D kinematic data. This output includes the positions of virtual markers and joint angles during the movements, which are available for download and subsequent modeling.
By streamlining the motion capture process, OpenCap provides an accessible, cost-effective alternative for biomechanical analysis outside laboratory environments. Its reliance on smartphone cameras and neural networks ensures accurate 3D data generation, even in less controlled settings, making it a potentially effective ideal tool for analyzing construction work tasks.

11.1.1. 3D kinematics from smartphone video

A key advantage of OpenCap is its ability to generate 3D kinematic data from minimal inputs, which is made possible through advanced neural network algorithms. The process begins with OpenPose, a convolutional neural network that identifies body keypoints from 2D images captured by the cameras. These 2D keypoints are synchronized across multiple camera angles, and triangulation techniques are then applied to reconstruct a set of 3D keypoints.
To enhance the anatomical accuracy of the reconstructed data, a long short-term memory (LSTM) neural network is employed. This network, trained on extensive motion capture datasets, refines the 3D keypoints into a more comprehensive and anatomically accurate marker set that represents the subject. The final step involves applying inverse kinematics to compute 3D kinematics using a musculoskeletal model constrained by biomechanical principles.
This integration of neural networks allows OpenCap to deliver accurate motion data in a highly efficient manner, bypassing the complexity and cost associated with traditional marker-based systems. By leveraging these computational methods, OpenCap makes 3D motion analysis accessible for use in real-world environments, such as construction sites, where traditional systems would be impractical. [32]

11.1.2. Musculoskeletal model

OpenCap supports two primary musculoskeletal models for motion capture: the LaiUlrich2022 model and the LaiUlrich2022shoulder model. Both are derived from the Rajagopal model, originally developed for muscle-driven simulations of human gait [33]. These models provide a robust framework for analyzing motion dynamics, with certain distinctions that make them suitable for different applications. The LaiUlrich2022 model represents a full-body musculoskeletal structure, see figure 11.3. It includes 80 muscles that actuate the lower limb coordinates, while 13 ideal torque actuators are used for the back, shoulders, and elbows. This design allows for accurate simulation of lower-body movements but does not account for upper extremity muscles. Instead, upper limb dynamics are modeled using ideal torque actuators [32].

The LaiUlrich2022shoulder model extends the LaiUlrich2022 model by introducing three additional translational degrees of freedom at each shoulder, enabling more precise representation of shoulder mechanics. Force actuators are added in the x, y and z directions to simulate the translational forces acting on the shoulder joint. These features make it suitable for analyzing tasks involving complex upper-body motions. However, like its predecessor, this model lacks muscle-driven simulation for the upper extremities.[34]

Although neither model includes muscles for the upper extremities, both are capable of calculating joint moments. This feature makes them suitable for evaluating the physical demands of tasks that involve repetitive or high-force shoulder and arm movements, such as those encountered in construction work. All results presented in this research use the LaiUlrich2022shoulder model, as this is recommended when measuring upper body kinematics.

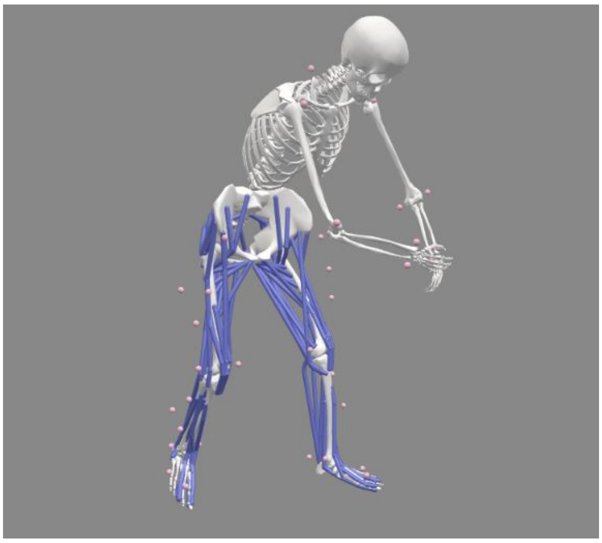


Figure 11.3: The LaiUhlrich shoulder model

Shoulder joint rotation sequence

In the LaiUlrich2022shoulder model, the clinical terms flexion and abduction of the shoulder are not used as these are not constant in 3D. Instead an Euler decomposition is used to describe shoulder kinematics as recommended by ISB. In this model the axis of rotation that are defined as the glenohumeral plane of elevation, glenohumeral elevation and glenohumeral axial rotation. These axis of rotation are shown in figure 11.4.[35] [34] Because this system is used in the model, the results obtained from the biomechanical analysis tool will also follow this convention.

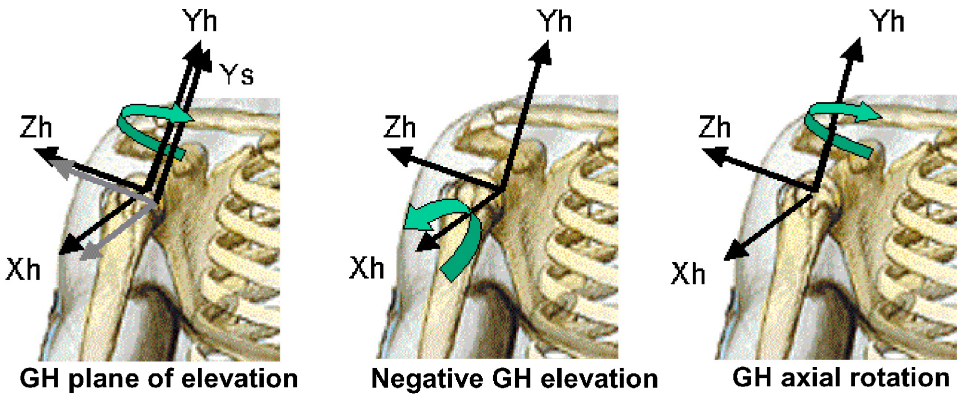


Figure 11.4: Humerus coordinate system and definition of glenohumeral motions. Y_s is the local axis for the scapula coordinate system.

11.1.3. Inputs and Outputs

The inputs used by OpenCap are the following:

- Anthropometric data (height, weight and age)
- Calibration image of checkerboard
- Calibration image of human subject
- Video footage from two smartphone camera's

The outputs created by OpenCap are the following:

- Marker data (x,y and z coordinates of 63 markers over time, TRC file)
- Kinematic data (joint angles and joint offset for 39 DoF, .mot file)
- The scaled human model (.osim file)
- Session meta data

11.1.4. System requirements

OpenCap provides very clearly on their website what exactly is required to perform measurements. At least two iphones that were released during or after 2018 are required for recording. A laptop is required for remotely operating the camera's. As the data is processed on an OpenCap server, no hardware requirements are in place for the laptop. Two tripods are also needed to position the cameras.
Apart from this, there are some best practices for doing measurements. The cameras should be placed at an angle between 30-45 ° from the front line of the subject. The subject should stay in the capture volume during the measurement. All body parts of the subject should be visible by at least two cameras during measurement.
Some of these best practices can be used in design but most are required for doing accurate measurements with the OpenCap software. [34]

11.2. OpenSim human modeling

With the kinematics from OpenCap the subject can be modeled in a software like OpenSim. Data from OpenCap is however still full of noise and lacks data of the external forces. Therefore data is filtered and external forces are estimated and added to the model. Running an inverse dynamics simulation can then result in the wanted biomechanical analysis of the shoulder and elbow joint. In this section the OpenSim inverse dynamics, data filtering, external force estimation and data processing is shown.

11.2.1. OpenSim inverse dynamics

The OpenSim software was utilized to perform inverse dynamics on the 3D kinematic data obtained through OpenCap. This process calculates joint moments across all joints included in the musculoskeletal model by solving the equations of motion. The equation used for these calculations is expressed as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau}$$

where N is the number of degrees of freedom, and:

- $\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}} \in \mathbb{R}^N$ are the vectors of generalized positions, velocities, and accelerations, respectively;
- $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{N\times N}$ is the system mass matrix;
- $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^N$ is the vector of Coriolis and centrifugal forces;
- $\mathbf{G}(\mathbf{q}) \in \mathbb{R}^N$ is the vector of gravitational forces; and
- $\boldsymbol{\tau} \in \mathbb{R}^N$ is the vector of generalized forces.

This equation is solved iteratively at each timestep to compute the joint moments $(\boldsymbol{\tau})$, enabling detailed insights into the biomechanical loads experienced during movement. Using OpenSim, these computations are streamlined, allowing for the evaluation of various dynamic tasks.

To optimize processing efficiency, a MATLAB script was employed to batch-process multiple movements in a single run. This integration of OpenSim with custom MATLAB scripts significantly reduces the time required for analysis, facilitating the evaluation of biomechanical loads across a range of construction-related tasks.

11.2.2. Filtering kinematic data

Data acquired with OpenCap has some unavoidable noise. This can cause rapid accelerations in joints that are not present in reality. It is therefore necessary to filter the kinematics with a low pass Butterworth filter. Standards for filtering motion data consider how much of the total power of the signal is lost after filtering. One standard found in the paper by Uhlrich et al. suggest that 99.7 % power should be preserved [32]. It is also known that human arm movements are mainly around the frequency of 1 Hz. With a cutoff frequency of 2 Hz, the signals from the joint angles in the shoulder and elbow retained 99.7 % of the cumulative signal power of the Fourier transformed for all movements. Therefor 2 Hz was chosen as a safe cutoff frequency to use for filtering. The script used for kinematic data filtering is shown in E.2.

11.2.3. External forces estimation

When the subject is interacting with the environment, external forces need to be added. In this tool two scenarios for external forces are taken into account.
The first is when the subject is lifting an object. This can be integrated into the analysis by creating a model in OpenSimCreator that has a mass attached to its hand. If a different object is handled by the subject, the mass can be changed. In appendix E.1 a modified model can be seen.
The second scenario is when the subject is not lifting the object but exerting force in a different direction than upwards. This can, for example, be pulling on a wrench to tighten a bolt. Here the magnitude of peak force required for such a task is measured manually with a luggage scale. The direction of the force can be determined from the marker data obtained from OpenCap. For example, pulling on a wrench can be modeled as a force perpendicular to plane that is spanned by the two markers in the hand and one at the elbow. With matlab a file containing the force direction and magnitude over time can be made. The script used to create this force file is shown in appendix E.3.

11.2.4. Data processing

In order to go from the data acquired from the OpenCap measurements to the desired results, modeling, filtering and processing steps are taken. In figure 11.5 the steps that are part of the modeling subsystem are shown in a flowchart.

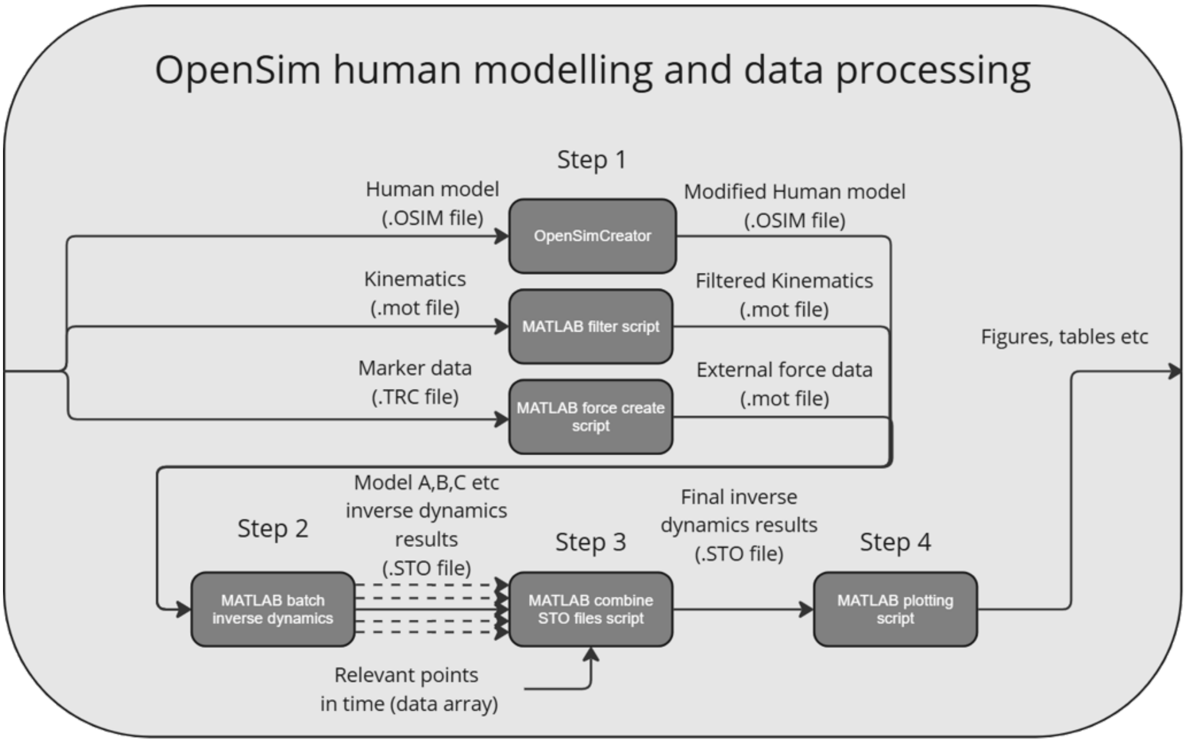


Figure 11.5: In the flowchart all steps that are necessary to create the results from the measured OpenCap data are shown. The arrows depict a file that is an output from the block in front of it and an input for the block at the end of the arrow. This represent the second process shown in figure 11.1.

Step 1: Several inputs from the OpenCap software are used for the modeling subsystem. The human model contains an .OSIM file that defines the model used for the pose estimation. The kinematics contain a .mot file with the joint angles of all model specified joints. The marker data contains the xyz coordinates of all markers that are projected on the specific model in the used coordinate system. The human model is modified to, for example, inculde a mass that represents the mass handled by the subject during a certain task. This is done in OpenSimCreator, which is software that can be used to modify a .OSIM model. The kinematic data is filtered as previously specified. The filtered kinematics are outputted. The marker data is used to determine the force direction for tasks where external forces are applied. This is done as described above. A file with the external forces applied to the model in the coordinate system of the model is outputted.

Step 2: The three outputs that are created in step 1 are combined to calculate the inverse dynamics from the measured movements with OpenSim. By using a batch file all measurements can be processed for a single model with one click. When a tasks includes the handling of different weight objects, inverse dynamics are calculated for several different models with different attached weights. When the subject for example grabs objects with the weight of 2,5 and 10 kg, three different models are made and processed. This results in the inverse dynamics of all required movements with the different models. In these inverse dynamics files all the joint moments over the time of the measurement are listed. In appendix E.4 the script for batch processing of the inverse dynamics in OpenSim is shown.

Step 3: In this step the inverse dynamics results are put together into a combined inverse dynamics file that accounts for the different handled weights. Apart from the inverse dynamic files, the timestamps where the subject starts to manipulate a certain item is also needed. The MATLAB script then creates a single .STO file that is put together from several .STO files. In appendix E.5 the script for combining the different .STO files is shown.

Step 4: In the final step, the inverse dynamics results of the different tasks are plotted over time, and values like the maximum moments and average moments are outputted with a MATLAB script. In appendix E.6 the script for plotting the different result figures is shown.

11.2.5. Inputs and Outputs

The inputs used for this subsystem are:

- Marker data (x,y and z coordinates of 63 markers over time, TRC file)
- Kinematic data (joint angles and joint offset for 39 DoF, .mot file)
- The scaled human model (.osim file)
- Weight of handled objects
- Magnitude of external forces

The outputs from this subsystem are:

- Filtered kinematic data (joint angles and joint offset for 39 DoF, .mot file)
- Joint moment data (joint moment values for 41 DoF over time, .STO file)

11.2.6. System requirements

As OpenSim runs locally on the pc it is installed on, it has some basic requirements. For the software, Windows 10 or newer is needed or macOS 10.12 or later. For hardware, a memory of at least 2 GB is needed and at least 1 GB hard disk space.
For kinematic data filtering and data processing, only a recent version of MATLAB is needed to run the scripts.
For external force estimation, a simple luggage scale is required. This can be used to measure the weight of different objects that are handled and measure the force that needs to be exerted to operate certain tools.

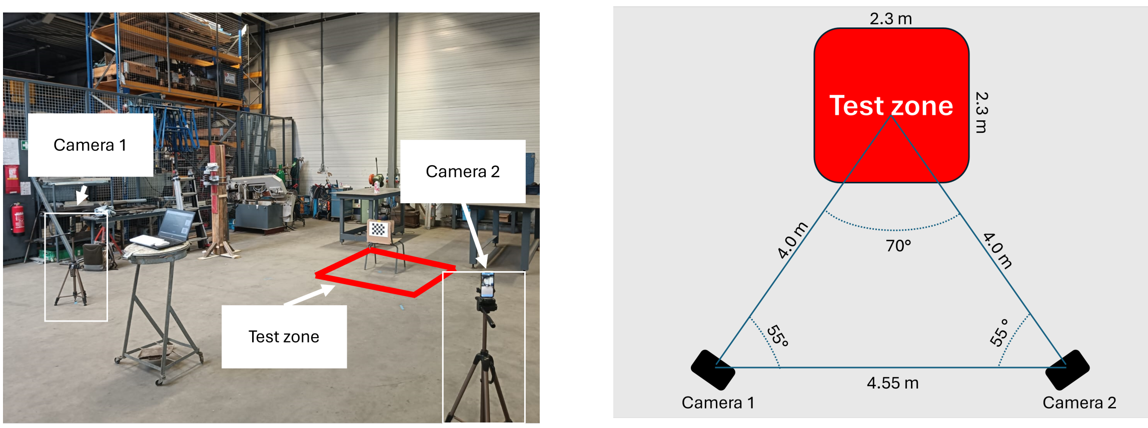
12

Pilot Validation

In this chapter, the test measurements that are performed to validate the tool designed for the biomechanical analysis of construction tasks are presented. These tests are performed to evaluate the requirements and validate the design. The test environment is presented in section 12.1, followed by an overview of the control tests that are performed in section 12.2 and the construction task tests that are performed in 12.3. Finally, the user and system requirements are evaluated in section 12.4.

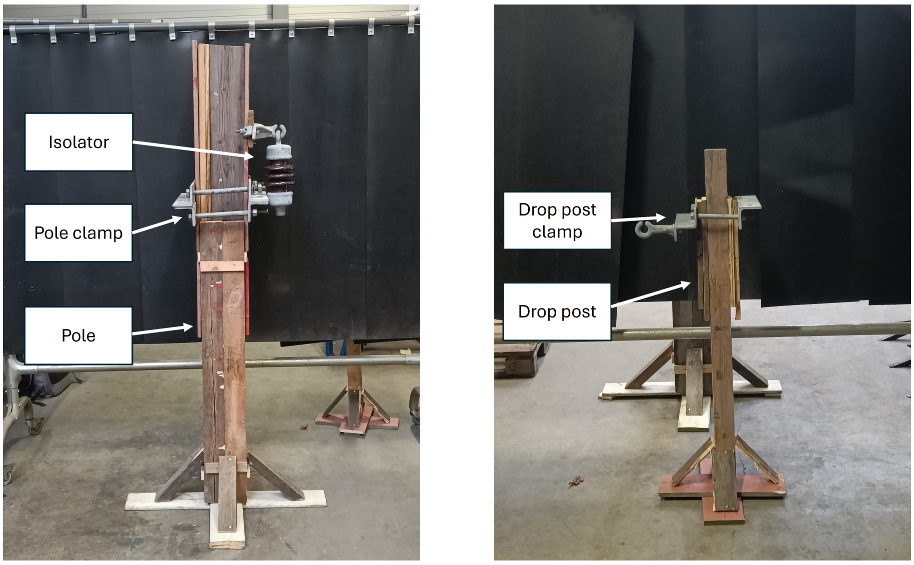
12.1. Test environment

For the test measurements that were performed, a measurement environment was built in a storage facility at Strukton. This was a good location, as some free space is needed for the measurements. Regarding the required equipment, apart from the equipment that was specified before for OpenCap measurements, some other attributes were also used to effectively simulate the test measurements. The attributes were required to simulate the construction environment in a different setting. In figure 12.1a a photo of the test environment can be seen and in figure 12.1b a schematic of the test setup can be seen. In figures 12.2 and 12.3 the attributes that were used to perform several test tasks are shown. These attibutes include a pole, drop post and two versions of a piece of contact wire.



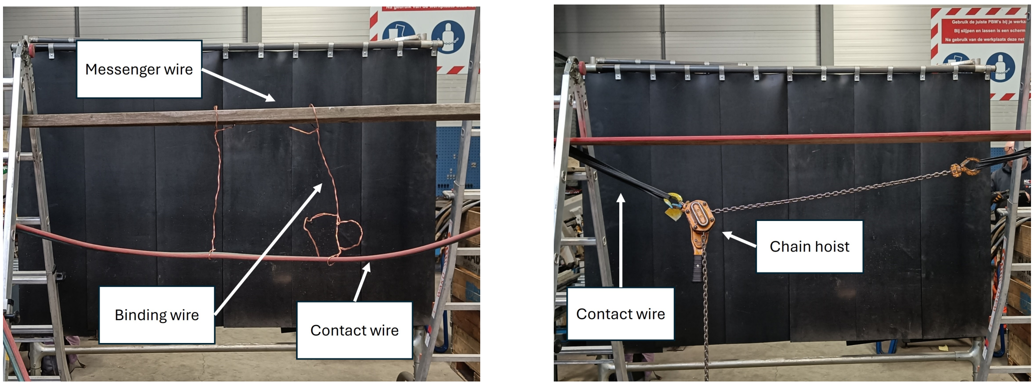
(a) (b)

Figure 12.1: Two depictions of the test environment that was used. a) Here a photo of the test environment in the storage facility of Strukton is shown. b) Here a schematic drawing of the test setup is shown with the used dimensions of the test setup.



(a) (b)

Figure 12.2: a) The reconstructed pole from the support portals used for tasks related to the pole. b) The reconstructed drop post used for tasks related to the drop post.



(a) (b)

Figure 12.3: a) The reconstructed contact wire and messenger wire with binding wire in between. Tasks where the contact wire is secured with binding wire can be simulated. b) A different type of reconstructed contact wire with an inner tube from a bike. The chain hoist can be used to tension the reconstructed contact wire.

12.2. Control movements

As a kind of sanity check for the measurements in this newly created environment, some very simple movements were measured with the setup while also recording the subject with a 3rd camera from an angle perpendicular to the movement plane. Like this, the angle of a joint can be measured in 2D as validation. Using the free software from Kinovea the joint angles can be drawn on the image, see figure 12.4. Comparing the joint angle and acceleration results with the results from the newly developed tool gives some sense on the validity of the measurements. In the results, joint angles and accelerations are compared between Kinovea and the designed tool. These control movements include:

- Shoulder elevation
- Shoulder abduction
- Shoulder axial rotation
- Elbow flexion
- Pronation/supination forearm

Figure 12.4: An example of how a measurement with the Kinovea software looks like. With the help of markers a joint angle can be measured from video.

12.2.1. Results

In this section the measurements from the control movements are shown. The measured angles are compared between the Kinovea method and the OpenCap method and the caclulated angular accelerations are compared as well. In figure 12.5 the joint angles recorded during the control movement measurements are shwon. Each graph shows the joint angles measured with OpenCap and Kinovea. What stands out is that the angles measured for shoulder flexion, shoulder abduction, and elbow flexion seem to correspond quite well. However, the measured angles for the axial rotation and the pronation of the forearm are rather poor.

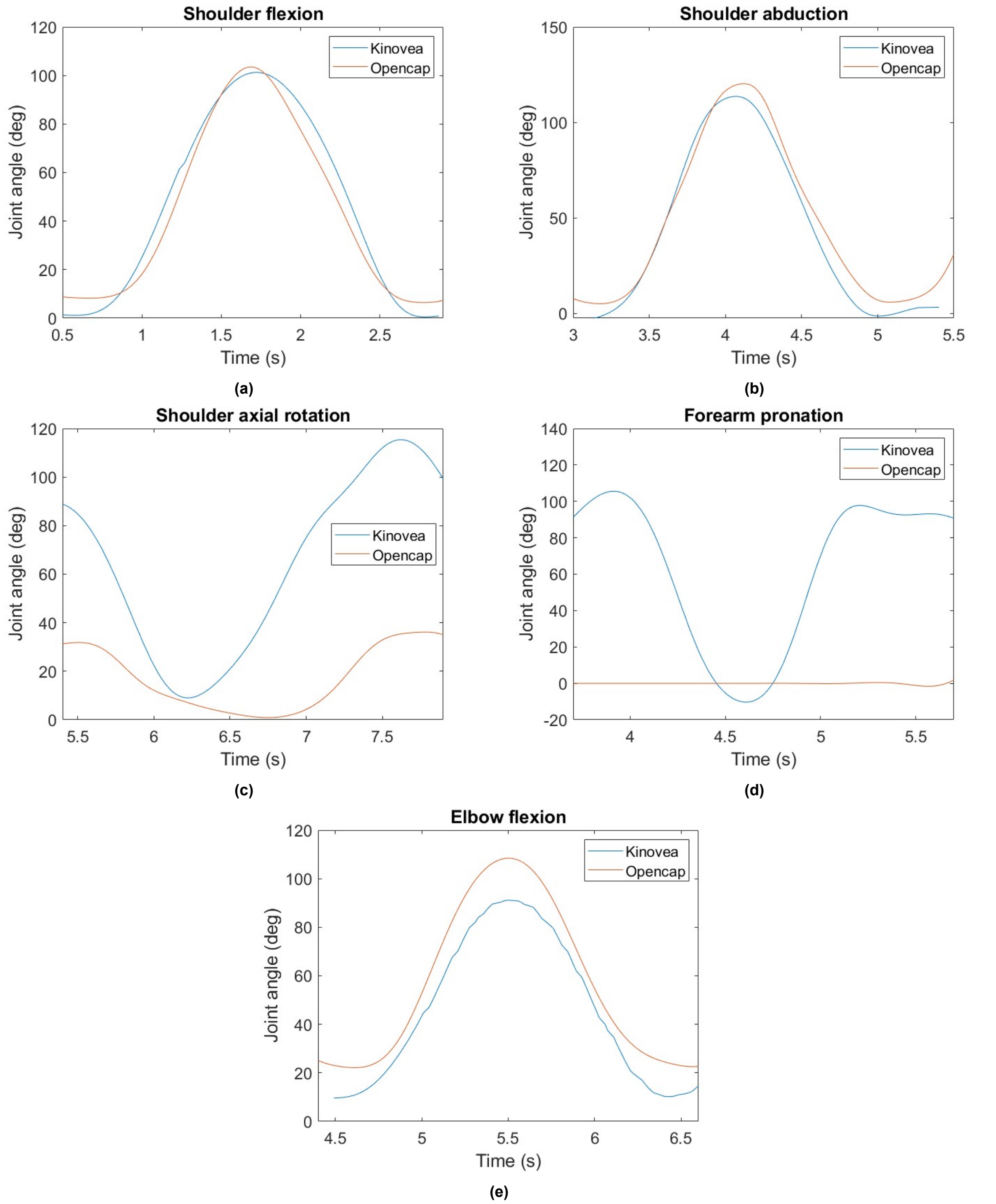


Figure 12.5: Joint angles plotted against time for five different movements. Both the measurements with Kinovea and with OpenCap are shown. Blue indicates angles from Kinovea and orange angles from OpenCap. a) Shoulder flexion angle during a shoulder flexion movement b) Shoulder abduction angle during a shoulder abduction movement c) Shoulder axial rotation angle during a shoulder axial rotation movement d) Forearm pronation during a forearm pronation movement e) Elbow flexion during an elbow flexion movement

Next, the angular acceleration results from the shoulder flexion and elbow flexion movements are shown in figure 12.6. The values for shoulder flexion and elbow flexion are in the same order of magnitude but do not correspond very closely.

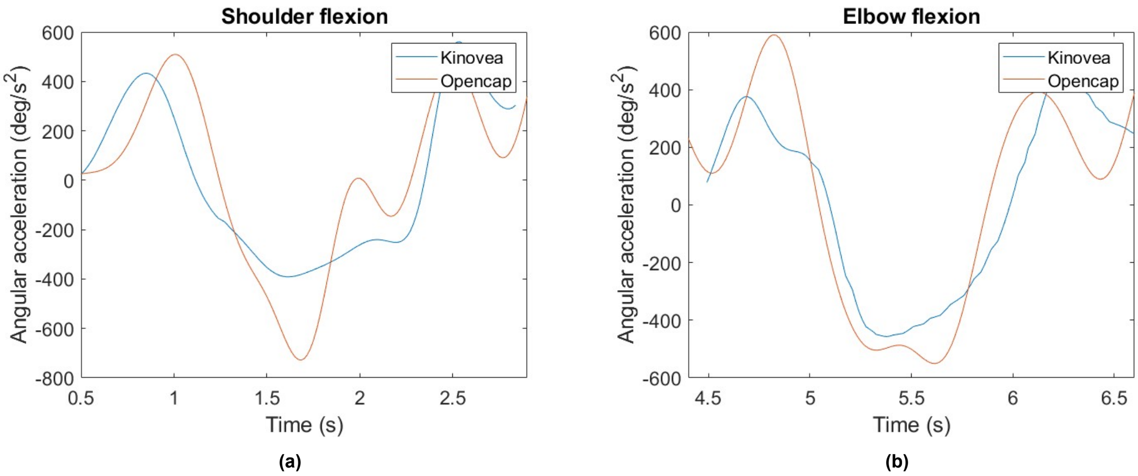


Figure 12.6: Joint angular acceleration plotted against time for two different movements. Both the measurements with Kinovea and with OpenCap are shown. Blue indicates angles from Kinovea and orange angles from OpenCap. a) Shoulder flexion angular acceleration during a shoulder flexion movement b) Elbow flexion angular acceleration during an elbow flexion movement

12.3. Construction tasks

Based on the task analysis in part one of this thesis, five frequently occurring construction tasks were selected for evaluation. These tasks were selected to represent the spectrum of movements present in rail catenary construction, from precision tasks that require fine motor control to high-force tasks that require significant muscular effort. The results were gathered using the designed tool while the subject performs certain tasks. The tasks were first performed in the controlled test environment and then performed by an experienced worker. All tasks were performed two times by a Strukton worker. The tasks included:

1. **Installation of an isolator on a pole (see figure 12.7a)**
   - Pick up the 5kg weighing isolator from waist height
   - Lift the isolator to shoulder height
   - Connect the isolator to a hook connected to the pole
2. **Installation of a clamp on a hanging column (see figure 12.7b)**
   - Pick up the 5 kg weighing clamp from waist height
   - Slide the clamp around the hanging column at waist height
   - Hold the clamp in place with one hand and pick up the impact driver with the other hand
   - Tighten the nuts on both ends of the clamp to fasten the clamp on the column
3. **Installation of a clamp on a pole (see figure 12.8a)**
   - Pick up the 10 kg weighing clamp from waist height
   - Lift the clamp above shoulder height
   - Slide the clamp over the column and rest it on another clamp
   - Pick up impact drill
   - Bend around column to fasten the nuts on both end of the clamp to fasten the clamp to the column
4. **Securing the contact wire (see figure 12.8b)**
   - Pass the biding wire under the contact wire
   - Lift up the contact wire by pulling the binding wire up
   - Fasten the binding wire by twisting it around itself

5.1. Tensioning the contact wire in normal posture (see figure 12.9)

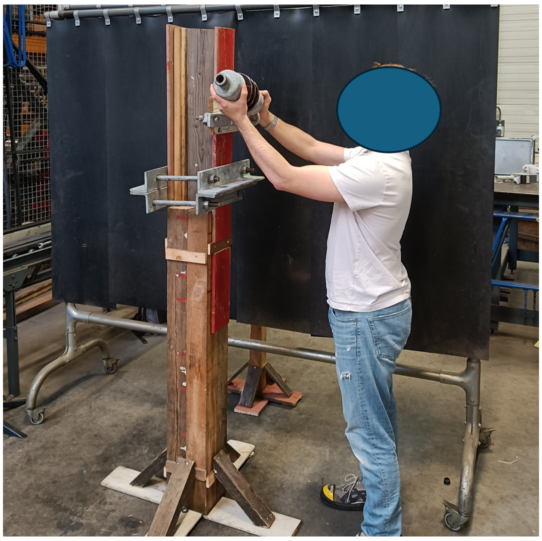
- Stand close to the chain hoist
- Grab the handle of the chain hoist
- Move the handle back and forth to tension the contact wire, force is exerted in the puling motion

5.2. Tensioning the contact wire in far off position

- Stand far off from the chain hoist, should be reachable with stretched arms
- Grab the handle of the chain hoist
- Move the handle back and forth to tension the contact wire, force is exerted in the puling motion

5.3. Tensioning the contact wire above head

- Kneel down close to the chain hoist
- Grab the handle of the chain hoist
- Move the handle back and forth to tension the contact wire, force is exerted in the puling motion



(a)

(b)

Figure 12.7: a) A subject performing task 1 b) A subject performing task 2.

(a)

(b)

Figure 12.8: a) A subject performing task 3 b) A subject performing task 4.

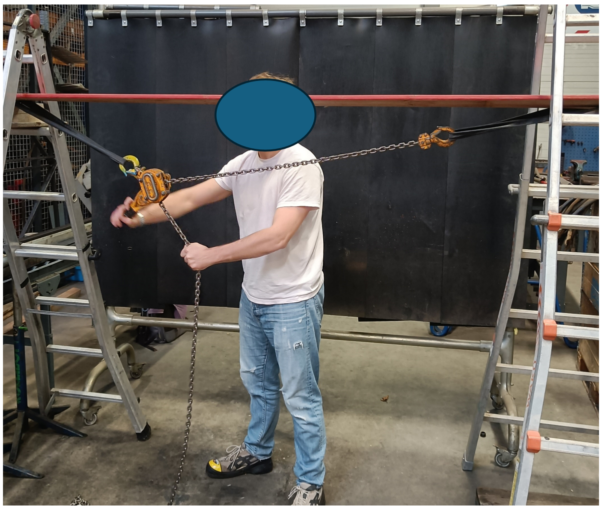


Figure 12.9: A subject performing task 5.1

12.3.1. Simplifications of the movements

The tasks simulated real life tasks as closely as possible, but some simplifications had to be made. The worker did not stand on the working platform of a boom lift or another vehicle like in real-life working conditions. The contact wire used for task 4 was also made of rubber instead of copper, which resulted in a much lower weight. For the contact wire used for task 5, an inner tube of a bike was used, which allows much less tension in the contact wire. This also enables less force on the chain hoist.

12.3.2. Force estimation

As specified in chapter 11 two ways of simluating external forces are used: adding masses to the model and applying external forces in OpenSim. For tasks 1 to 3 a model with a mass attached rigidly to its hands is used. As the subject is not carrying the same load during the entire measurement, it is needed to combine results from different inverse dynamics calculations. For task 4 no mass or external force is accounted for as the external forces are relatively low. For task 5 the force that is required to tension the inner tube is measured with a luggage scale. The direction of the force was chosen to be the direction perpendicular to the surface that is spanned between the two markers at the wrist and one at the elbow, pointing in the direction of the body. How exactly this is calculated is shown in appendix E.3.

12.3.3. Results

From the measurements of the construction tasks, results on the joint angles and joint moments are obtained. The measured joint angles and filtered joint angles are presented for the shoulder and elbow joint during task 3, ”Installation of a clamp on a pole”. The joint moments during this task are also presented. The shoulder and elbow moments are shown during Task 5, ”tensioning the contact wire”. Finally, the maximal and mean absolute values for the shoulder and elbow joints are shown for all five tasks.
In appendix D all other results from the measurements of the five different tasks are shown.

Joint angles

The results for the joint angles during the task ”Installation of a clamp on a pole on top of a top bar” are shown in figure 12.10. It is seen that the unfiltered data sometimes behave quite jumpy because of noise in the measurements. The filtered data show much less noise. As specified before, all data are filtered with a 2 Hz cutoff frequency Butterworth filter. In appendix D.1 it can be seen what is the preserved signal power after filtering.

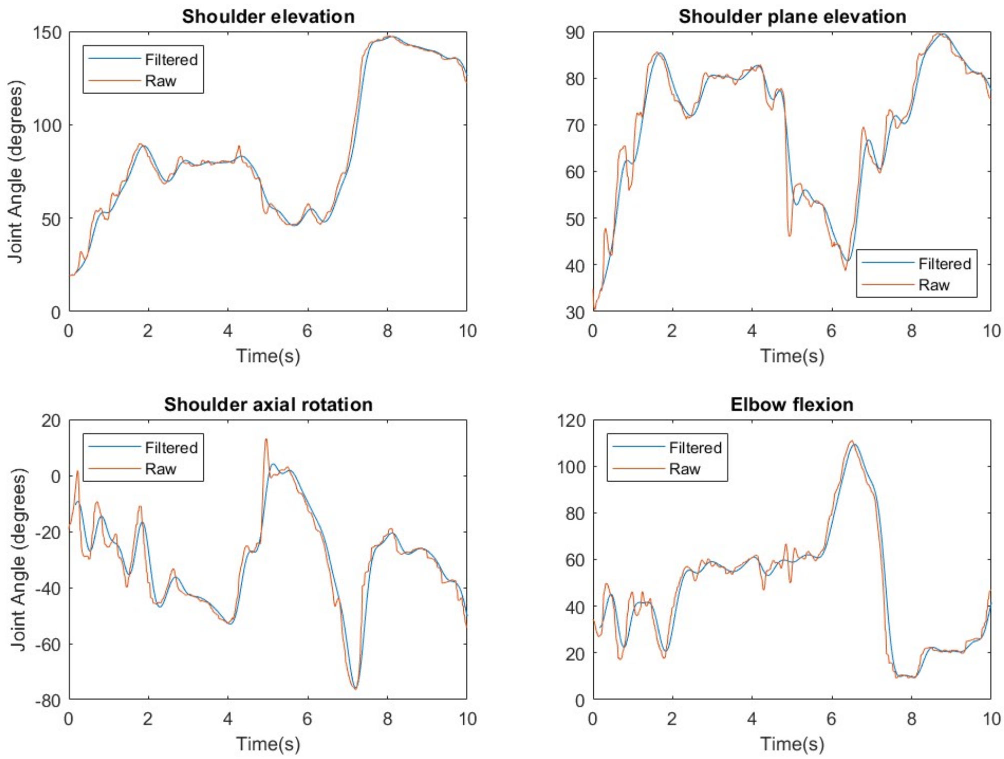


Figure 12.10: The joint angle during task 3 plotted versus time for the filtered and unfiltered signals from OpenCap. Blue indicates the filtered signal and oranje the unfiltered signal

Joint moments

In figure 12.11, the moments in the shoulder and elbow joint are shown during task 3, ”Installation of a clamp on a pole”. For this specific task, three models are used. The first model is the model with empty hands. The second model has a 5 kg weight in both hands. This is for when the 10 kg weighing clamp is grabbed. Then the model without additional weight is used again when the object is released. The third model is for when the subject is holding the drill. During that time the model with 2.5 kg added to the right arm is used. When drilling is performed, the model without added weight is used.

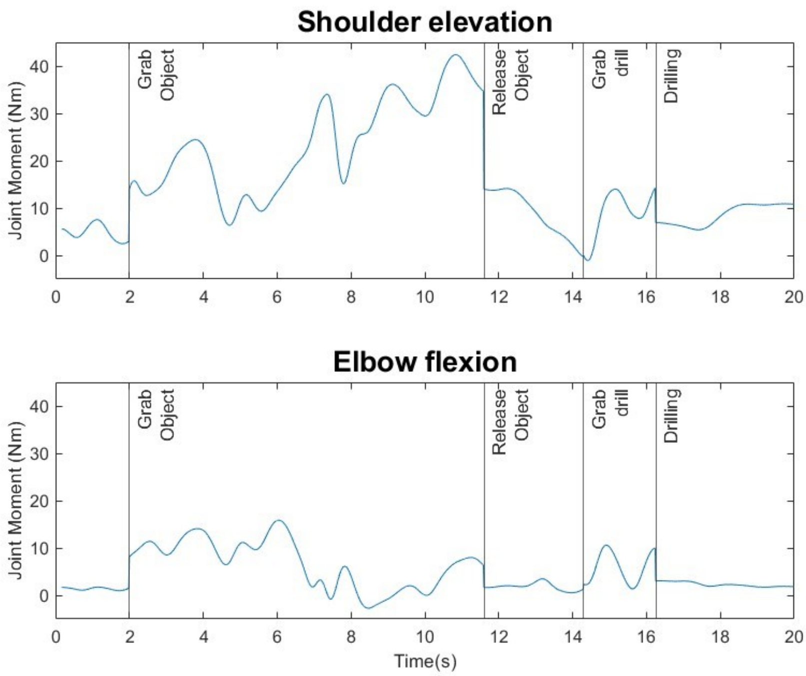


Figure 12.11: The shoulder elevation and elbow flexion moment plotted against time during task 3. With the vertical lines, several time stamps are indicated where the subject grabs or releases an object.

In figure 12.12, the calculated moments in the shoulder and elbow are shown from task 5, "tensioning the contact wire". Here, the shoulder plane elevation moment is also shown as this is more relevant for this task. It can be seen that the moments for shoulder elevation are still the highest. For this task, an external force is added to the model that only acts on the model when the subject is performing a pulling motion.

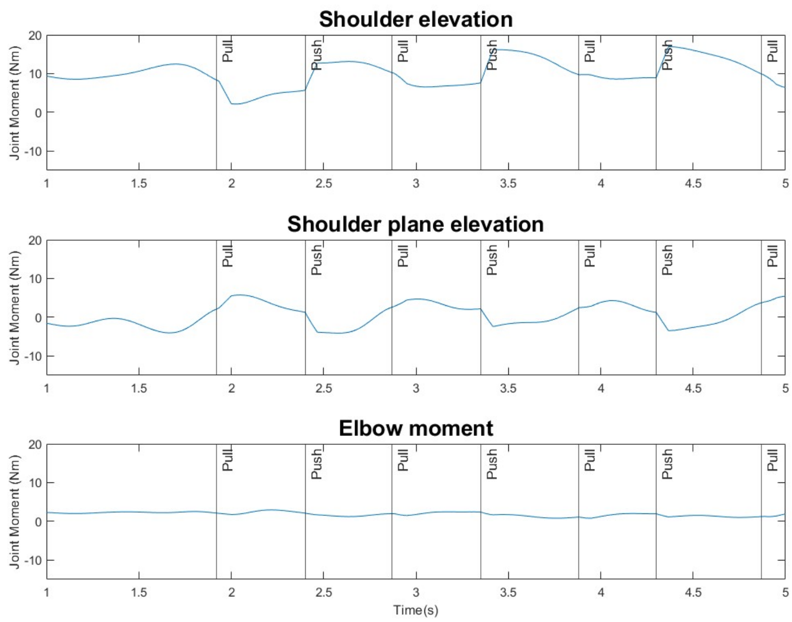


Figure 12.12: Shoulder elevation, shoulder plane elevation and elbow flexion momenets during a wire tensioning task.

The maximum moments during the five different tasks in the four degrees of freedom of interest are shown in figure 12.13. It can be seen that task 3 causes the highest moment in three of the four degrees of freedom. Also, it can be seen that for every task the shoulder elevation moment is the highest.

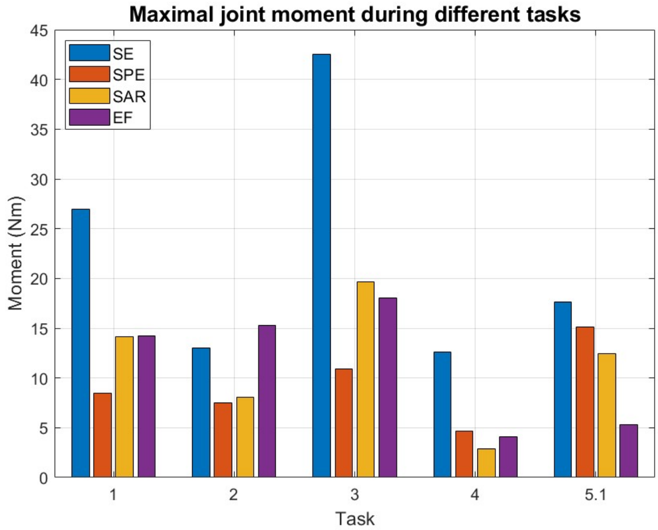


Figure 12.13: The maximal absolute value for joint moments during different tasks. The different DoF plotted are Shoulder Elevation (SE), Shoulder Pane Elevation (SPE), Shoulder Axial Rotation (SAR) and Elbow Flexion (EF).

Apart from the maximal moment during a task, the average of the moments delivered by the subject during a certain task is also of interest, as this tells more about the task as a whole. The mean absolute value moments during the five different tasks in the four different degrees of freedom of interest are shown in figure 12.14. Here can be seen that task 3 does not score highest in all different degrees of freedom. The shoulder plane elevation for example is higher for task 1 compared to task 3. Also, the elbow flexion moment is highest for task 2.

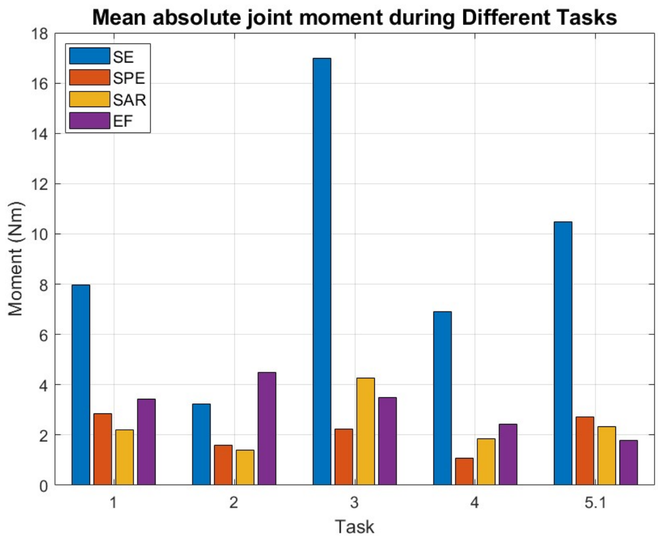


Figure 12.14: The mean absolute value for joint moments during different tasks. The different DoF plotted are Shoulder Elevation (SE), Shoulder Pane Elevation (SPE), Shoulder Axial Rotation (SAR) and Elbow Flexion (EF).

12.4. Evaluation design requirements

After performing the test measurements, the user and system requirements can be evaluated for the designed tool. Below, the user requirements are evaluated.

- Joint angle: The tool is able to measure joint angles. Elbow flexion and shoulder axial rotation is not measured with the desired accuracy.
- Joint angular acceleration: The tool is able to measure joint angular acceleration for several joints. However, it cannot be concluded whether the desired accuracy is achieved.
- Joint moment: The tool is able to estimate the joint moment. However, it cannot be concluded whether the desired accuracy is achieved.
- Construction work activities: All test tasks were effectively measured. Some tasks were less fit than others due to the occlusion of body parts.
- Object handling: The tool is able to incorporate tool handling to some degree. Object lifting is effectively modeled but other external forces are still manually added.
- Hardware: The hardware required is readily available at low cost.
- Software: OpenCap and OpenSim are free software packages. MATLAB is not free, but could be substituted by for example Python.
- Portability: All hardware required for measurements is portable in a single backpack.
- Setup time: The setup time, including calibration, takes about 15 minutes.
- Complexity: Most of the steps in the measurement process are straightforward. Data processing is not yet streamlined. As of now, this would require more extensive explanation.
- Environment: The tool was able to successfully take measurements in the storage facility. It was not tested if measurement at a construction site would be possible. Different height levels are likely to cause problems.
- Safety: The tool is completely safe to use for both subject and user.

The system requirements are a collection of general requirements and specific OpenCap and OpenSim requirements. For each subsystem, the setup requirements are evaluated. Starting with subsystem 1, markersless MC.

- Cameras: By using iPhones that were released in or after 2018, the requirement for the cameras is met.
- Stable underground: The floor in the storage facility where the measurements were made is flat and did not cause any problems.
- Tripods: Tripods available at Strukton were used. Phone clamps were bought.
- Capture volume: When the cameras were strategically placed, it was not problematic to keep the subject in the captured volume during the tasks.
- Clear line of sight: During test measurement, it was not a problem to maintain a clear line of sight between the camera and the subject.
- Subject clothing: During measurements, the subject was wearing a black sweater, which did not cause any problems.
- Light: Lighting was not a problem in the storage facility.
- Camera angle: It was possible to apply the recommended angle between the frontal line of the subject during the measurements.
- All body parts visible: during several moments of the measurements, an arm would not be visible by one of the two cameras. This did not cause significant errors in the measurements.

Below, the requirement evaluation of the system requirement for subsystem 2, modeling, is shown.

- Inverse dynamics: The OpenSim software was able to perform inverse dynamics on the kinematics from OpenCap.

- Data flow: As could be seen in the data processing section, the data flow needs more streamlining.
- Output graphics: Several different output graphics were made with the possibility of many more.
- Different human models: Different human models were used without problems.
- External forces: External forces were implemented mainly manually. The accuracy of the external forces and their influence on the inverse dynamics have not been validated. The luggage scale used here is also easily available.
- Understandable: The OpenSim software is quite easy to understand and has good documentation. The coding for data processing is not yet streamlined.
- Laptop hardware: The hardware required for the OpenSim is satisfied by almost every laptop. The 7 year old HP laptop used here had no problem.
- Processing software: Here, MATLAB was used for processing. This could be substituted by Python to make it more accessible.

13 Discussion

The tool presented in this work uses markerless motion capture and modeling to enable in situ biomechanical analysis of workers during construction tasks. The tools consist of a subsystem for the motion capture of movements during construction tasks and a subsystem for analyzing these kinematic data with a human model. This tool has shown to be usable in almost real in situ situations. A worker performing simulated rail caternary construction tasks is measured, and data from the joint angles and estimated joint moments are gathered. Although the measurements are not fully validated, sanity check measurements are also performed to validate if the measurements make sense. Several aspects of the tool might need further refinement, such as the external forces that are added and the low-pass filtering that is applied. The tool has a relatively high ease of use and limited hardware requirements. This shows the potential for the tool to be used on a larger scale. However, some practical issues, such as occlusion and measuring on a boom lift, still pose problems. In this chapter, the results of this thesis part are discussed and conclusions from the results are drawn. Several recommendations are made for the improvement of the tool. Lastly, the results are compared to the literature, and a potential application of the tool is shown.

13.1. Test results

In the chapter on tool validation, the test setup is shown and several different test results are shown. The test setup was carried out in relatively little time and required no more than a little free space and some spare construction materials. The tasks simulated in this environment are tasks from real construction work activities.

The results of the measurement of the control movements show that the OpenCap software is not equally effective in measuring all the angles of the joints. Where bigger movements such as shoulder flexion and abduction do not seem to pose a problem, smaller movements such as pronation and axial rotation of the shoulder are not measured accurately. This could be explained by the orientation in which the movements are performed in relation to the camera. Another explanation could be that the OpenCap model is not trained in the movements of construction workers.

From the construction task measurements, the recorded joint angles and joint moments are shown in the results. The joint angles measured for the shoulder and elbow joints seem to be within the normal range of motion of a human. Comparison of the recorded video with the measured angles also does not point out any strange values. Sometimes when an arm is not in the image for one of the cameras, unexpected displacement takes place due to occlusion, but this is seen rarely. The unfiltered movement data contain quite some noise. However, most of the noise in the measurements seems to be suppressed by the low-pass filter that is applied. A 2 Hz butterworth filter is applied as human movements are normally in the 1 Hz regime.

Considering the joint moments that are calculated in OpenSim, the results also correspond to expectations. When the objects that are handled by the subject are modeled, large shoulder moments are seen. During a task where a subject is required to lift a 10 kg object above shoulder height, a maximum shoulder moment of 40 Nm is seen for the right shoulder. A quick calculation confirms that lifting 10 kg

straight in front of your body already requires approximately 35 Nm per arm, with an average human arm of 70 cm. With the addition of dynamic forces this could very well be around 40 Nm for a task like this. The dynamic forces are expected to be smaller than the static forces in tasks like these as movements are relatively slow.
From these results, the maximal and mean absolute values of the moments in the shoulder and elbow joints can also be calculated. This can tell a lot about the overall physical demand of a certain task, allowing comparison between different construction tasks. From the results here it could be concluded that the tasks where a heavy clamp is installed on a pole is the most demanding for the subject both in maximal and mean absolute value. It is subject to further research how these values could be used to objectively compare different tasks, as other factors like the duration and repetition of a certain task should also be considered.
Overall, promising results are shown for the measurement of relevant construction tasks in a controlled environment. However, the results shown here should be subject to more validation with, for example, EMG measurements. In addition, a measure for effectively defining the amount of physical demand for a certain construction task from these measurements is still missing.

13.2. Design requirements and limitations

Performance requirements such as joint angles and joint moments are, as already mentioned, partially satisfied. More validation would be needed to confirm the accuracy of the tool. The construction tasks selected for the test measurements appear to fit the measurement, but other movements that induce more occlusion might prove difficult to measure. A general solution to implement the handling of any object has not yet been found. For now, the external forces have to be measured and added to the model manually.
With regard to more practical requirements, the hardware, software, portability, setup time, and safety requirements are met. The complexity requirements are not yet passed, as the tool is not as streamlined as could be yet. Integrating more of the software and coding into a single program could help with this. The environmental requirements are also not met as the only environment tested here was inside of the storage facility. Measurement on a real construction site could still prove difficult.
Regarding the system requirements for subsystem 1 most are satisfied. In the controlled environment, it was relatively easy to satisfy requirements such as lighting, a clear line of sight, and stability under the ground. However, requirements might pose problems when the tool is used under different conditions. The occlusion of body parts for cameras might also pose more of a problem in a more dynamic measurement environment. Further research on how these requirements can be satisfied would be recommended. Other measurement methods, such as wearable sensors, might impose less demanding system requirements. Regarding the system requirements for subsystem 2 also most requirements could be satisfied. The ease of use might need to be increased for effective use. In addition, the implementation of external forces is still rather complex and labor intensive. The use of a 3D force sensor might improve this process, but it will probably remain a difficulty for these types of measurements.

13.3. Comparison with literature

OpenCap is relatively new; thus, there are only a couple of validation studies [36] [32]. As OpenCap has been designed with a focus on studying the lower extremities, these studies focus only on the validation of hip, knee and ankle joints. As mentioned in the introduction, several studies are found in the literature focused on developing a tool with a similar goal. Here, some of the earlier presented results are compared with results from the literature. Seo et al. performed a comparison study between several markerless motion capture systems and a validation marker motion capture system. A multicamera-based approach is used that is quite similar to the method used for the tool developed in this thesis. In this research arm-raising to the side and front shows quite realistic values while larger errros are shown for elbow bending. This is comparable to the validation tests performed in this thesis, where shoulder elevation and shoulder flexion correspond well to the validation data, and elbow flexion had a larger offset from the validation results. The axial rotation of the shoulders and the pronation of the forearm are not measured in the study by Seo et al [37]. In a study by Wang et al. a computer vision method is used to perform a static biomechanical analysis of the shoulder and elbow joint during lifting tasks. Here, a 10 kg box is lifted and moved to a higher position. A maximum right shoulder moment of 30 Nm is reported. For the right elbow, a maximum moment of 15 Nm is reported. In the results presented in

this thesis, 40 Nm is reported as the maximal reported moment for the shoulder and 15 Nm for elbow flexion. The difference in shoulder moment might be explained by the dynamic forces that are taken into account in the biomechanical analysis used in this thesis. A notable difference between the studies is that Wang et al. use an insole to measure the physical load, while the tool uses estimated external forces [27]. Both studies report that the tools used could experience a greater error due to occlusion during in vivo measurements.
Overall, the tool developed in this thesis appears to perform relatively well compared to tools found in the literature. However, some factors reduce the degree to which this thesis could be compared to the results of the literature. The lack of quantitative measures such as the angular accuracy makes it hard to quantitatively compare the developed method here with methods in the literature. The tasks measured in this thesis were more complex compared to most tasks seen in the literature. Apart from this, no paper has been seen in which the angular acceleration is reported from a computer vision method.

13.4. Potential applications of biomechanical analysis tool

Two potential applications of the developed tool are presented in this section.

13.4.1. Automatization of Ergonomic risk assessment

An application of this tool that was also seen in the literature is the automation of the objective ergonomic risk assessment. The measured joint angles can be used to score each frame of the measurement with an ergonomic score. The REBA method uses four different regions of shoulder flexion to determine a score. In figure 13.1 it is shown how the measurements can be used to automatically score movements during a construction task. This result would suggest that this movement needs to be changed as too much ergonomic risk is present.

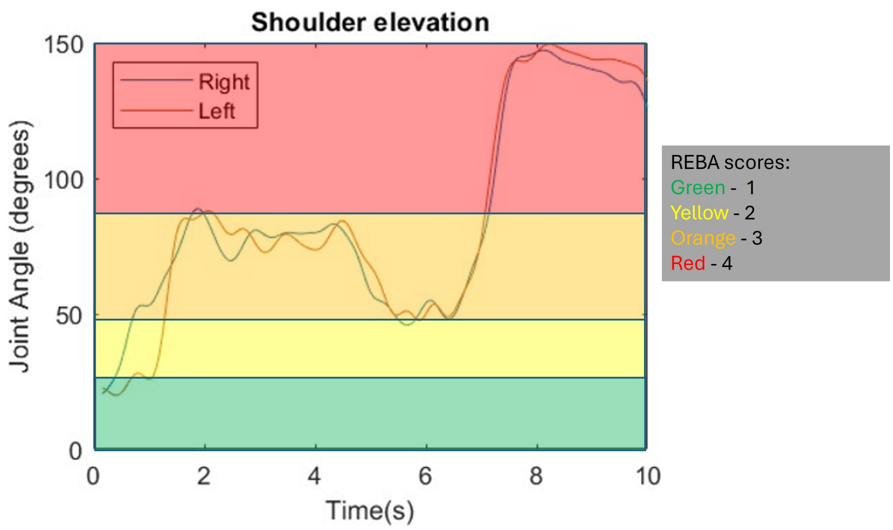
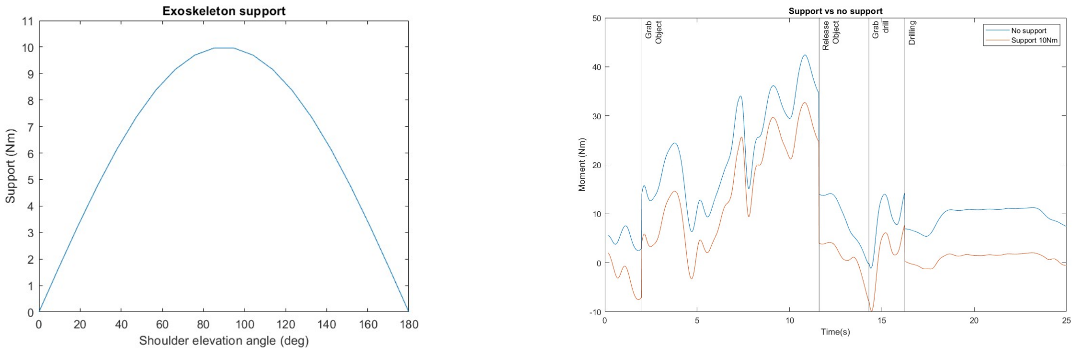


Figure 13.1: Shoulder elevation angle during task 3, installation of a clamp on a pole. The collored areas indicate the risk areas for a certain joint angle taken from the REBA method.

13.4.2. Evaluation of conceptual worker aids

A second potential application of the developed tool could be to evaluate certain worker supports prior to the actual design of the worker aid. This could be done by considering the joint moment required for a certain task and seeing how this moment changes when a virtual support is added. By, for example, adding the moment of a virtual exoskeleton with the support as shown in figure 13.2a to the measured joint moment, it can be seen if the total required joint moment increases or decreases. It can also be seen if the worker would have to counteract the support during a working task. When applying this support to task 3, ”installation of a clamp on a pole”, the remaining moment that the subject would need to apply can be shown in Figure 13.2b. The resulting maximal and mean absolute moments for

shoulder elevation during this task are shown in figure 13.3. As can be seen, both the maximal and the MAV moments would decrease by adding this support.
Several assumptions are made for this application. The first is that the movements of the subject would not change due to this applied support. Secondly, the support moment is now only added for one degree of freedom while in reality the support would not only be applied in this single degree of freedom. For this tool to be used for this application, further research on how such a support force would be incorporated into the model would be recommended.



(a) (b)

Figure 13.2: a)The support moment delivered by a virtual worker aid. b) The shoulder elevation joint moment during task 3 with and without worker aid.

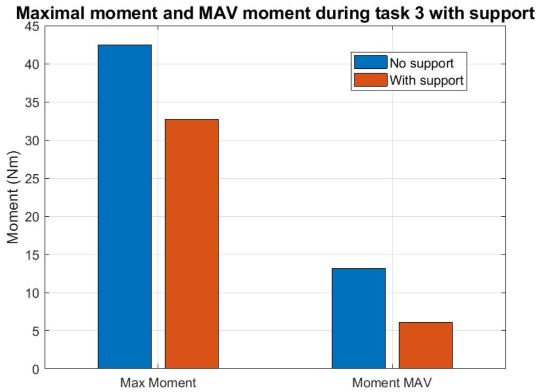


Figure 13.3: A comparison between the maximal joint moment and mean average value (MAV) joint moment during task 3 with and without added support.

14 Conclusion

This thesis part presents the development of a tool for in situ biomechanical analysis of construction tasks, designed to balance accessibility and accuracy. The tool uses minimal hardware and integrates OpenCap for markerless motion capture and OpenSim for human modeling, enabling the measurement of joint angles and moments during various tasks. While the tool performed well in controlled settings, translating its use to real construction sites remains a challenge.

The V-model guided the development process, starting from a clear problem statement and user requirements. The main goal was to create a tool capable of accurately measuring joint moments and angles while being easy to use in different environments. Pilot tests showed promising results, with accurate measurements of shoulder flexion and abduction angles, though elbow flexion and forearm rotation were less reliable. The joint moment results appeared realistic and aligned with the values reported in the literature, although limited validation and differing methodologies make comparisons difficult.

The tool met most accessibility and performance requirements, such as low cost and ease of use, but challenges such as lighting conditions and line-of-sight issues for cameras were noted for site measurements. These findings are consistent with the challenges reported for similar tools in the literature. More research is needed to validate the tool for in situ measurements, expand the testing to more construction tasks, and refine how external forces are incorporated into the model.

Potential applications for the tool include automating ergonomic assessment and evaluating the effectiveness of worker aids, such as lift supports, and identifying tasks that would benefit the most from automation or ergonomic improvements. While still in its prototype stage, the tool demonstrates potential as an accessible and efficient solution for biomechanical analysis in construction. Future work should focus on adapting the tool for real-world environments, which may involve exploring alternative motion capture methods that are less dependent on cameras.

15 General conclusion

The goal of this thesis was to identify which aspects of rail catenary construction work make it most physically demanding. To achieve this, a qualitative ergonomic risk assessment was conducted at Strukton alongside the development of a new tool for quantitative biomechanical analysis, focusing on rail catenary construction tasks.

The motivation for this research stemmed from the shortage of construction workers at Strukton, partly attributed to musculoskeletal disorders (MSDs). MSDs are the second leading cause of work leave in the Netherlands. Reducing the prevalence of these disorders could alleviate workforce shortages by improving workers' physical well-being. One key strategy is to lower the physical load on workers through the implementation of effective tools and worker aids. However, selecting the wrong tools may fail to address, or even exacerbate, the problem. Understanding the physical demands of the work and the origins of MSDs is therefore critical, and this study aims to provide insights through both qualitative and quantitative methods.

With methods like interviews, site visits, questionnaires and Strukton documentation, the qualitative ergonomic risk assessment identified several factors contributing to the physical demands of rail catenary construction. First, an overview of all performed tasks is created. Evaluation of these tasks revealed that heavy lifting, awkward postures, and prolonged static positions during specific tasks impose significant strain on workers. Additionally, challenging working conditions, such as walking long distances on uneven ballast, wearing heavy safety equipment, and working in confined spaces like boom lifts, further increase the physical load. Back, shoulder and ankle pain were the most commonly reported complaints among workers, potentially linked to awkward postures, heavy lifting and walking on uneven surface.

Although the assessment provided valuable insights, it had limitations, including a small sample size, subjective responses, and insufficient detail on what makes certain tasks physically demanding. Future research should expand the study to the broader Dutch rail catenary workforce, include detailed analysis of MSD cases, and adopt more quantitative tools for task ranking to complement qualitative findings.

Some recommendations are made for Strukton to reduce the physical demand of their workers, such as constructing sidewalks at worksites to ease walking on ballast, redesigning boom lift platforms for better posture support, creating ergonomically designed tool bags, and introducing electric tools for force-intensive tasks like wire cutting and tensioning.

The second part of this thesis introduced the development of a biomechanical analysis tool using OpenCap and OpenSim to measure joint angles and moments during simulated rail catenary construction tasks. Validation showed the tool produced realistic shoulder and elbow joint angles and moments in lab settings, although additional validation is required. While the tool met most ease-of-use requirements, limitations included camera occlusion, the manual addition of external forces, and less accurate elbow measurements compared to shoulders. Despite these challenges, the tool demonstrated potential for dynamic force analysis and measurement of In-Situ work tasks. Potential applications of this tool include automatization of ergonomic risk assessment and evaluation of concept worker aids.

Future research should focus on refining the tool by improving external force modeling, validating it in real-life work conditions, and training the OpenCap software for construction-specific tasks. Comparisons with sensor-based motion capture methods could also help enhance its accuracy and practicality in real-world settings.

This thesis makes several contributions to the fields of ergonomic risk assessment and biomechanics. It is the first to assess ergonomic risks in rail catenary construction. By integrating qualitative and quantitative methods, it combines subjective worker insights and observations with objective biomechanical data for a more comprehensive understanding of physical demands. The study also advances motion capture technology by adapting it for simulated real-world tasks, bridging the gap between laboratory research and field applications. Compared to prior studies, the developed tool offers a more dynamic and user focused perspective, hopefully in the future enabling quantitative assessment for a wider audience.

In conclusion, this thesis explores two key areas of ergonomic risk assessment in rail catenary construction work. The qualitative assessment identifies tasks and conditions that make the work physically demanding and provides actionable recommendations to improve working conditions. The quantitative biomechanical analysis tool shows promise for supporting ergonomic assessments through motion analysis and the design of new worker aids, by offering insights into joint loads during simulated tasks. While further validation is required, the tool represents a step forward in the use of biomechanical modeling for real-world applications. By addressing ergonomic risks and developing innovative tools, this thesis contributes to improving worker safety, health, and productivity in the rail catenary construction industry. Its methodologies and findings also have potential applications in other industries, paving the way for safer and more sustainable working environments.

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A

Work Breakdown Structure

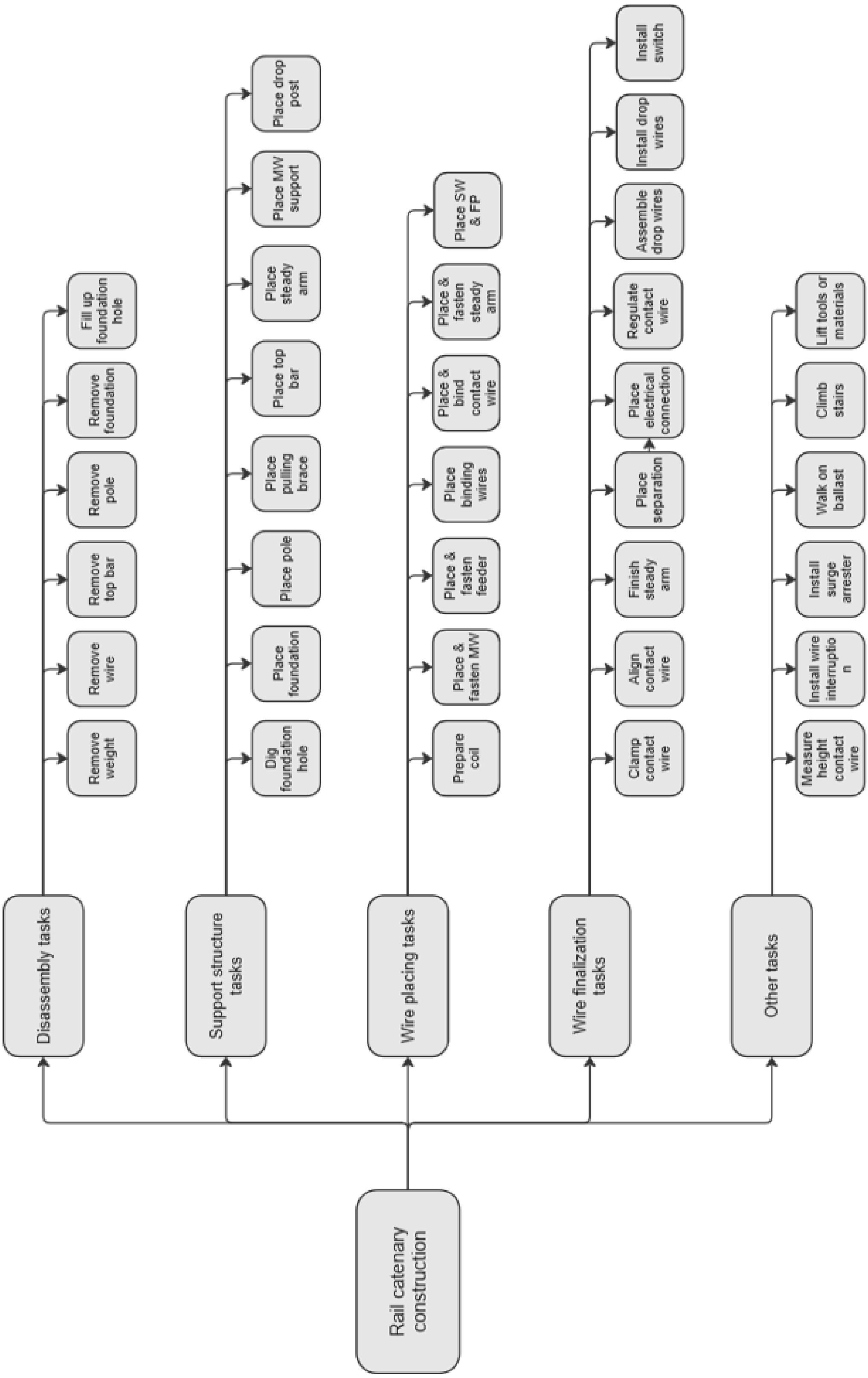


Figure A.1: Caption for your image.

B

Task score table

Task Nr	Task group	Task	Physical load score (1-5)	Duration score (1-5)	Frequency score (1-5)	Average score
1	**Support structure**	Dig foundation hole	3	2	5	3.3
2	**Support structure**	Place foundation	2	2	5	3.0
3	**Support structure**	Place pole	1	2	5	2.7
4	**Support structure**	Place pulling brace	3	2	2	2.3
5	**Support structure**	Place top bar	3	3	5	3.7
6	**Support structure**	Place cantilever	2	3	3	2.7
7	**Support structure**	Place drop post	2	2	3	2.3
8	**Support structure**	Place MW support	4	1	5	3.3
9	**Wire placing**	Do preparations	2	1	5	2.7
10	**Wire placing**	Place and fasten MW	3	2	5	3.3
11	**Wire placing**	Place and fasten feeder	4	1	5	3.3
12	**Wire placing**	Place binding wires	1	1	5	2.3
13	**Wire placing**	Place and bind contact wire	5	3	2	3.3
14	**Wire placing**	Place and fasten steady arms	3	2	5	3.3
15	**Wire placing**	Place SW and FP	1	2	3	2.0
16	**Wire finalization**	Clamp contact wire	1	1	5	2.3
17	**Wire finalization**	Align contact wire	1	1	4	2.0
18	**Wire finalization**	Finish steady arm	1	1	3	1.7
19	**Wire finalization**	Place seprations	4	3	2	3.0
20	**Wire finalization**	Place electrical connections	2	2	2	2.0
21	**Wire finalization**	Regulate contact wire	2	1	5	2.7
22	**Wire finalization**	Assemble drop wires	1	1	5	2.3
23	**Wire finalization**	Install drop wires	1	1	5	2.3
24	**Wire finalization**	Install swtiches	4	5	2	3.7
25	**Other**	Walk on ballast	2	4	5	3.7
26	**Other**	Install wire interruption	4	2	2	2.7
27	**Other**	Measure height contact wire	1	1	4	2.0
28	**Other**	Lift tools	5	2	2	3.0
29	**Other**	Climb stairs	2	1	4	2.3
30	**Other**	Install surge arrester	1	3	2	2.0
31	**Disassembly**	Remove weights	4	3	2	3.0
32	**Disassembly**	Remove wires	4	4	5	4.3
33	**Disassembly**	Remove top bar	2	3	3	2.7
34	**Disassembly**	Remove pole	1	3	3	2.3
35	**Disassembly**	Remove foundations	4	3	3	3.3
36	**Disassembly**	Fill up holes	2	2	4	2.7

Figure B.1: All tasks identified in the WBS with physical demand scores.

C
Worker questionnaire

Onderzoek naar ledemaat klachten bij draagconstructie en bovenleiding monteurs

12 antwoorden

Analyse publiceren

Ga je akkoord dat de resultaten uit deze enquête anoniem gebruikt mogen worden in mijn master thesis aan de TU Delft?

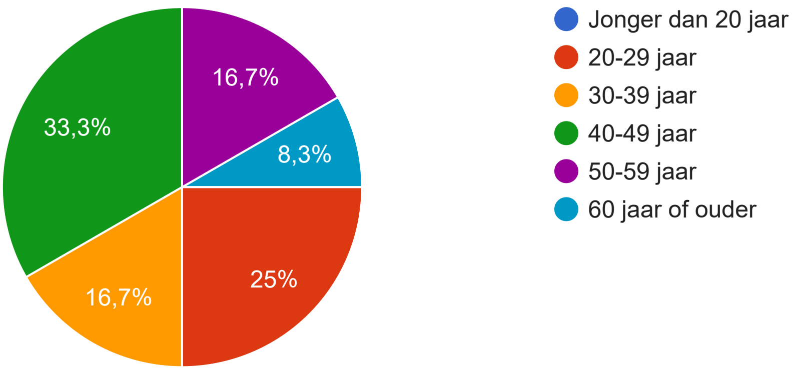
0 antwoorden

Nog geen antwoorden op deze vraag.

Wat is je leeftijd?

Kopiëren

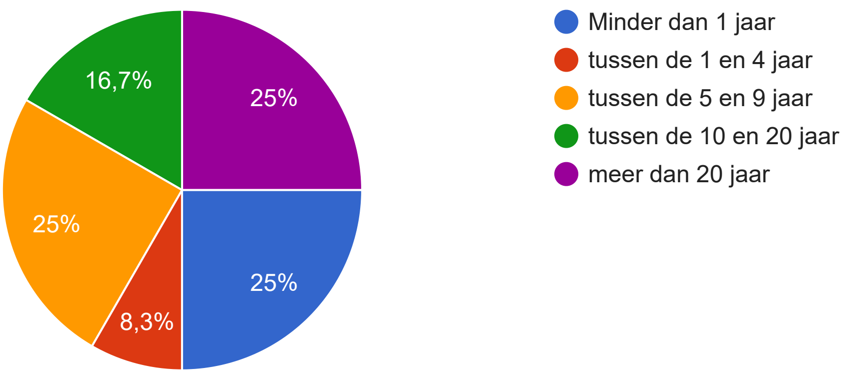
12 antwoorden



Hoeveel jaar werkervaring heb je in de bovenleidingen en draagconstructies?

Kopiëren

12 antwoorden



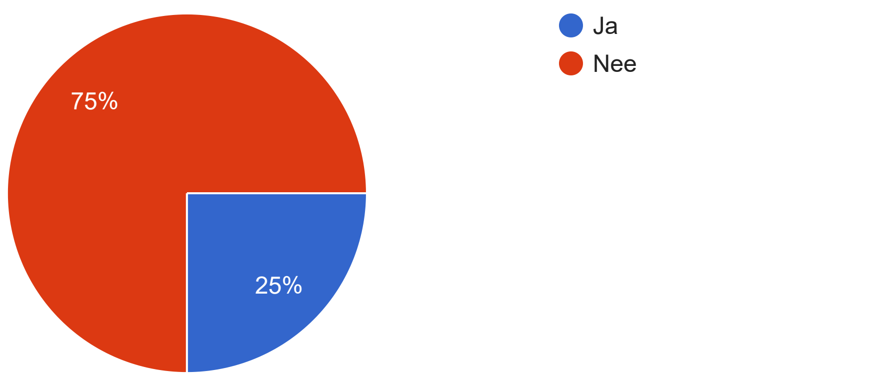
Uitleg ergonomie vragen

Nek

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je nek?

Kopiëren

12 antwoorden

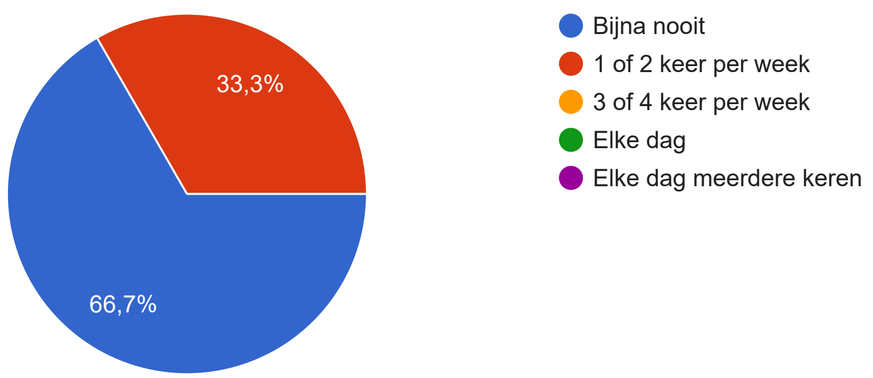


Nek klachten

Hoe vaak heb je last van je nek?

Kopiëren

3 antwoorden



Hoeveel last heb je op dat moment van je nek?

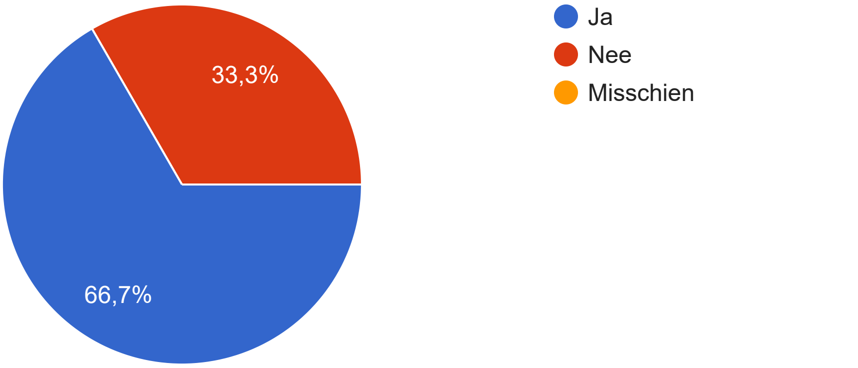
Kopiëren

3 antwoorden

Denkt je dat jouw klachten met werk te maken hebben?

Kopiëren

3 antwoorden

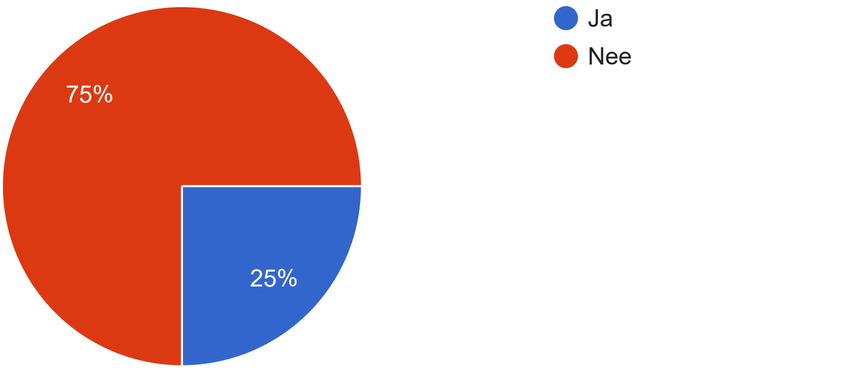


Linker schouder

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** schouder?

Kopiëren

12 antwoorden

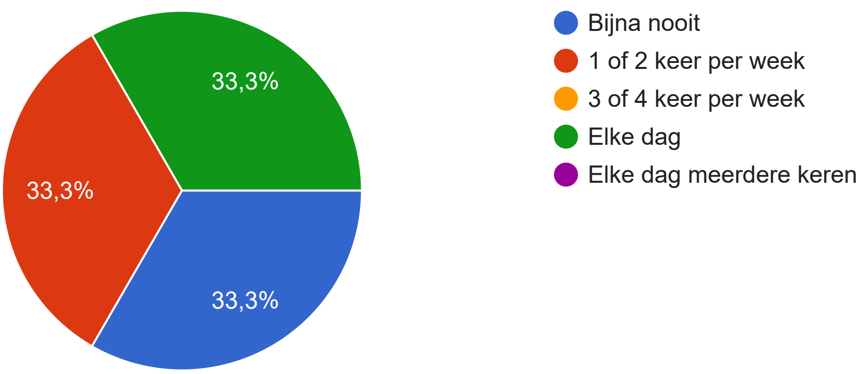


Klachten linker schouder

Hoe vaak heb je last van je **linker** schouder?

Kopiëren

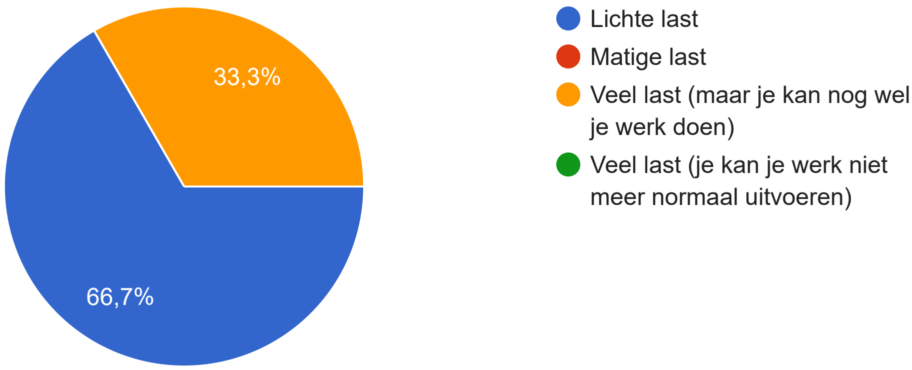
3 antwoorden



Hoeveel last heb je op dat moment van je **linker** schouder?

Kopiëren

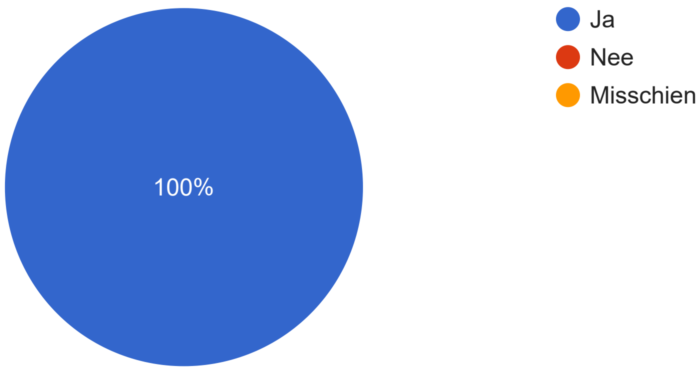
3 antwoorden



Denk je dat deze klachten met werk te maken hebben?

Kopiëren

3 antwoorden

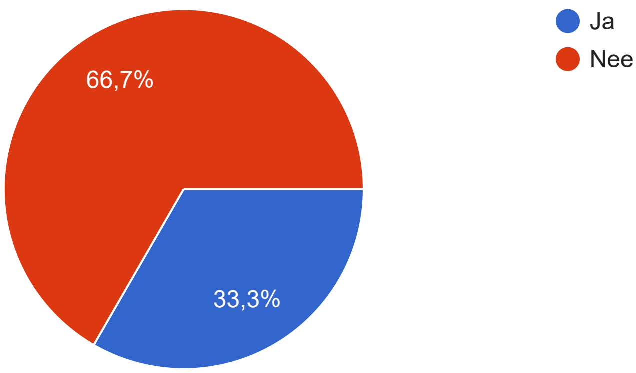


Klachten rechter schouder

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** schouder?

Kopiëren

12 antwoorden

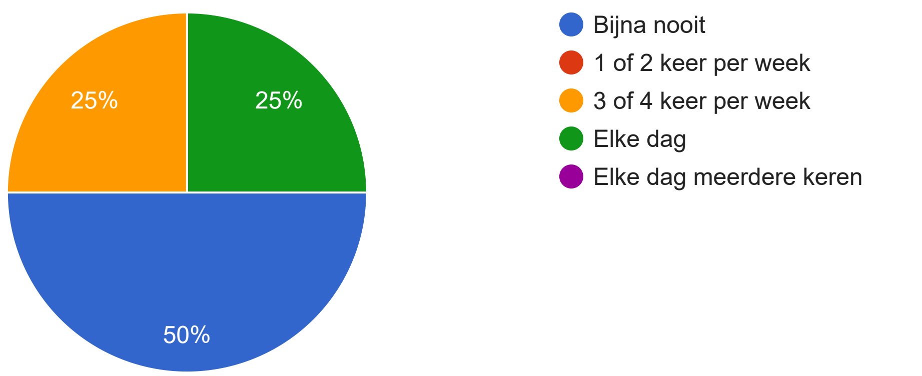


Klachten rechter schouder

Hoe vaak heb je last van je **rechter** schouder?

Kopiëren

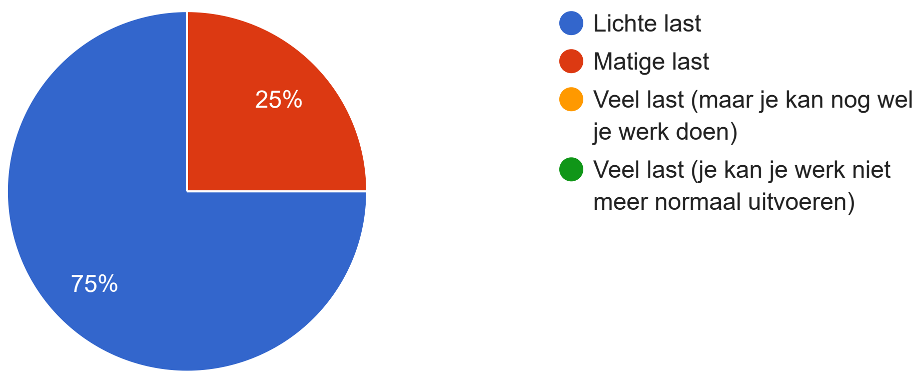
4 antwoorden



Hoeveel last heb je op dat moment van je **rechter** schouder?

Kopiëren

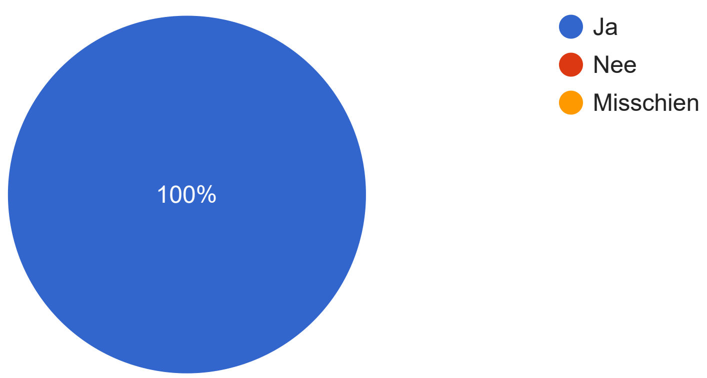
4 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

4 antwoorden

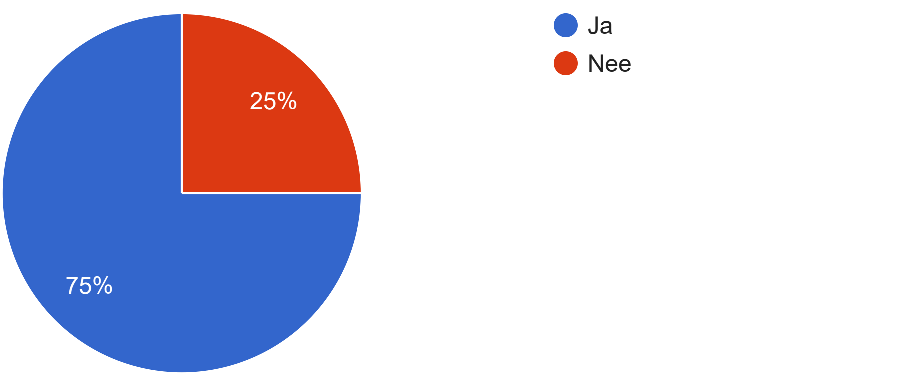


Rug

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je rug?

Kopiëren

12 antwoorden

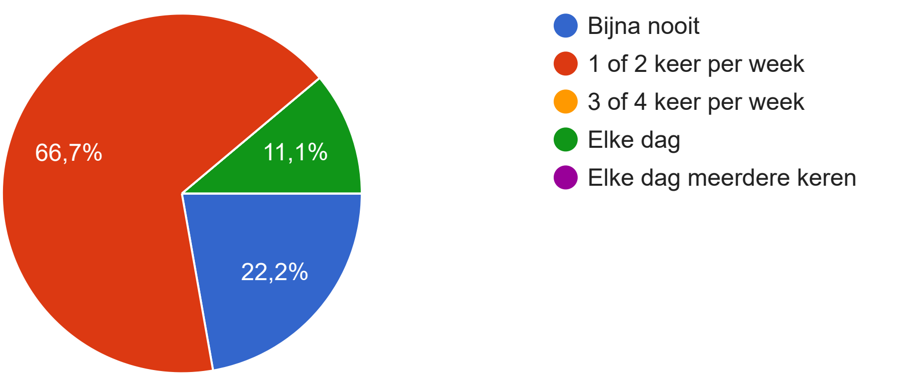


Klachten rug

Hoe vaak heb je last van je rug?

Kopiëren

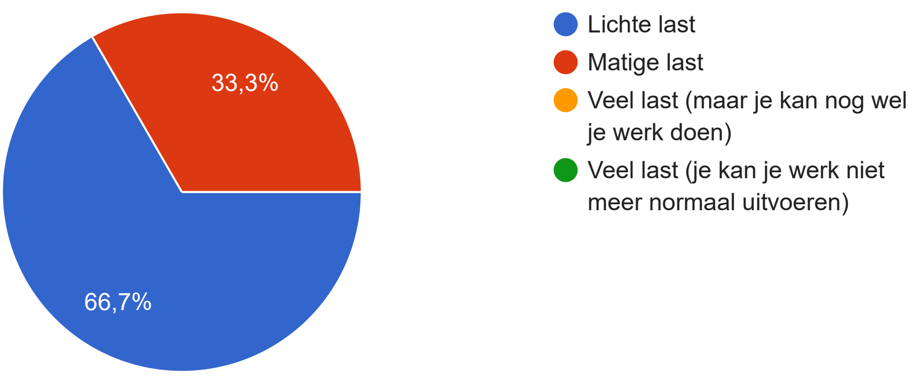
9 antwoorden



Hoeveel last heb je op dat moment van je rug?

Kopiëren

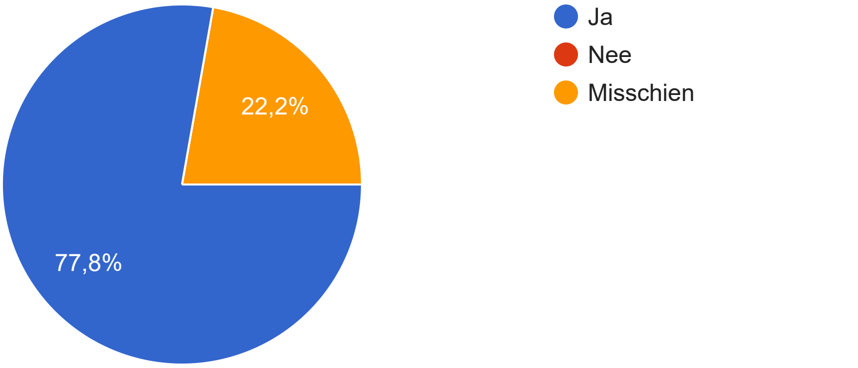
9 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

9 antwoorden

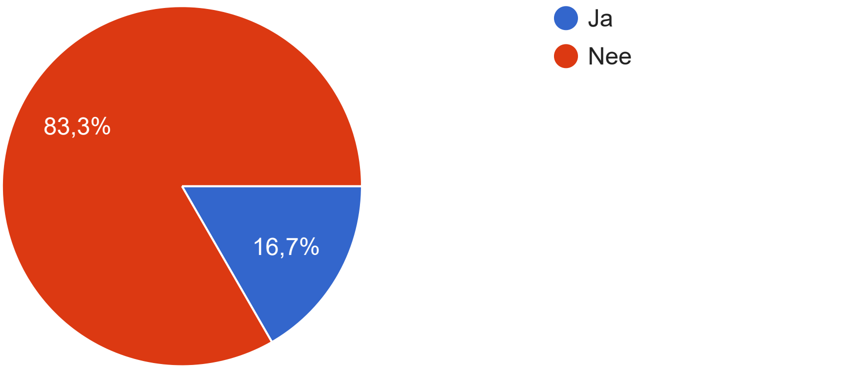


Linker elleboog

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** elleboog?

Kopiëren

12 antwoorden

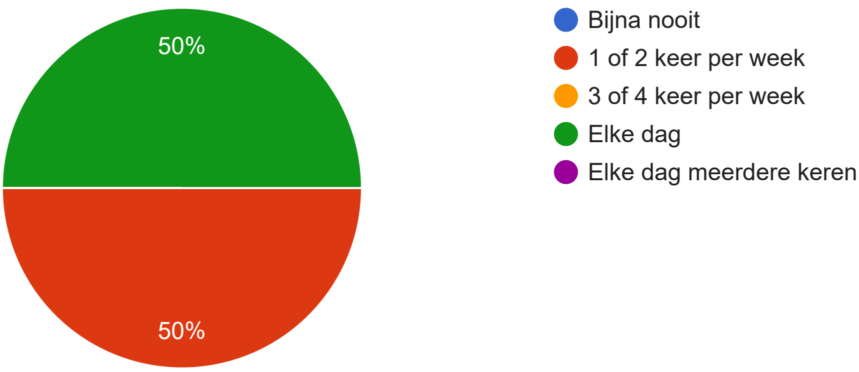


Klachten linker elleboog

Hoe vaak heb je last van je **linker** elleboog?

Kopiëren

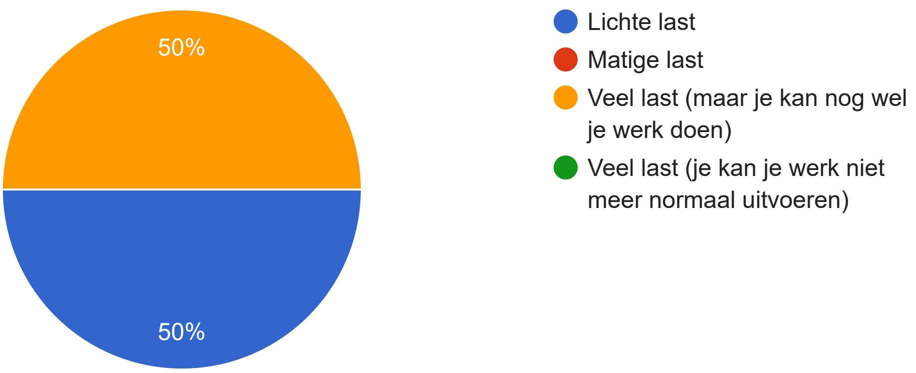
2 antwoorden



Hoeveel last heb je op dat moment van je **linker** elleboog?

Kopiëren

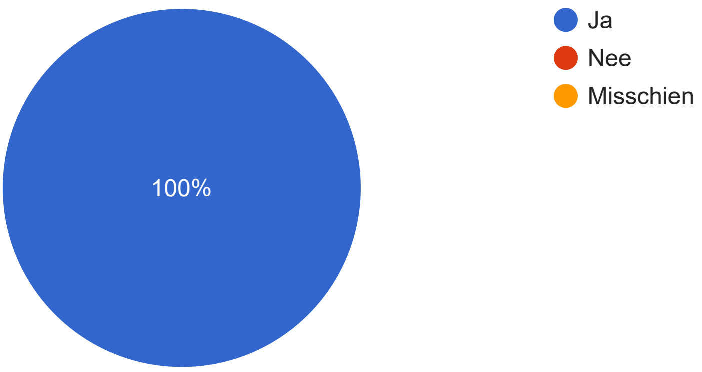
2 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

2 antwoorden

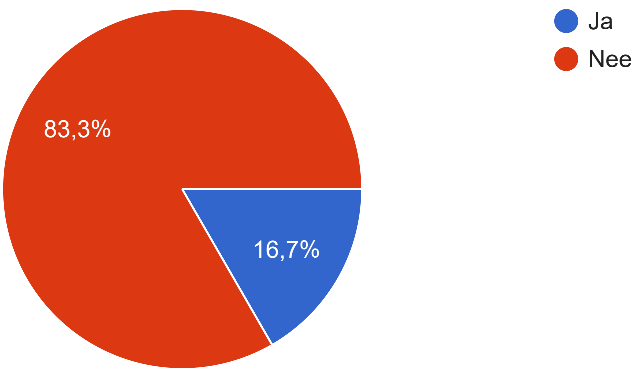


Rechter elleboog

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** elleboog?

Kopiëren

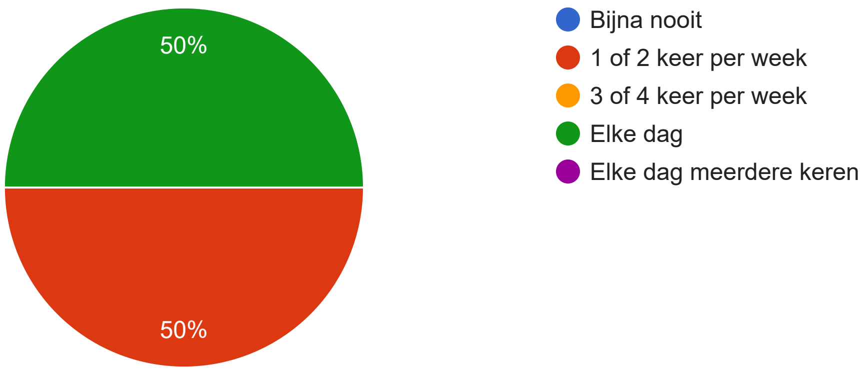
12 antwoorden



Klachten rechter elleboog

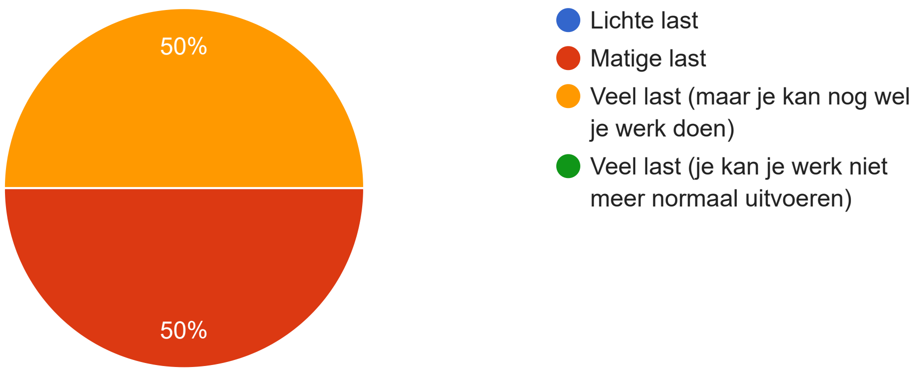
Hoe vaak heb je last van je **rechter** elleboog? Kopiëren

2 antwoorden



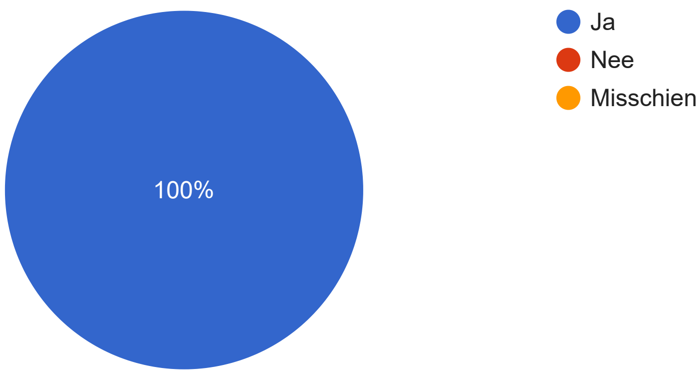
Hoeveel last heb je op dat moment van je **rechter** elleboog? Kopiëren

2 antwoorden



Denk je dat je klachten met werk te maken hebben? Kopiëren

2 antwoorden

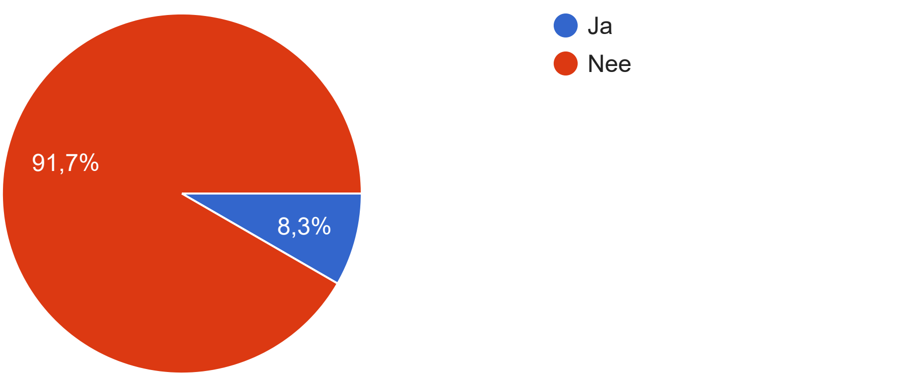


Linker pols/hand

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** hand/pols?

Kopiëren

12 antwoorden

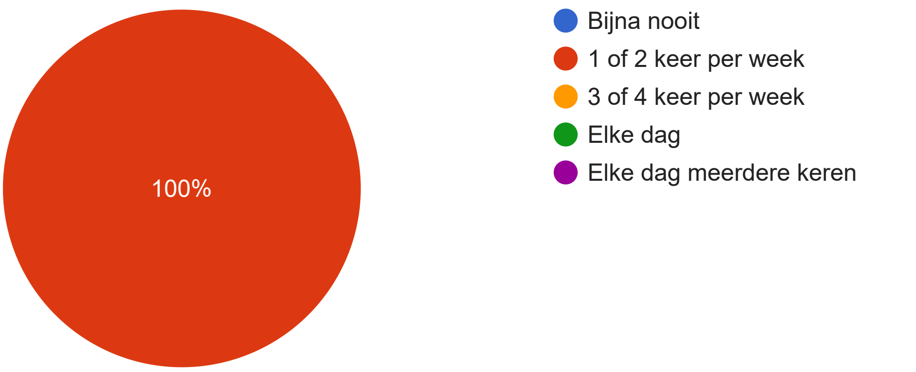


Klachten linker pols/hand

Hoe vaak heb je van je **linker** pols/hand?

Kopiëren

1 antwoord



Hoeveel last heb je op dat moment van je **linker** pols/hand?

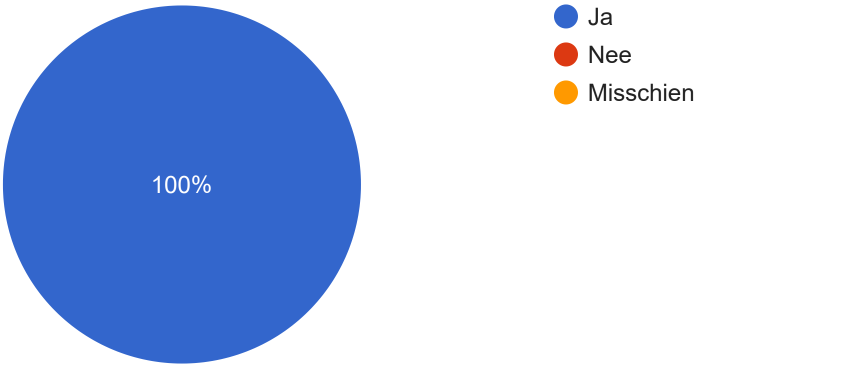
Kopiëren

1 antwoord

Denk je dat je klachten met werk te maken hebben?

Kopiëren

1 antwoord

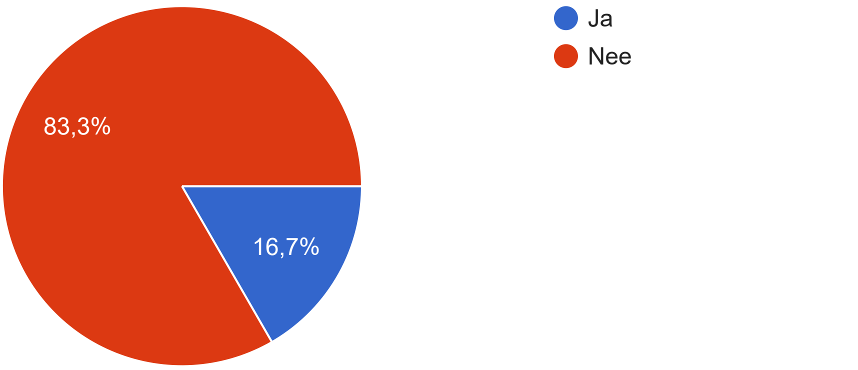


Rechter pols/hand

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** hand/pols?

Kopiëren

12 antwoorden

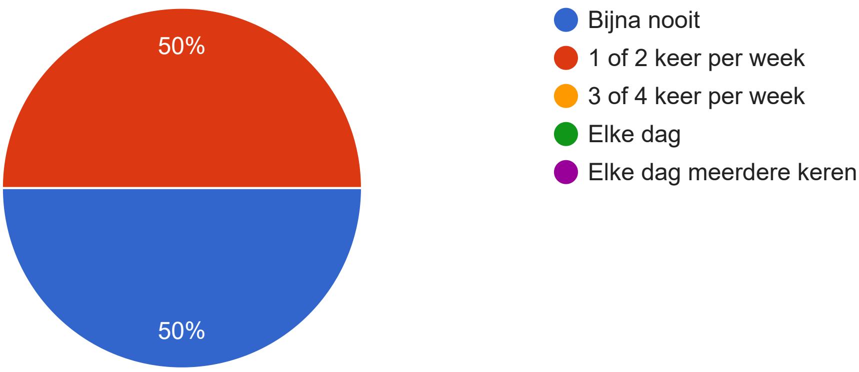


Klachten rechter pols/hand

Hoe vaak heb je last van je **rechter** pols/hand?

Kopiëren

2 antwoorden



Hoeveel last heb je op dat moment van je **rechter** pols/hand?

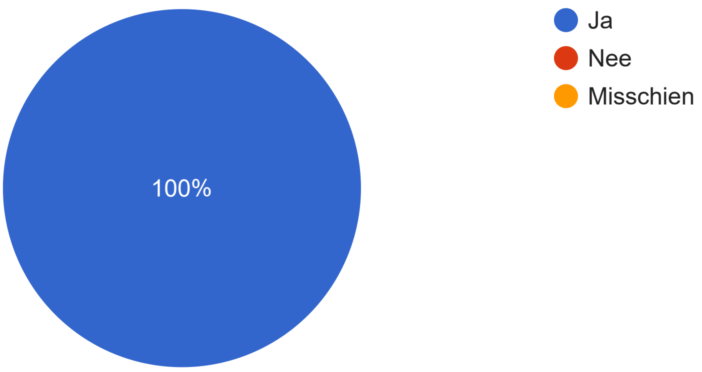
Kopiëren

2 antwoorden

Denk je dat je klachten met werk te maken hebben?

Kopiëren

2 antwoorden

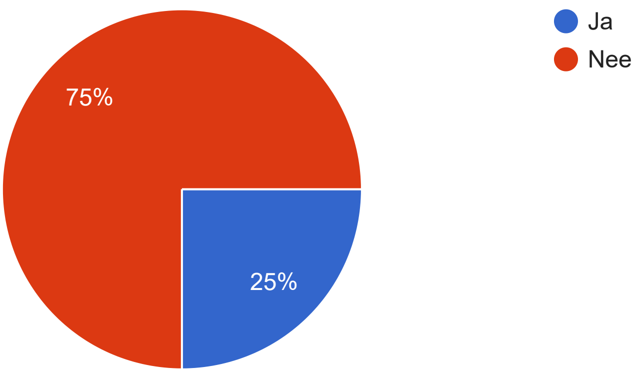


Heup

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je heup?

Kopiëren

12 antwoorden

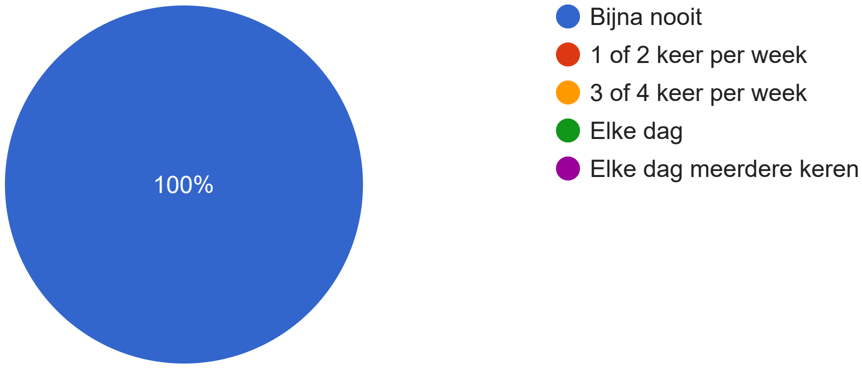


Klachten heup

Hoe vaak heb je ast van je heup?

Kopiëren

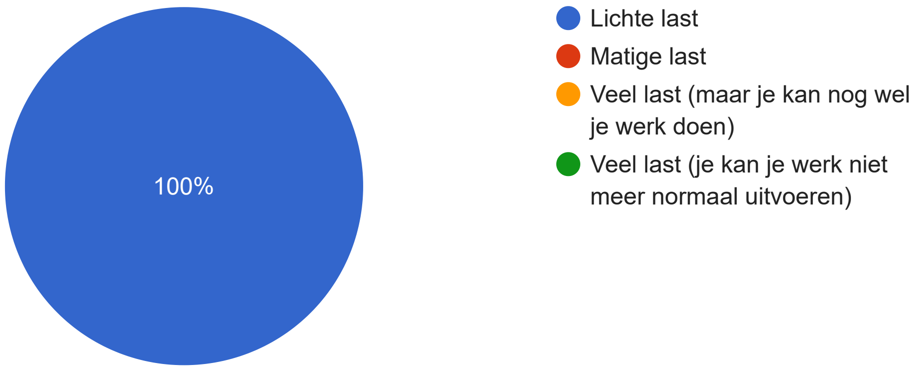
3 antwoorden



Hoeveel last heb je op dat moment van je heup?

Kopiëren

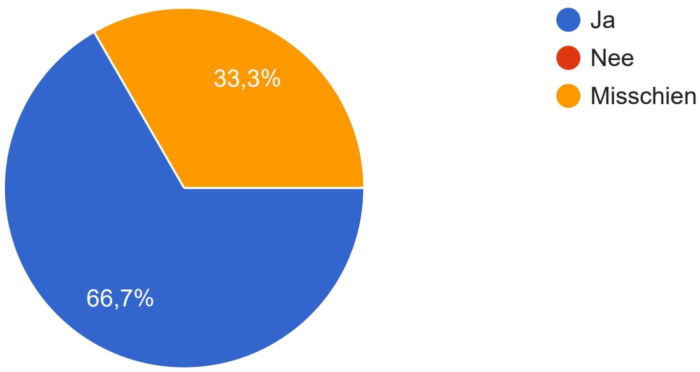
3 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

3 antwoorden

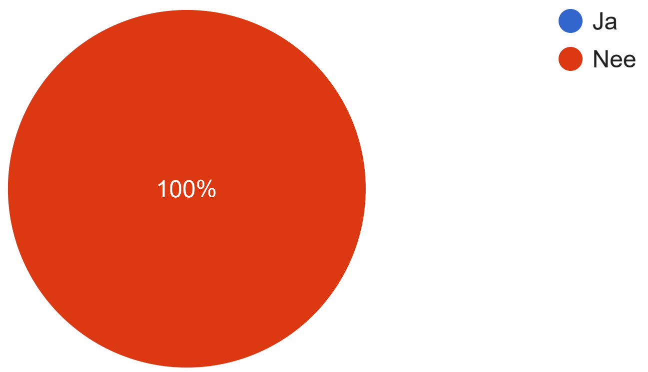


Linker bovenbeen

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** bovenbeen?

Kopiëren

12 antwoorden



Klachten linker bovenbeen

Hoe vaak heb je last van je **linker** bovenbeen?

0 antwoorden

Nog geen antwoorden op deze vraag.

Hoeveel last heb je op dat moment van je **linker** bovenbeen?

0 antwoorden

Nog geen antwoorden op deze vraag.

Denk je dat je klachten met werk te maken hebben?

0 antwoorden

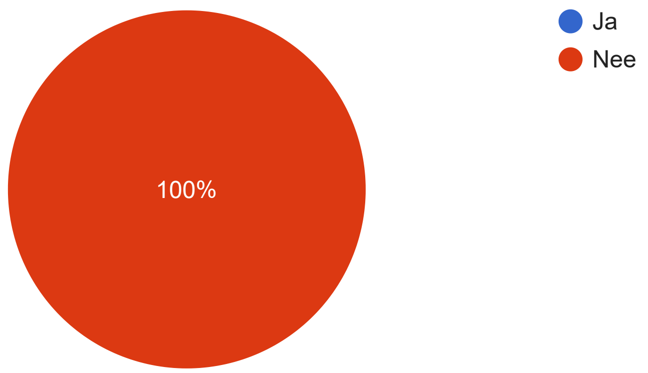
Nog geen antwoorden op deze vraag.

Rechter bovenbeen

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** bovenbeen?

Kopiëren

12 antwoorden



Klachten rechter bovenbeen

Hoe vaak heb je last van je **rechter** bovenbeen?

0 antwoorden

Nog geen antwoorden op deze vraag.

Hoeveel last heb je op dat moment van je **rechter** bovenbeen?

0 antwoorden

Nog geen antwoorden op deze vraag.

Denk je dat je klachten met werk te maken hebben?

0 antwoorden

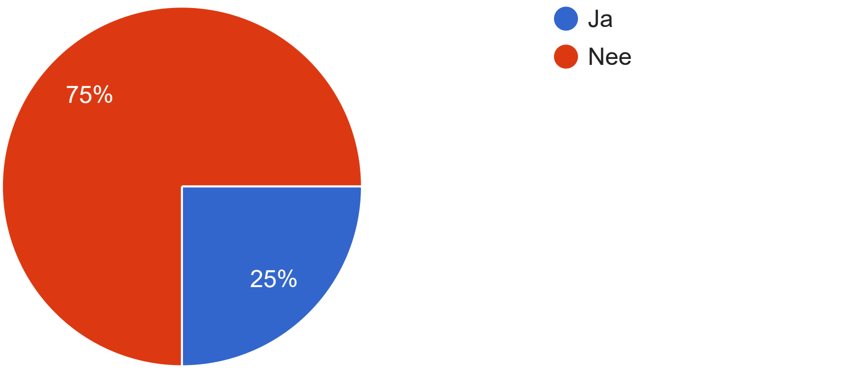
Nog geen antwoorden op deze vraag.

Linker knie

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** knie?

Kopiëren

12 antwoorden

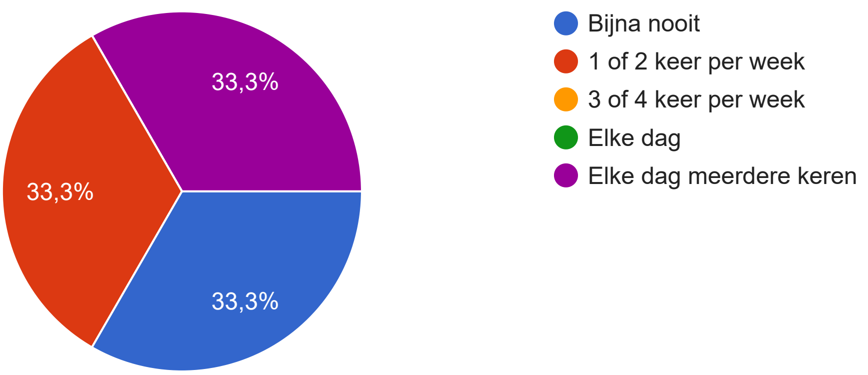


Klachten linker knie

Hoe vaak heb je last van je **linker** knie?

Kopiëren

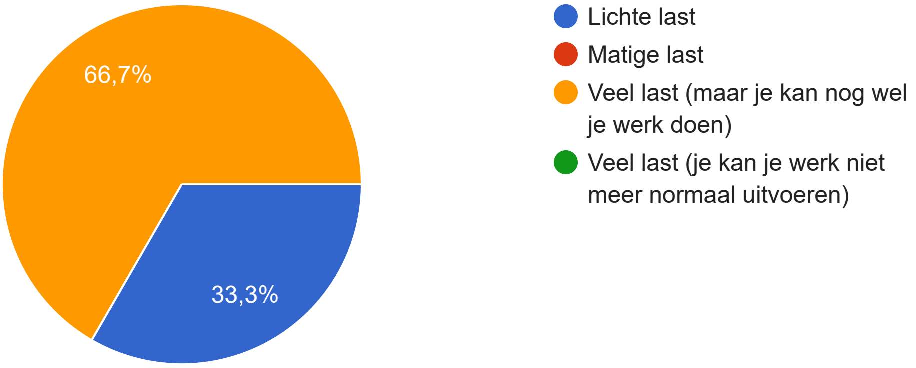
3 antwoorden



Hoeveel last heb je op dat moment van je **linker** knie?

Kopiëren

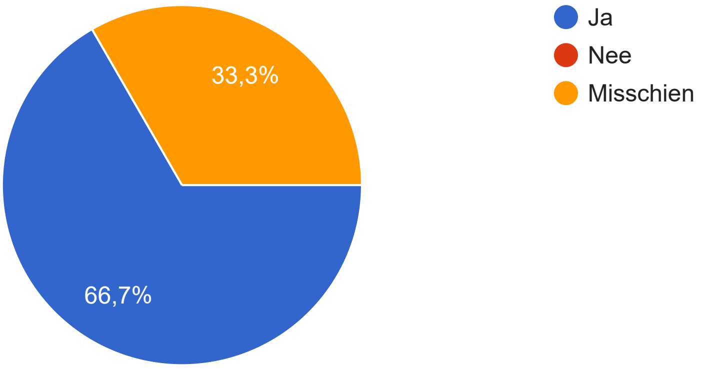
3 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

3 antwoorden

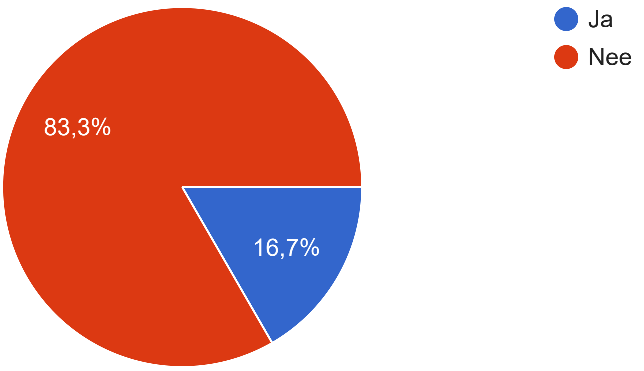


Rechter knie

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** knie?

Kopiëren

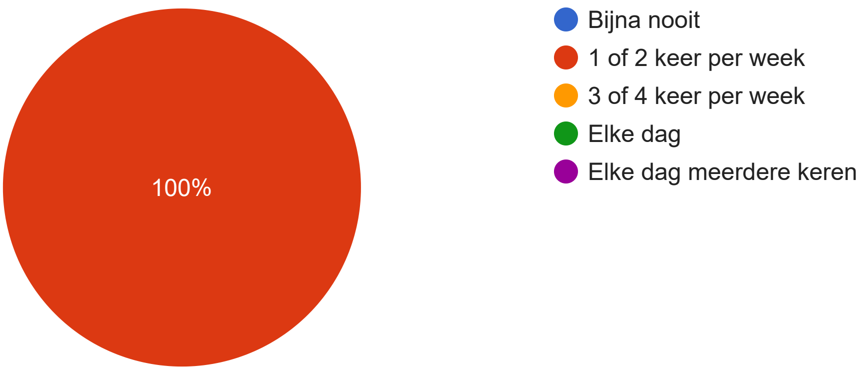
12 antwoorden



Klachten rechter knie

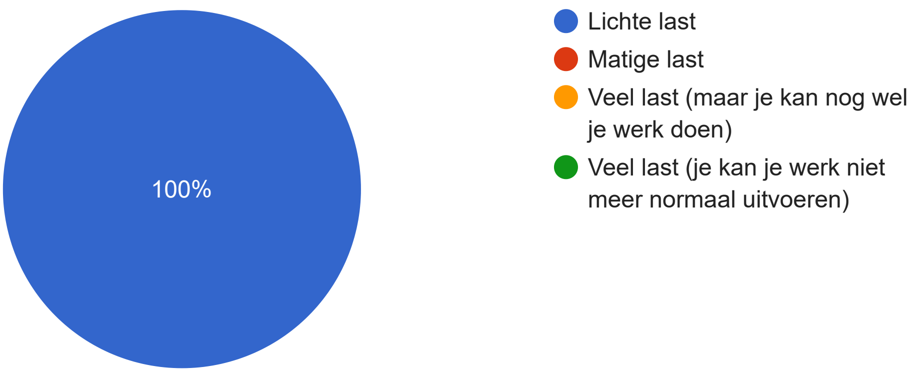
Hoe vaak heb je last van je **rechter** knie? Kopiëren

2 antwoorden



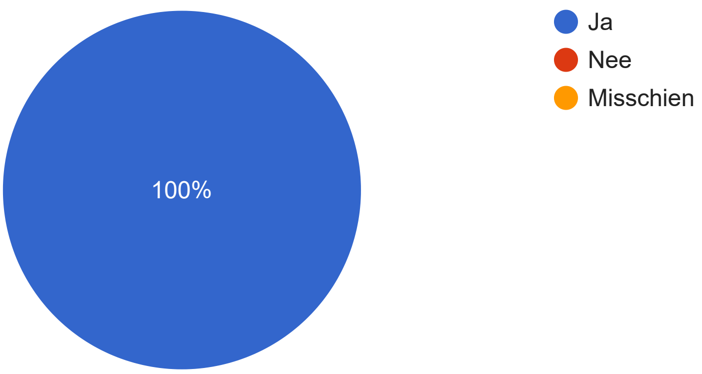
Hoeveel last heb je op dat moment van je rechter knie? Kopiëren

2 antwoorden



Denk je dat je klachten met werk te maken hebben? Kopiëren

2 antwoorden

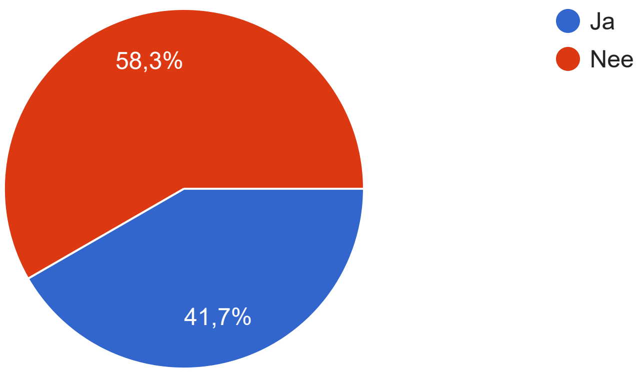


Linker enkel/voet

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **linker** enkel/voet?

Kopiëren

12 antwoorden

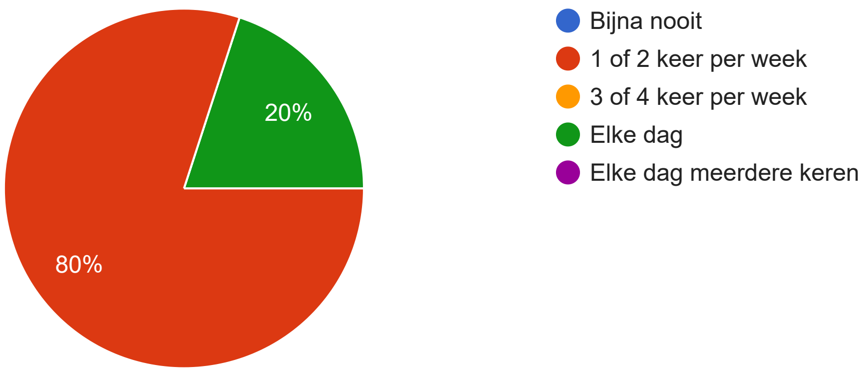


Klachten linker enkel/voet

Hoe vaak heb je last van je **linker** enkel/voet?

Kopiëren

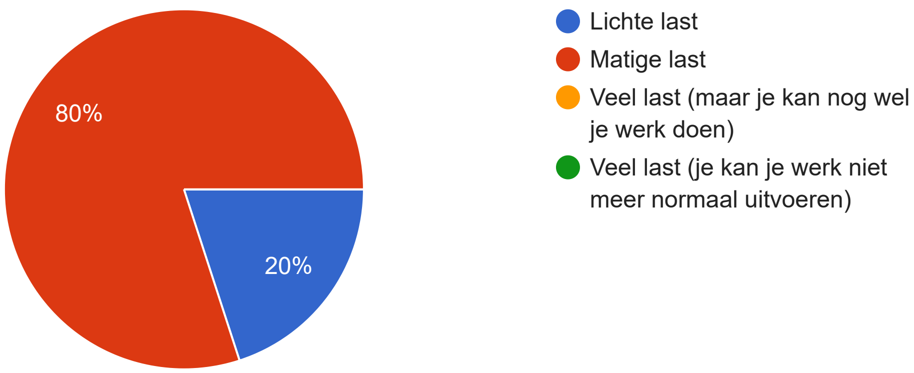
5 antwoorden



Hoeveel last heb je op dat moment van je **linker** enkel/voet?

Kopiëren

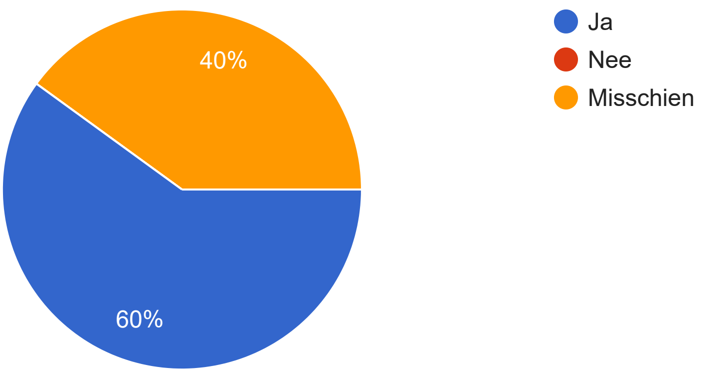
5 antwoorden



Denk je dat je klachten met werk te maken hebben?

Kopiëren

5 antwoorden

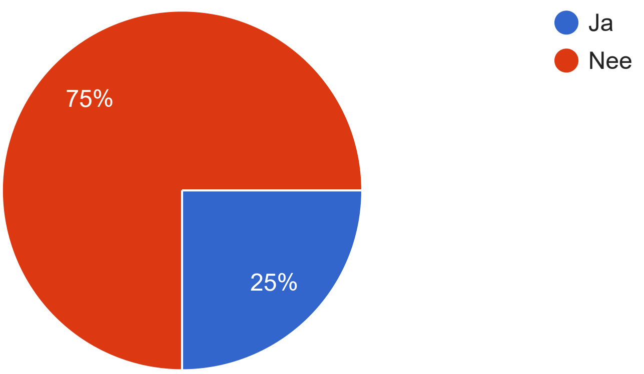


Rechter enkel/voet

Heb je in de afgelopen 12 maanden pijn gehad aan / last gehad van je **rechter** enkel/voet?

Kopiëren

12 antwoorden

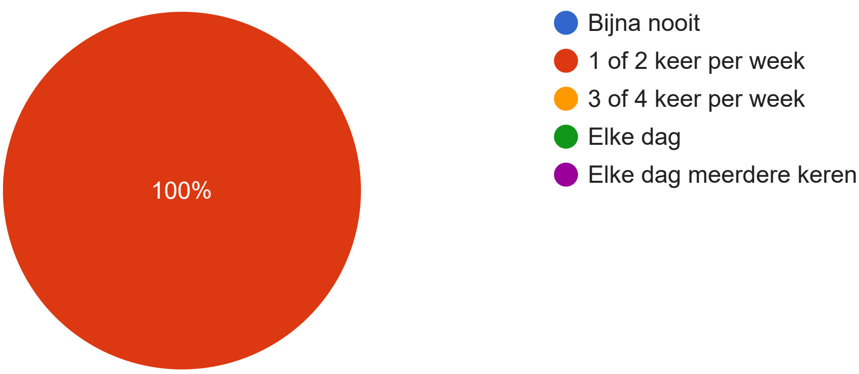


Klachten rechter enkel/voet

Hoe vaak heb je last van je **rechter** enkel/voet?

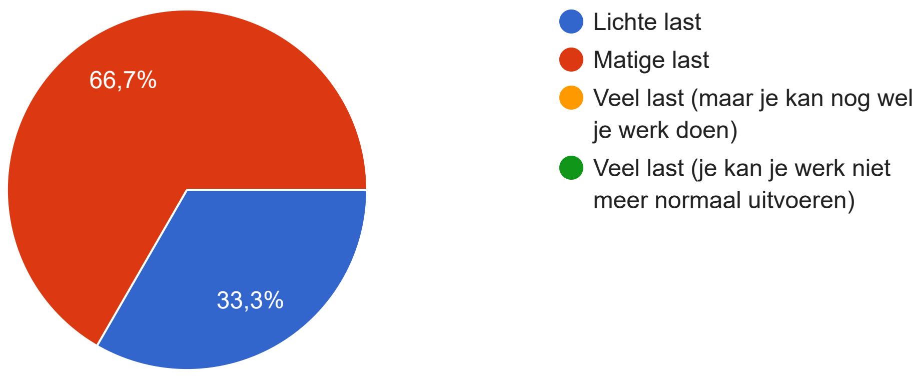
Kopiëren

3 antwoorden



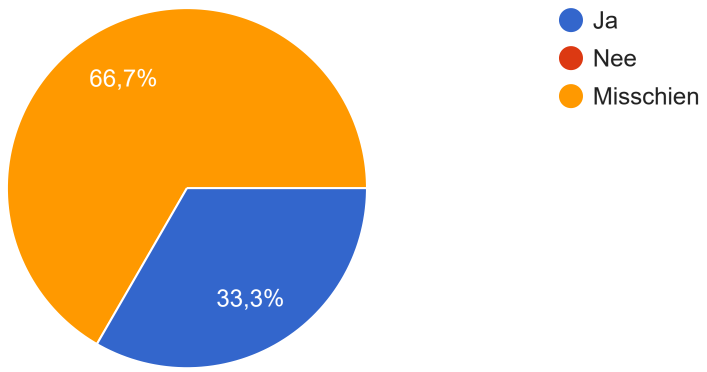
Hoeveel last heb je op dat moment van je **rechter** enkel/voet?

3 antwoorden



Denk je dat je klachten met werk te maken hebben?

3 antwoorden

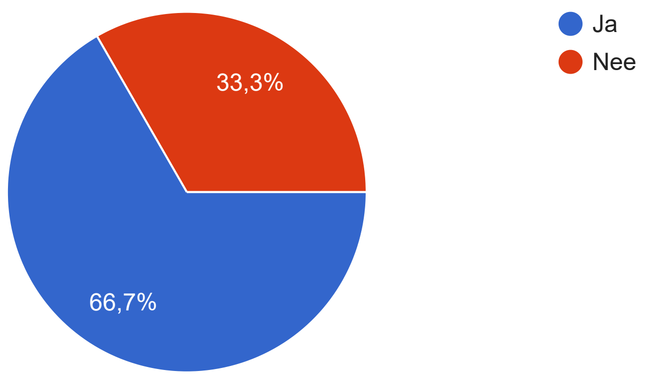


Werk gerelateerde vragen

Valharnas

Vind je het dragen van een valharnas oncomfortabel?

12 antwoorden

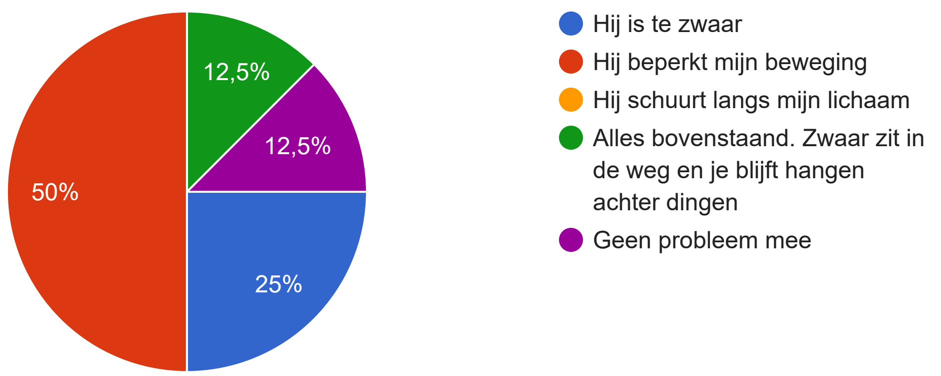


Oncomfortabel valharnas

Wat vind je het meest oncomfortabel aan het dragen van een valharnas?

Kopiëren

8 antwoorden

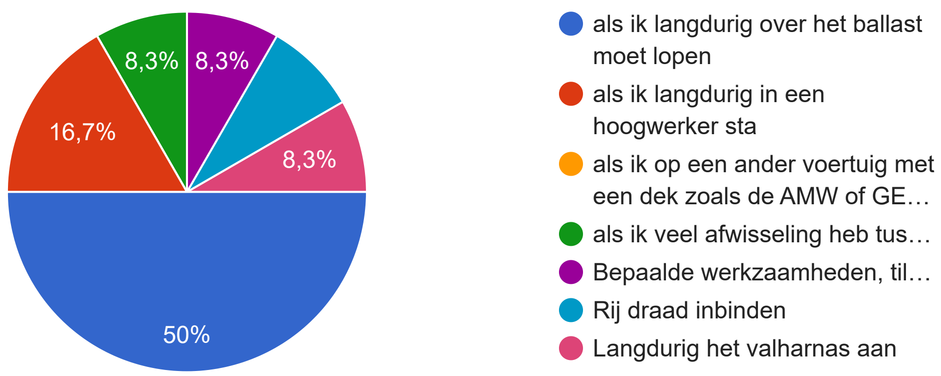


Soorten werkzaamheden

De zwaarste soort werksituatie vind ik

Kopiëren

12 antwoorden

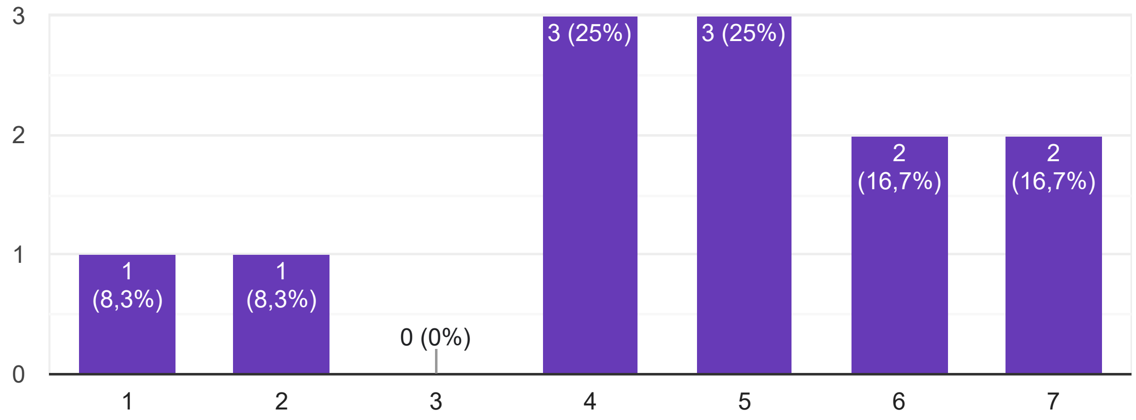


Geef bij de onderstaande vragen steeds aan per type werkzaamheid hoe fysiek belastend je deze werkzaamheid vindt.

Het monteren van palen en balken voor de draagconstructie.

Kopiëren

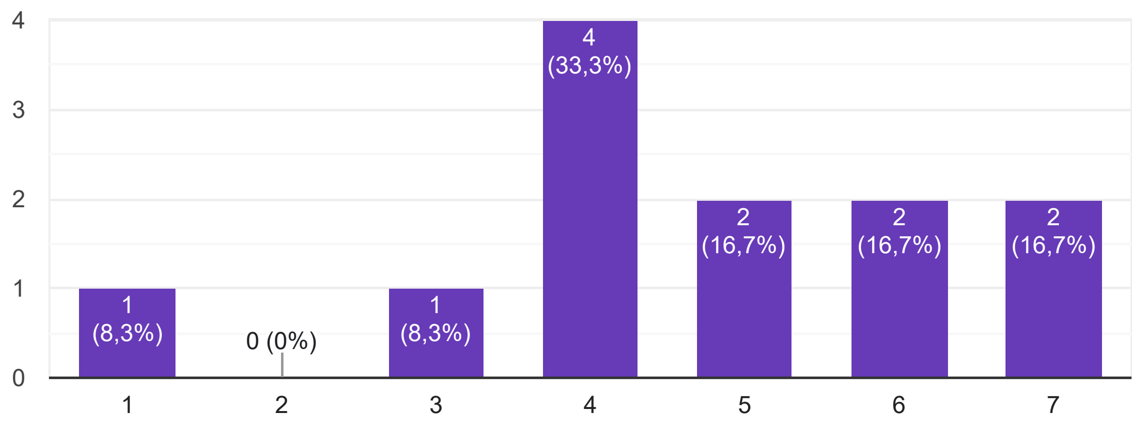
12 antwoorden



Het monteren van onderdelen aan de draagconstructie (bijv. kolommen, zijwaarste, bokken, etc.).

Kopiëren

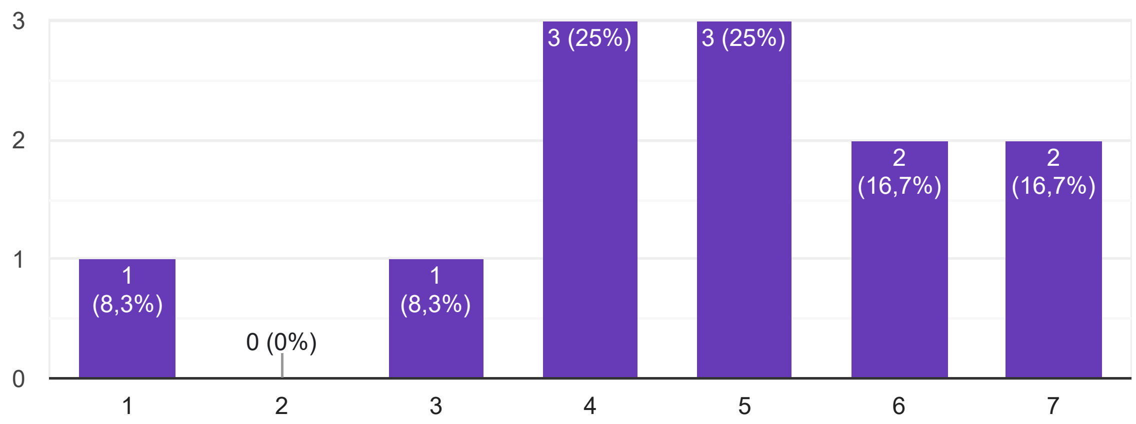
12 antwoorden



Het trekken van draagkabel of rijdraad.

Kopiëren

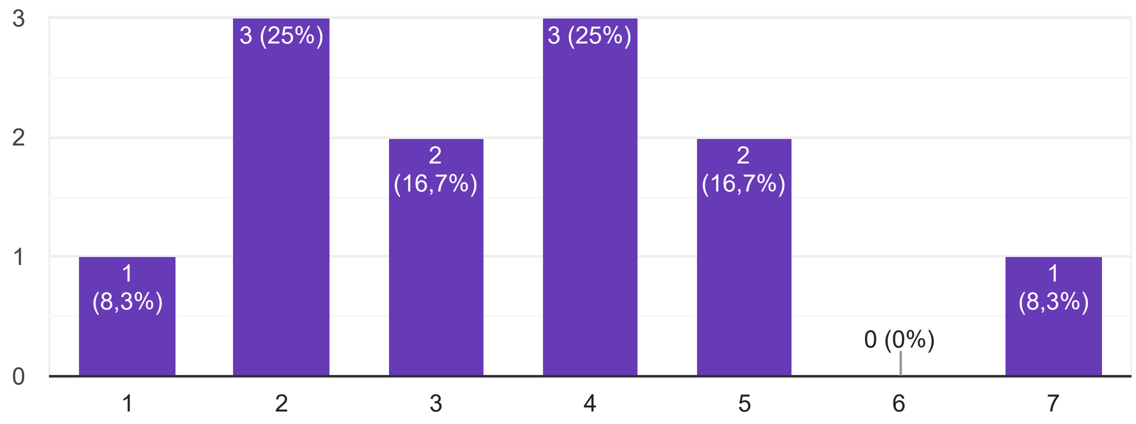
12 antwoorden



Het monteren van de hangdraden tussen draagkabel en rijdraad.

Kopiëren

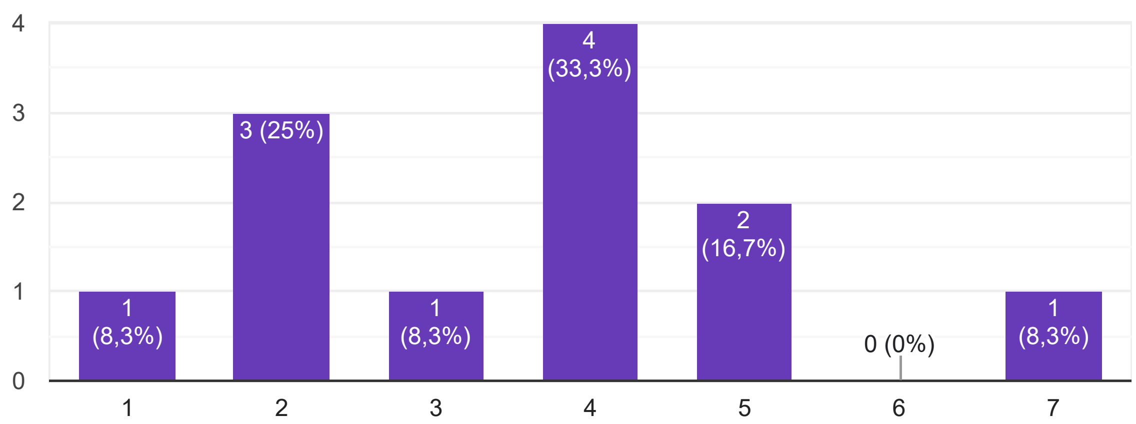
12 antwoorden



Het monteren van constructies in de rijdraad (bijv. kruizen, leidingonderbrekers, etc.)

Kopiëren

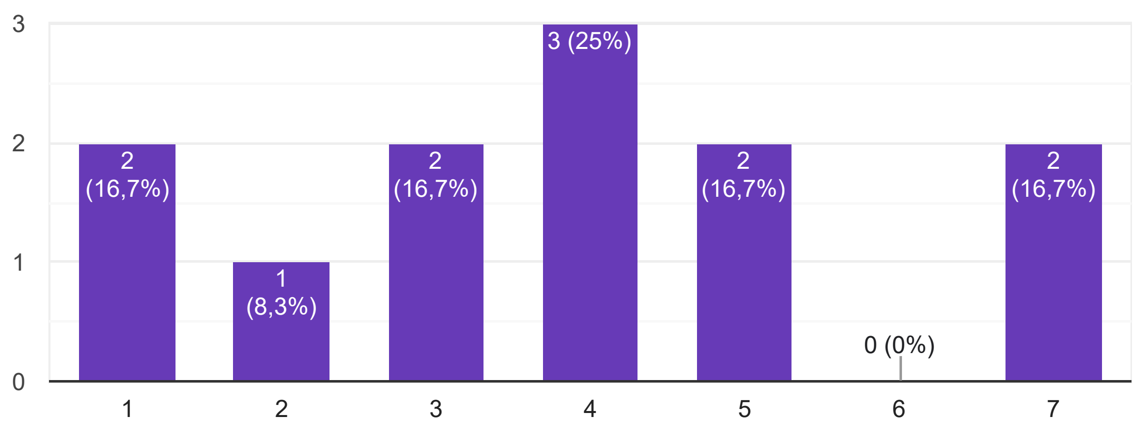
12 antwoorden



Het plaatsen van funderingen of ankerblokken

Kopiëren

12 antwoorden



Is er een type werkzaamheid niet genoemd die je wel belangrijk vindt om te noemen?

7 antwoorden

Kettin ratels tillen, isolatoren tillen. Gewichtenpakket buiten de bak ratelen

Nee

Nvt

Nee

Wisselende diensten

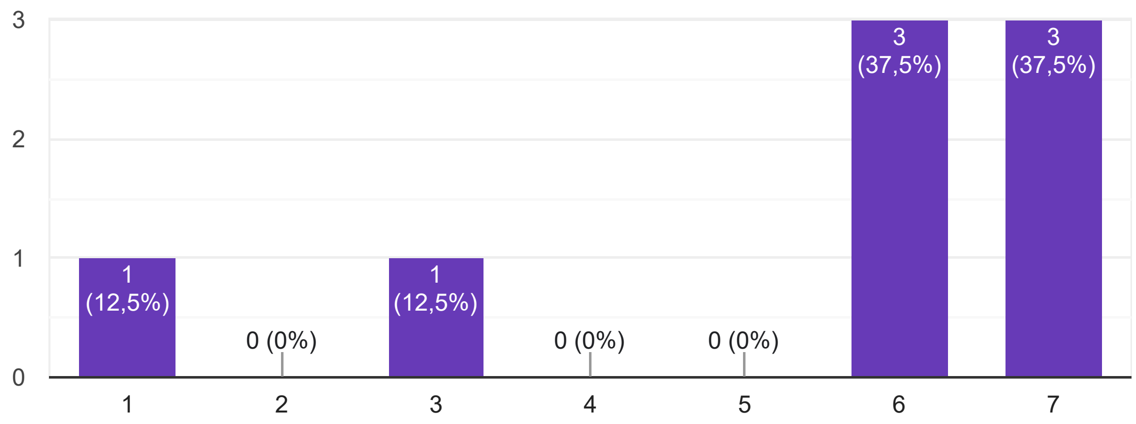
Het monteren van ijzerwerk in het algemeen

3kv trafo in de kast tillen of kasten plaatsen bijv sm kast weegt 110kg

Welk cijfer zou je deze zelf genoemde werkzaamheid geven? (hoeft niet ingevuld te worden als je niks opgeschreven hebt)

Kopiëren

8 antwoorden

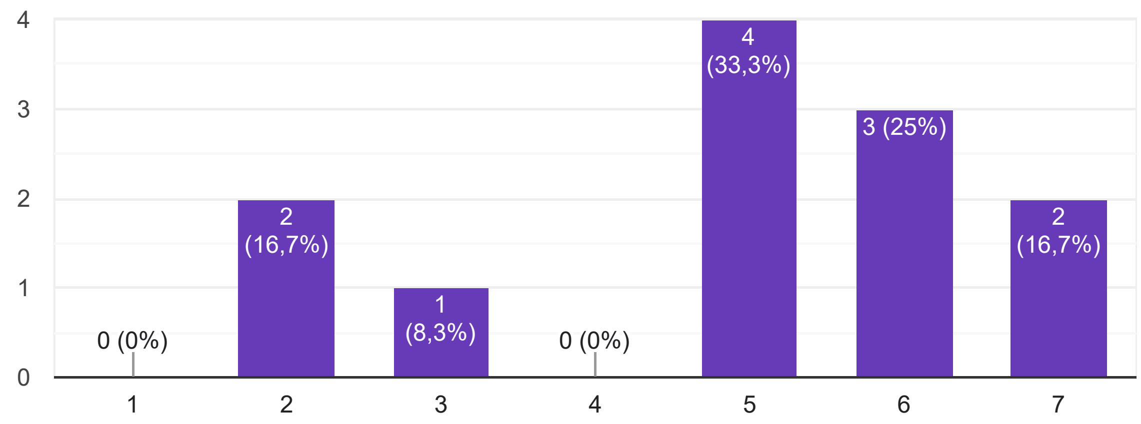


Vul hieronder in of je het werk in zijn geheel fysiek zwaar vindt. Dit staat dus los van specifieke onderdelen van het werk.

Ik vind mijn werk als monteur bovenleiding en draagconstructie fysiek gezien zwaar.

Kopiëren

12 antwoorden



Andere opmerkingen

Heb je nog andere dingen die je zou willen delen over je werkzaamheden. Denk hierbij aan dingen die je als belastend op het lichaam ervaart maar hier nog niet aan bod zijn gekomen. Ideeën over hoe het werk lichter gemaakt zou kunnen worden zijn ook welkom.

5 antwoorden

Vele uren auto rijden, werkzaamheden ook op de grond doen dus bukken, tillen van gereedschap, ratelen buiten de bak en tillen trap amw is net een Amsterdams grachtenpand trap..

Het contineu in en uitstappen uit de hwol werkbak is zwaar en vervelen met die trap en of balk, de een heeft 3 tredes de andere 4, of een ander deurtje dus je moet goed uitkijken.

Gebruik van de machines!!

De onregelmatige diensten zware weekenden,zware nacht diensten alle feestdagen werken vakanties alle weekenden

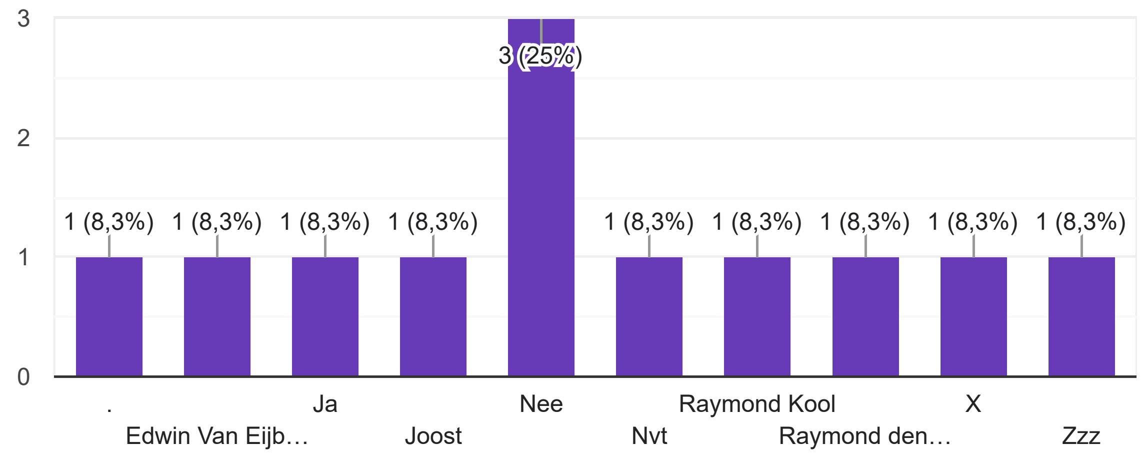
Nee

Het opvoeren van 1500v kabel op een balk schakelaar.

Mag ik contact opnemen met jou over je antwoorden? Als dit mag kan je je naam achterlaten zodat ik je een keer kan bellen.

Let op: je naam achterlaten is dus niet verplicht!

12 antwoorden



Einde van deze vragenlijst

D

Results pilot validation measurements

D.1. Preserved signal power after filtering

Task	Elbow (%)	Shoulder Elevation (%)
1	99.88	99.88
2	99.98	99.88
3	99.51	99.90
4	99.94	99.54
5	99.87	100.00

Table D.1: Preserved Signal Power for Elbow and Shoulder Elevation Across Tasks with 2Hz butterworth filtering

D.2. Kinematics and joint moments

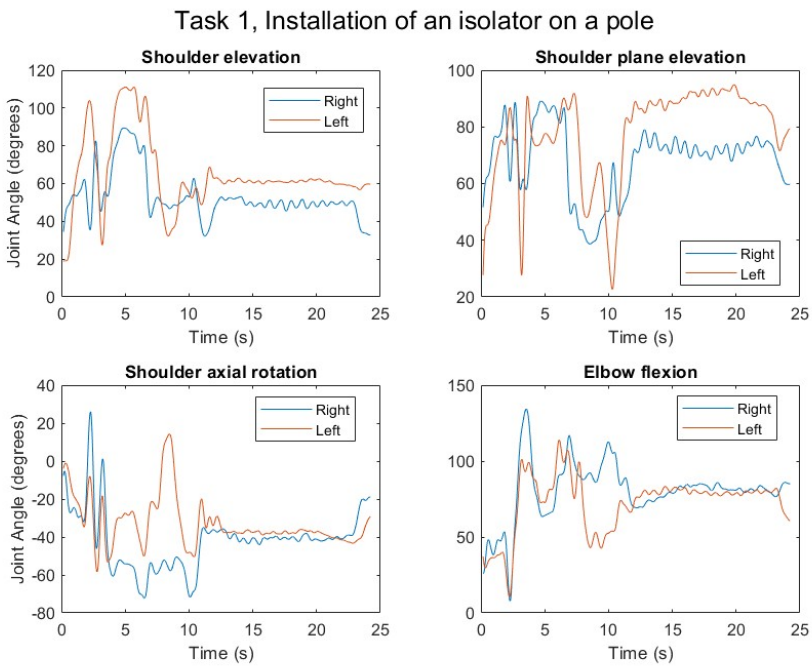


Figure D.1: Joint angles during the first measurement of task 1.

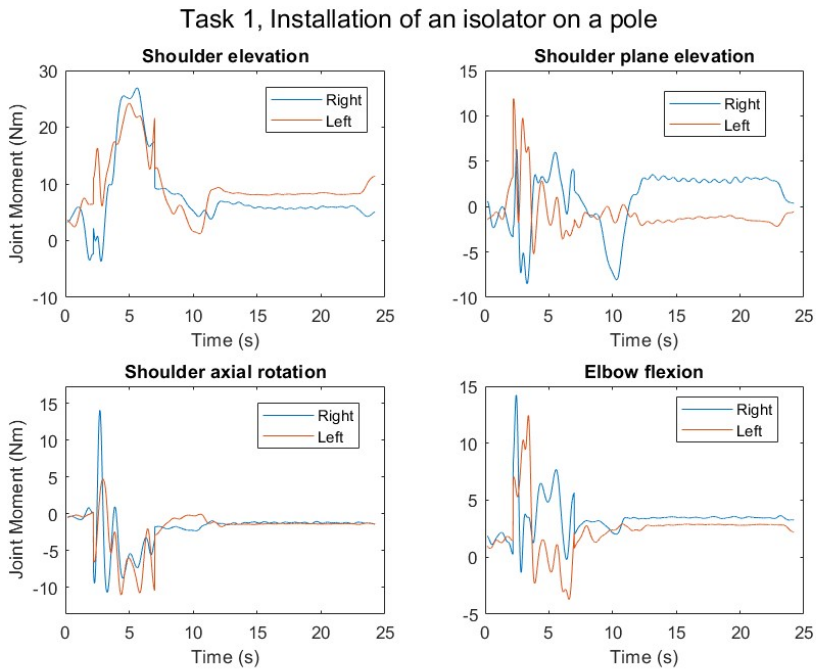


Figure D.2: Joint moments during the first measurement of task 1.

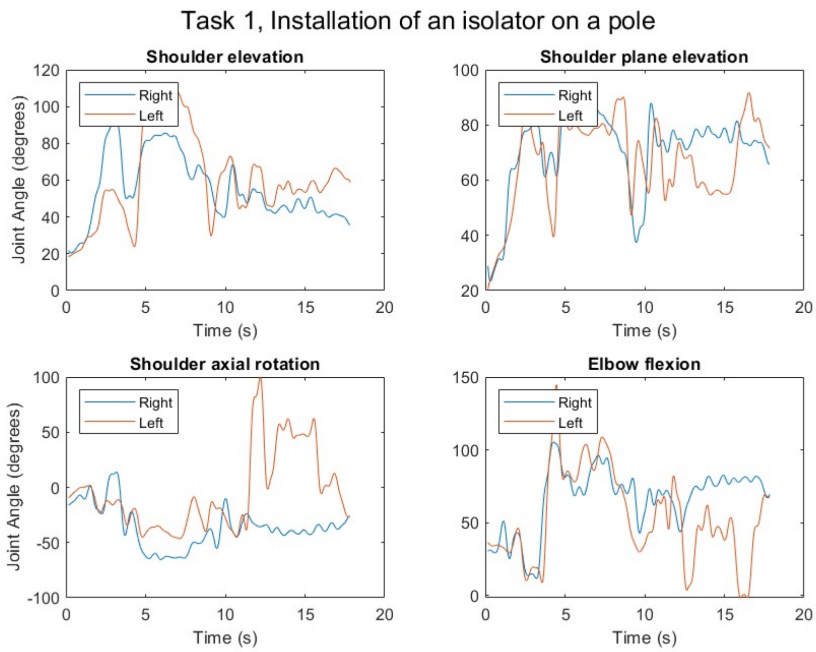


Figure D.3: Joint angles during the second measurement of task 1.

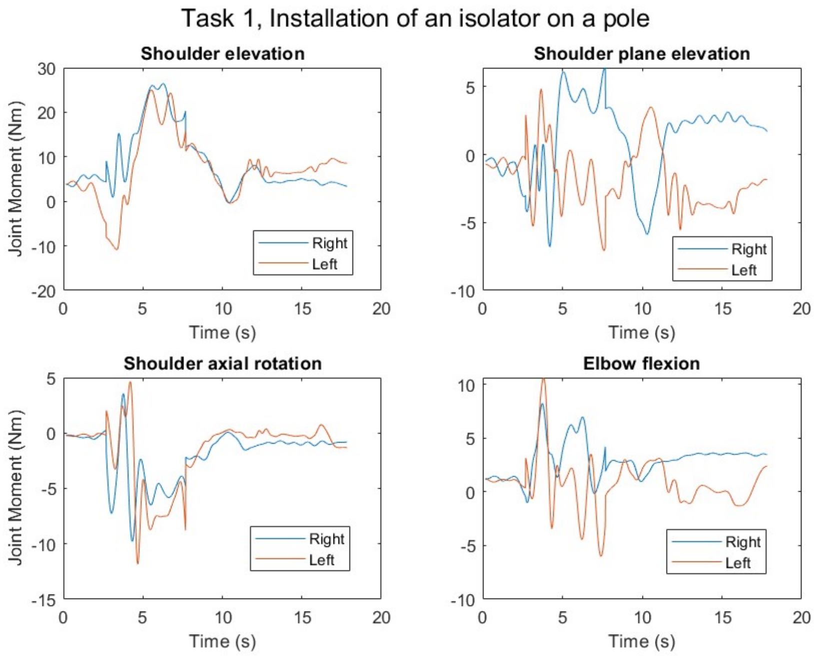


Figure D.4: Joint moments during the second measurement of task 1.

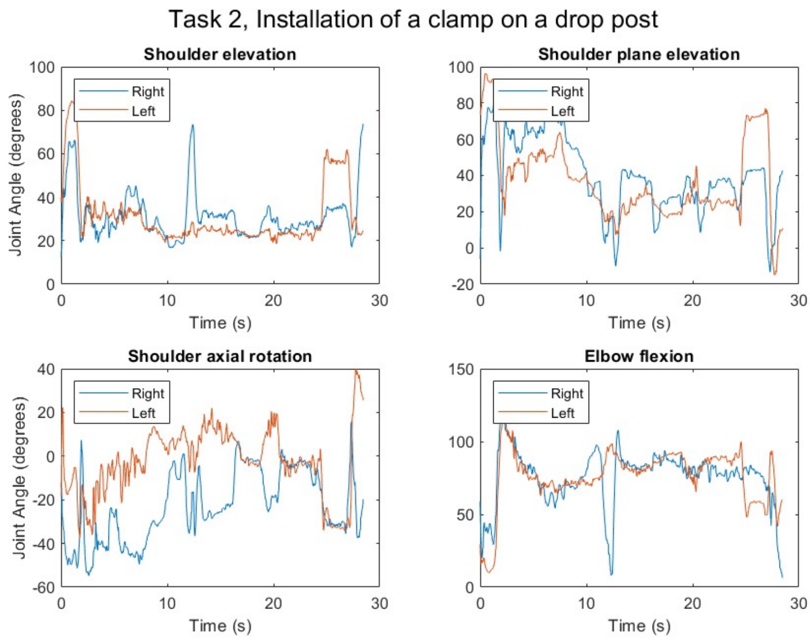


Figure D.5: Joint angles during the first measurement of task 2.

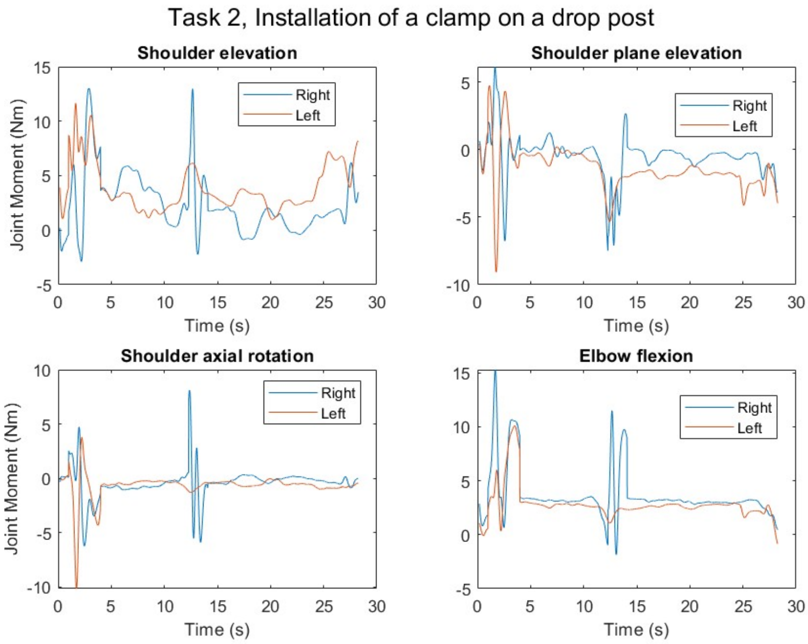


Figure D.6: Joint moments during the first measurement of task 2.

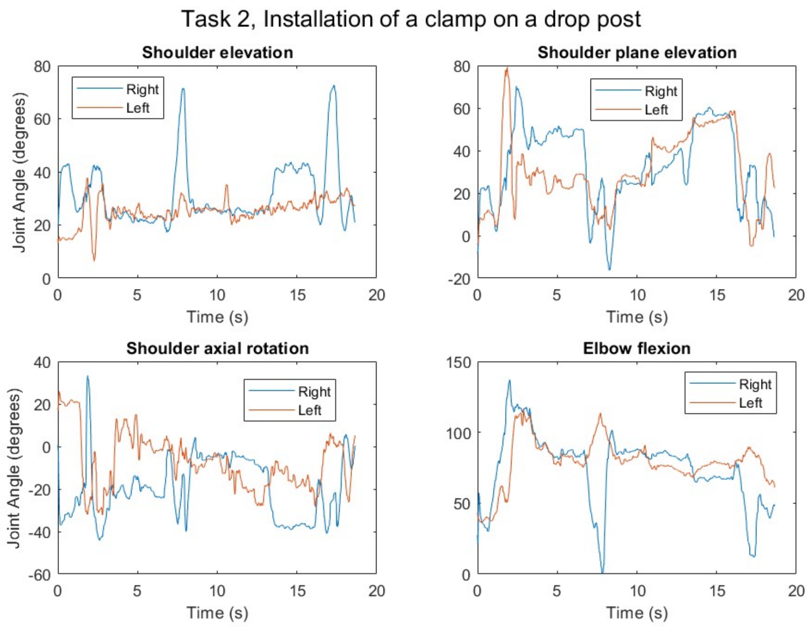


Figure D.7: Joint angles during the second measurement of task 2.

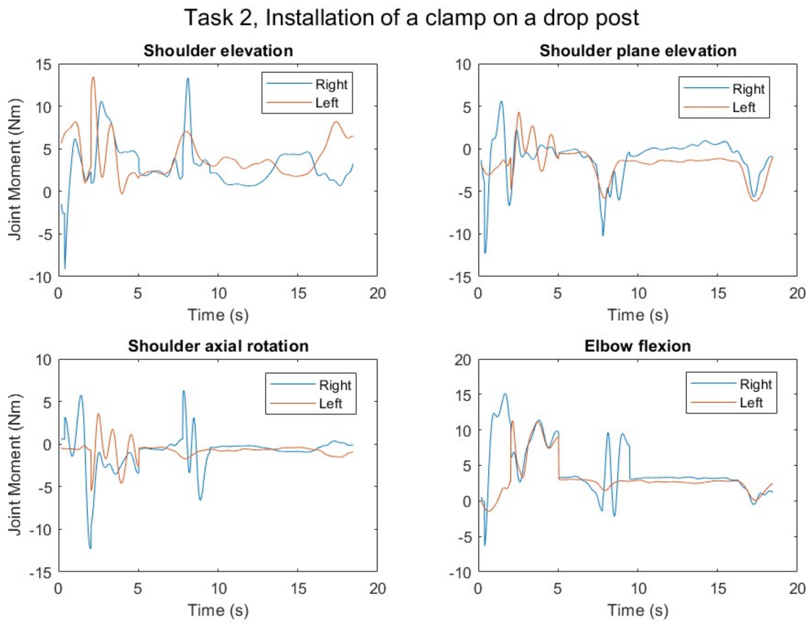


Figure D.8: Joint moments during the second measurement of task 2.

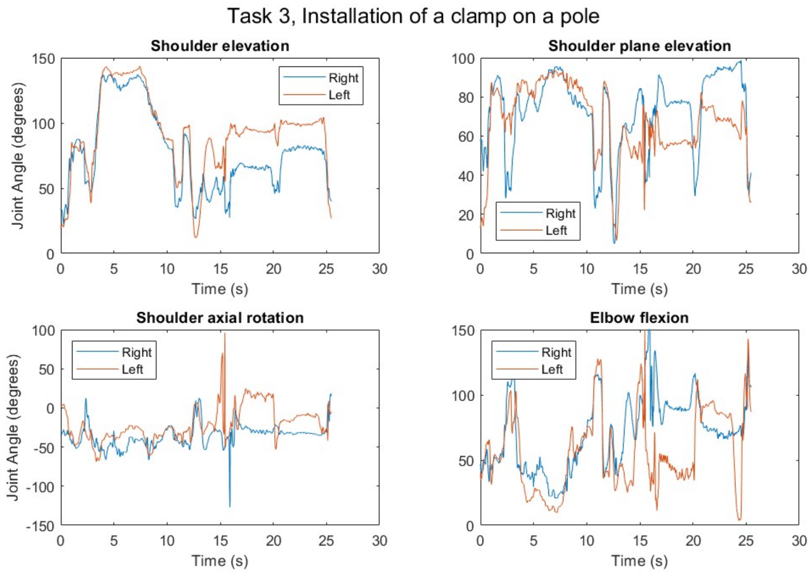


Figure D.9: Joint angles during the first measurement of task 3.

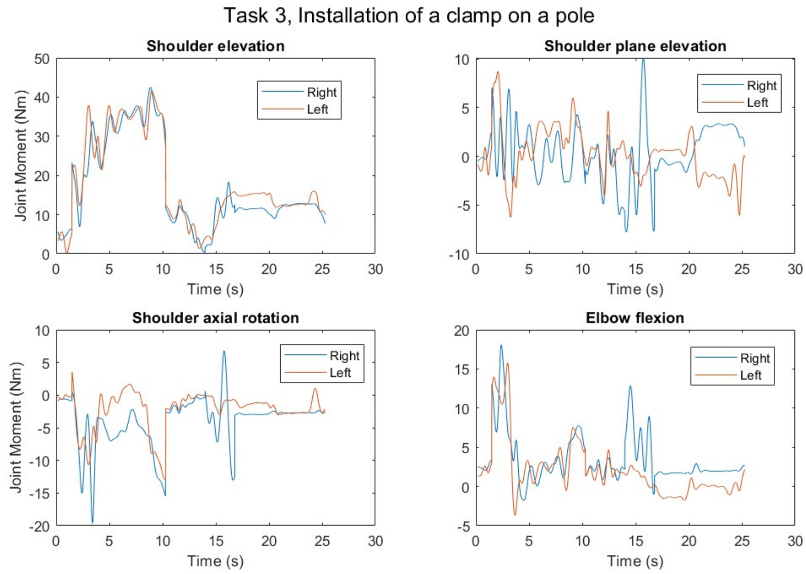


Figure D.10: Joint moments during the first measurement of task 3.

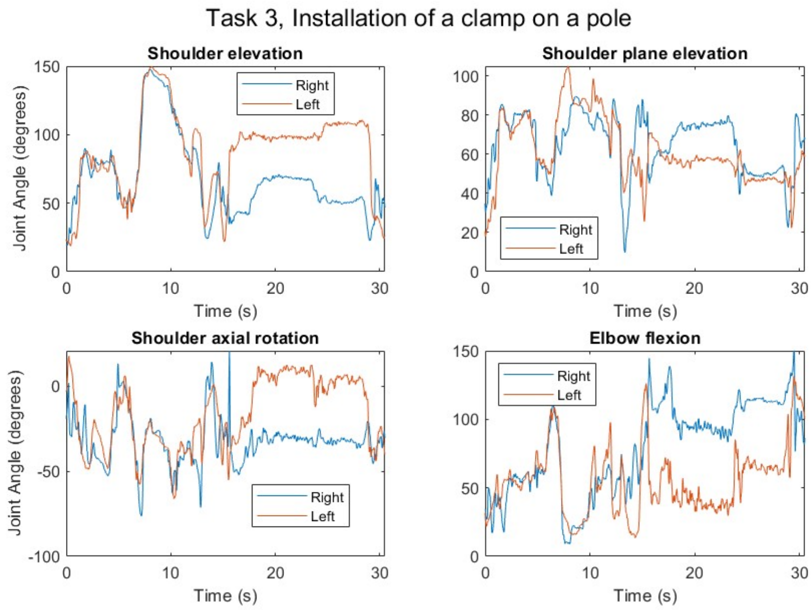


Figure D.11: Joint angles during the second measurement of task 3.

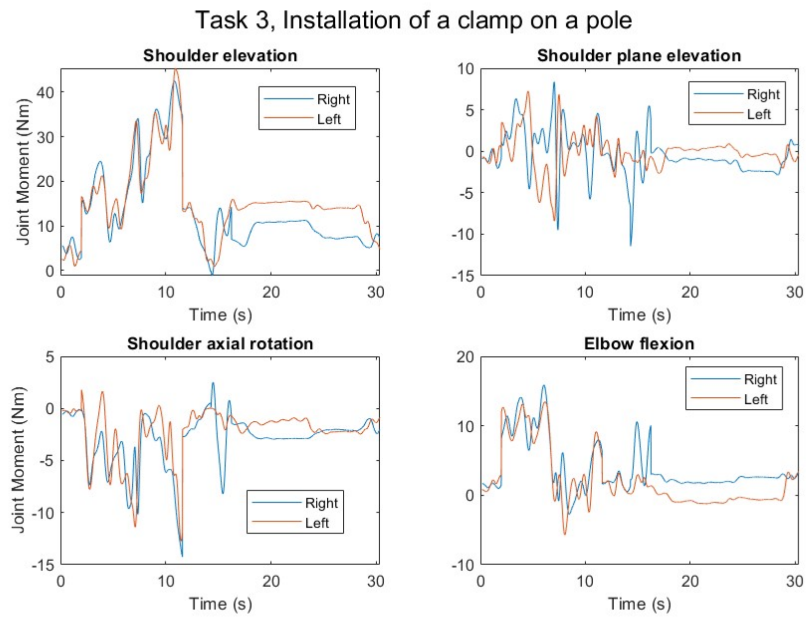


Figure D.12: Joint moments during the second measurement of task 3.

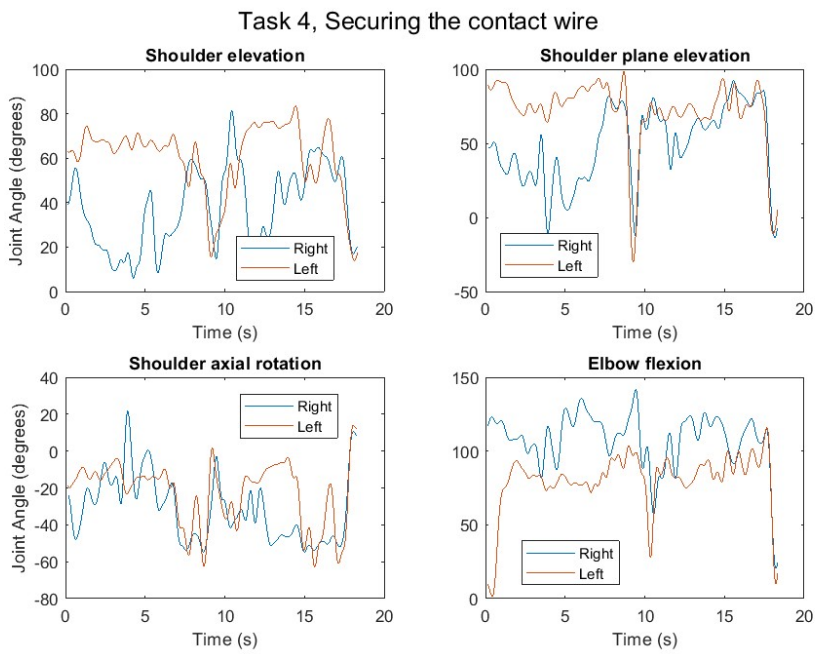


Figure D.13: Joint angles during the first measurement of task 4.

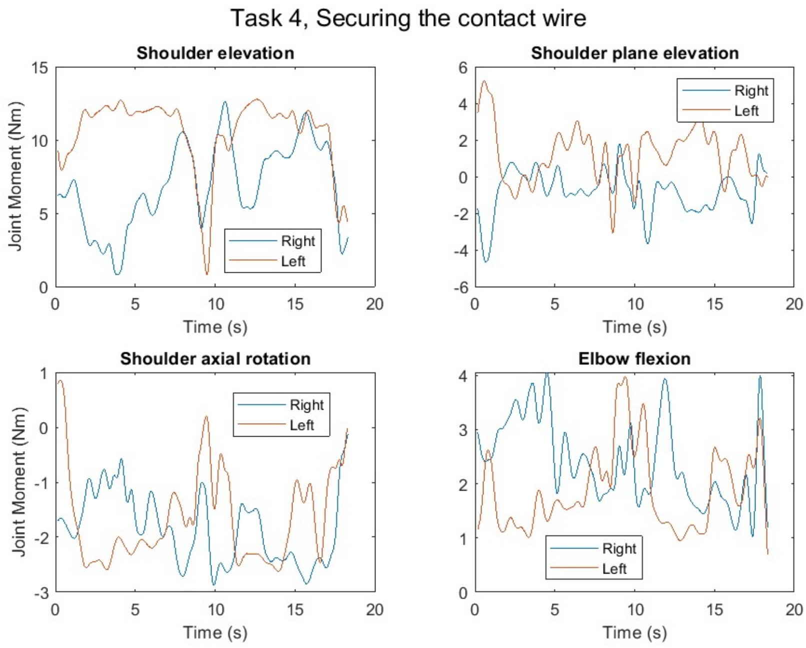


Figure D.14: Joint moments during the first measurement of task 4.

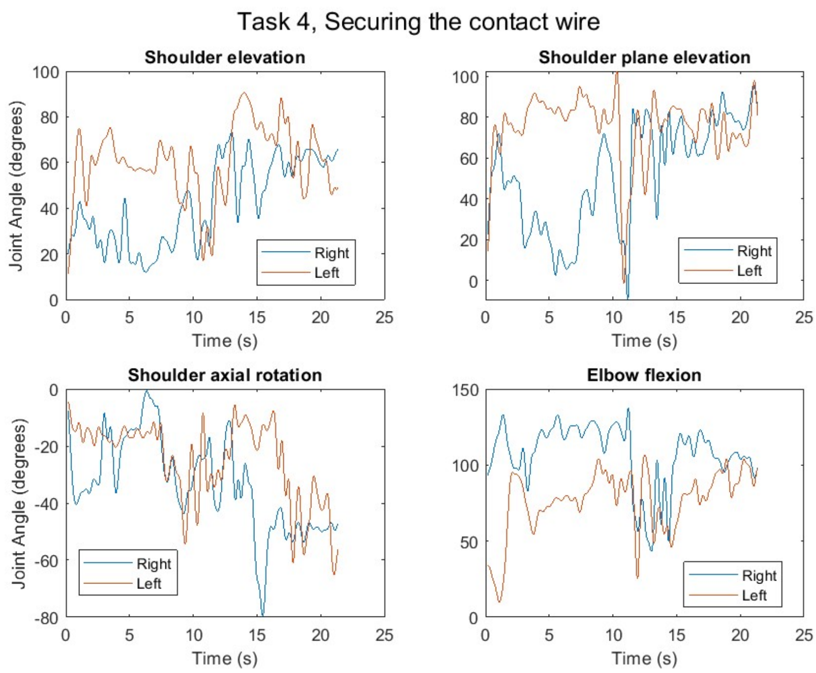


Figure D.15: Joint angles during the second measurement of task 4.

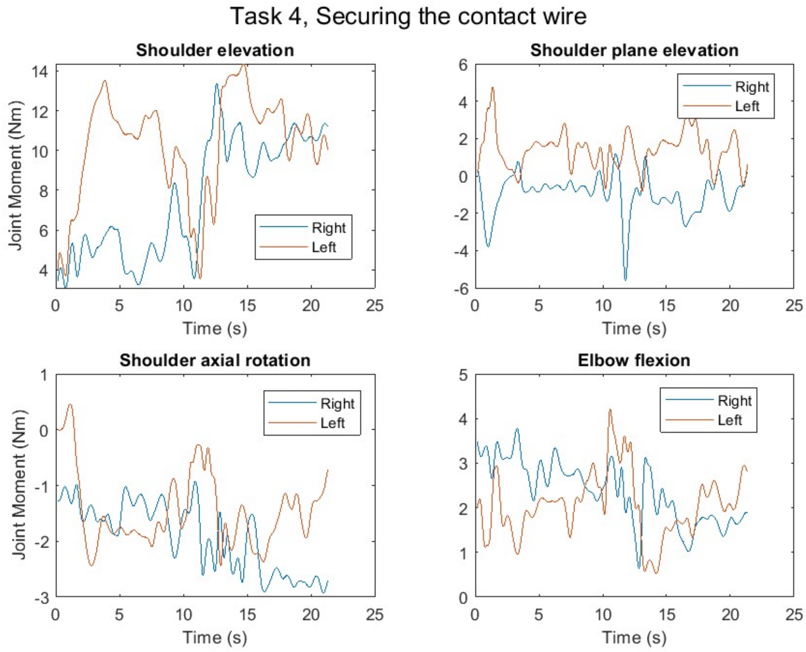


Figure D.16: Joint moments during the second measurement of task 4.

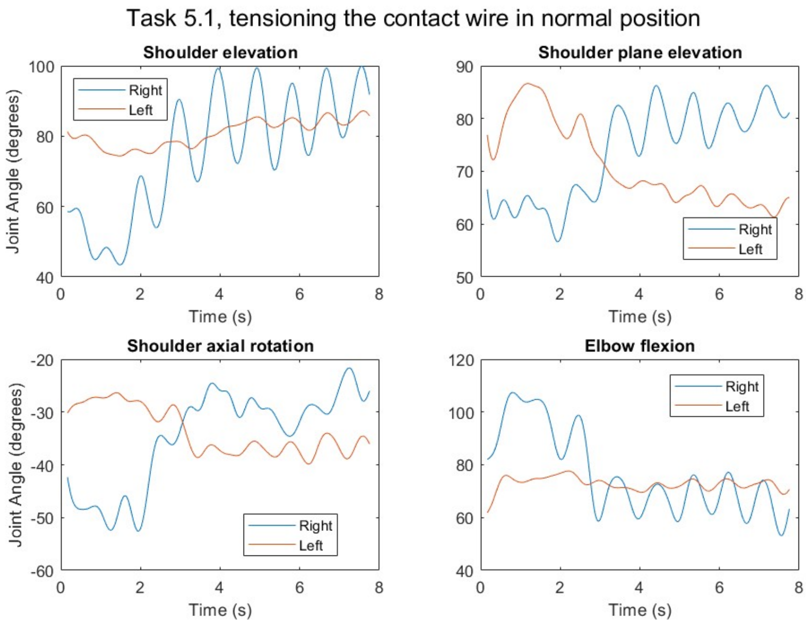


Figure D.17: Joint angles during the first measurement of task 5.1.

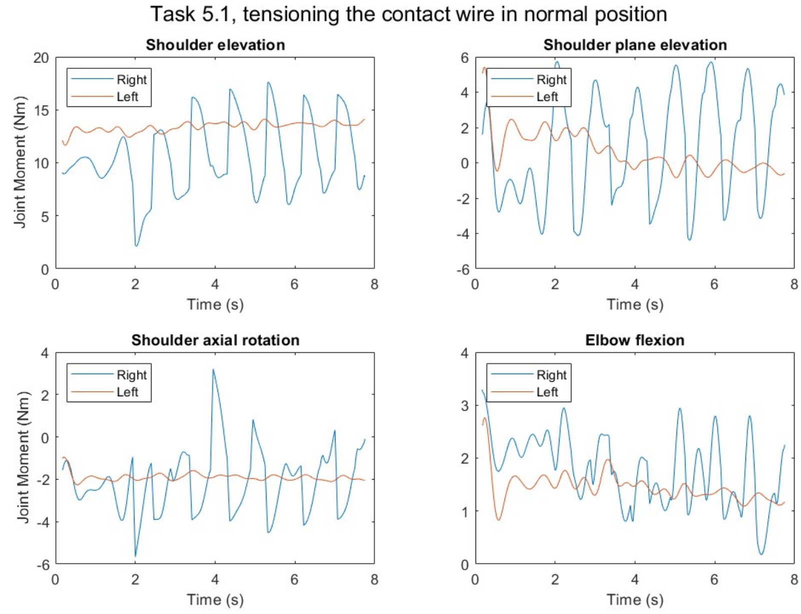


Figure D.18: Joint moments during the first measurement of task 5.1.

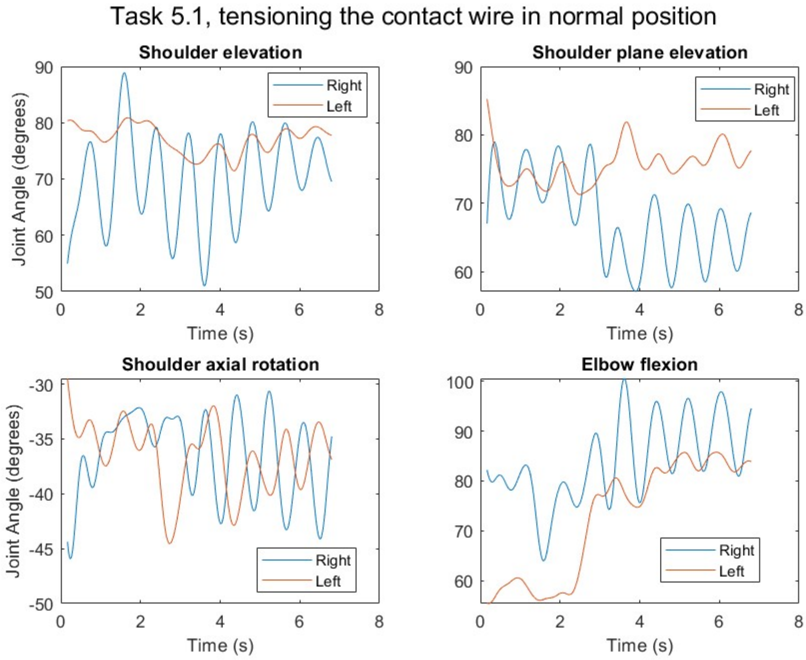


Figure D.19: Joint angles during the second measurement of task 5.1.

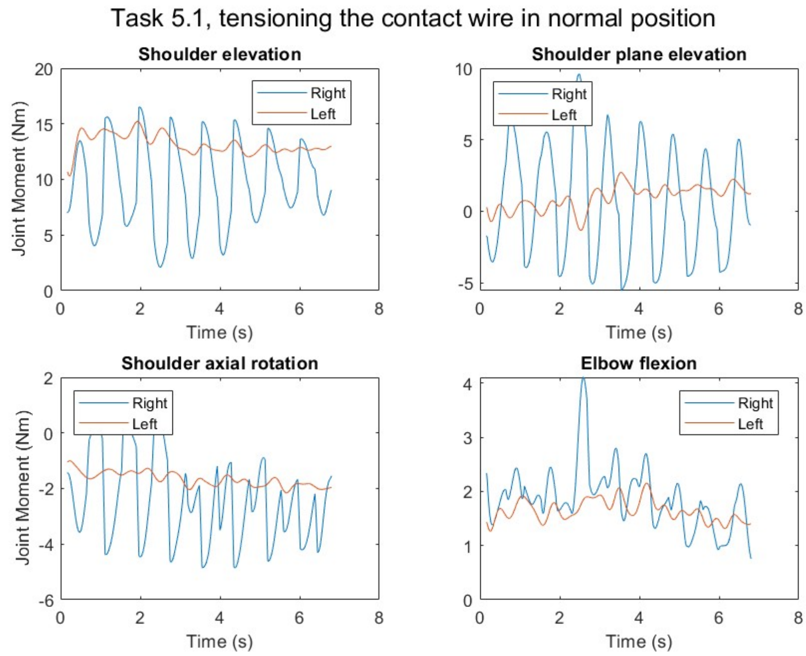


Figure D.20: Joint moments during the second measurement of task 5.1.

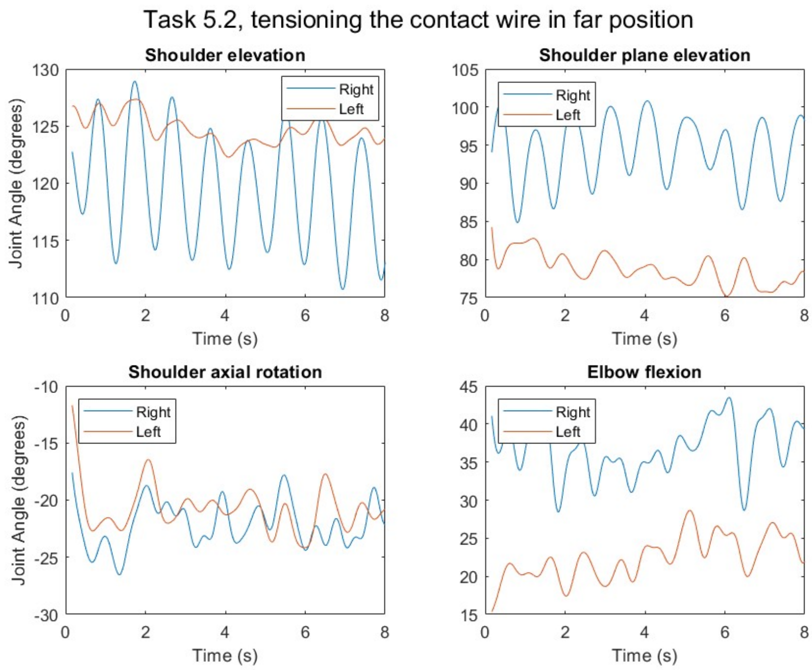


Figure D.21: Joint angles during the first measurement of task 5.2.

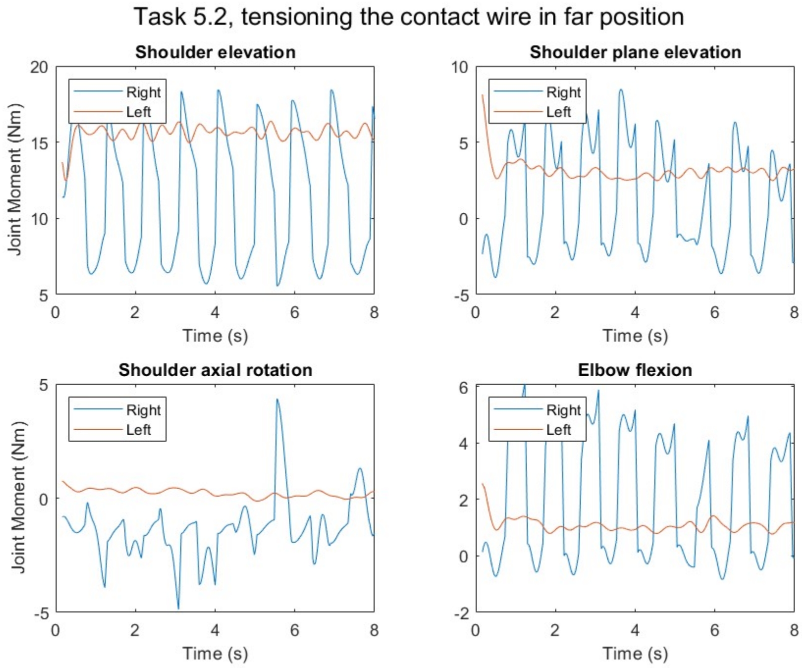


Figure D.22: Joint moments during the first measurement of task 5.2.

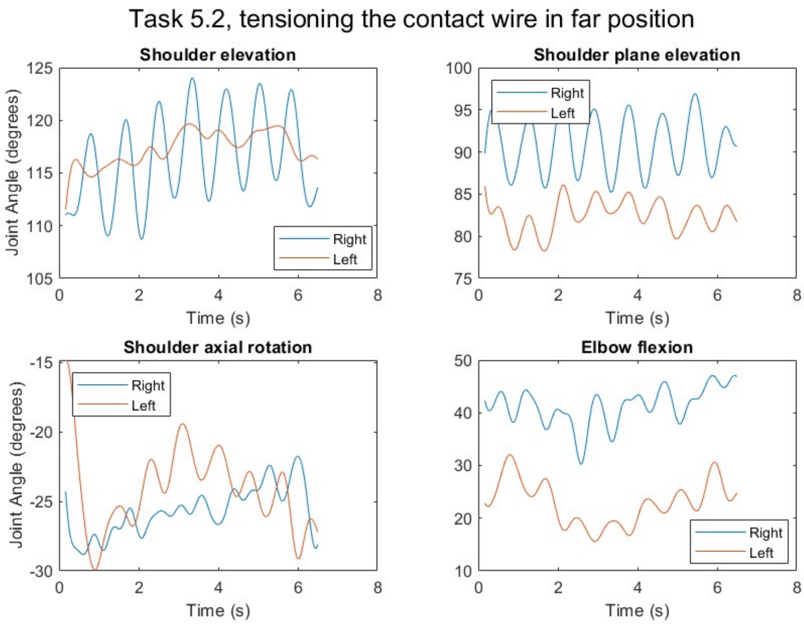


Figure D.23: Joint angles during the second measurement of task 5.2.

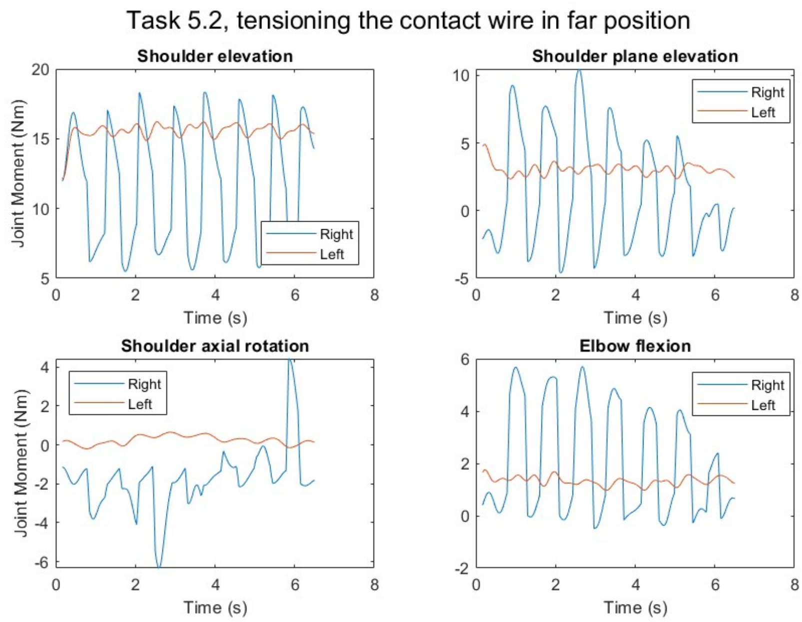


Figure D.24: Joint moments during the second measurement of task 5.2.

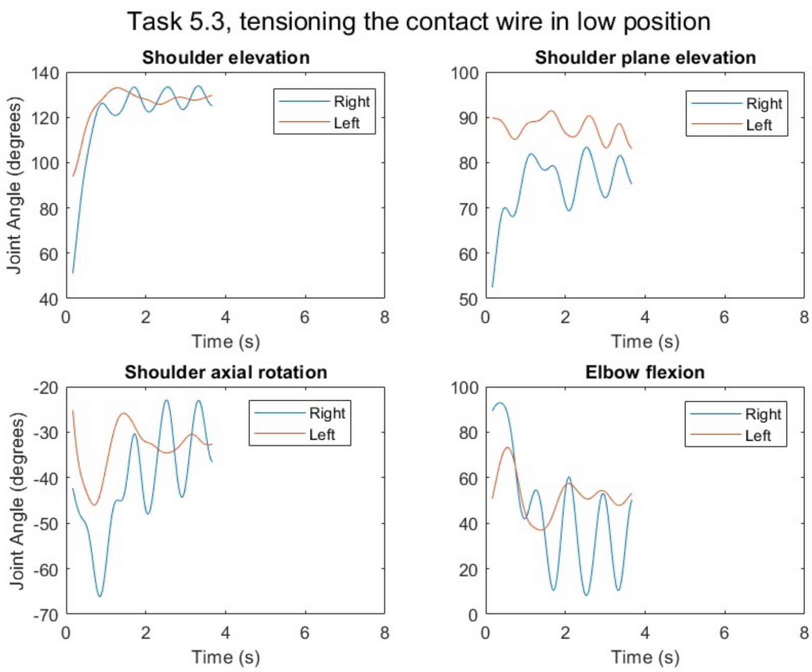


Figure D.25: Joint angles during the first measurement of task 5.3.

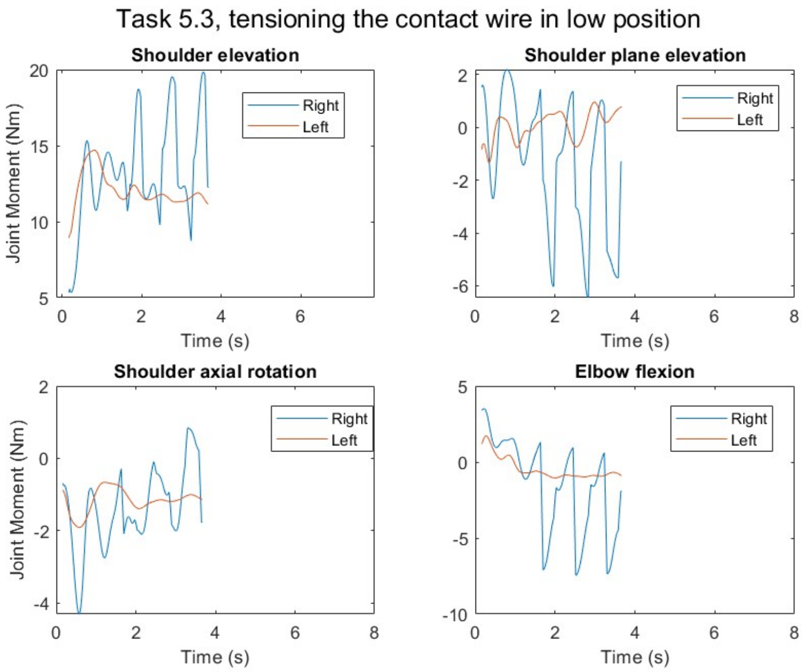


Figure D.26: Joint moments during the first measurement of task 5.3.

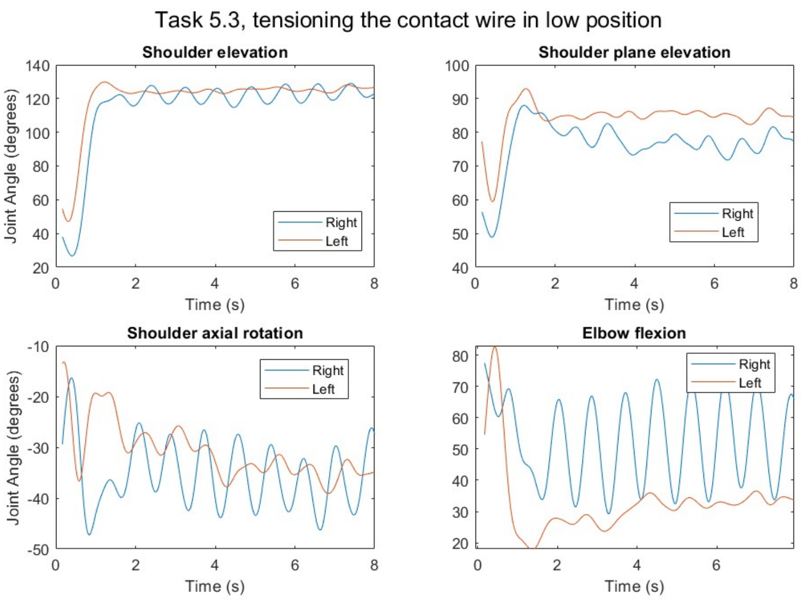


Figure D.27: Joint angles during the second measurement of task 5.3.

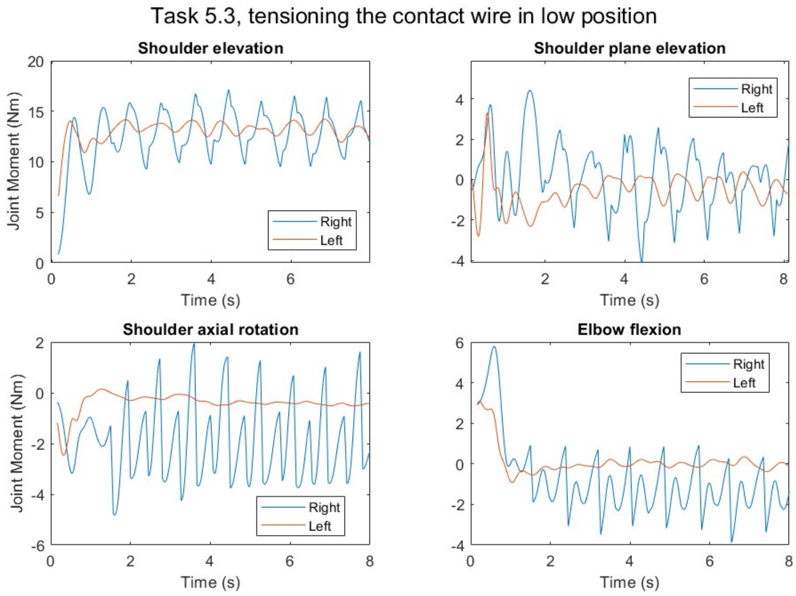


Figure D.28: Joint moments during the second measurement of task 5.3.

E

Modeling and data processing

E.1. Modified model

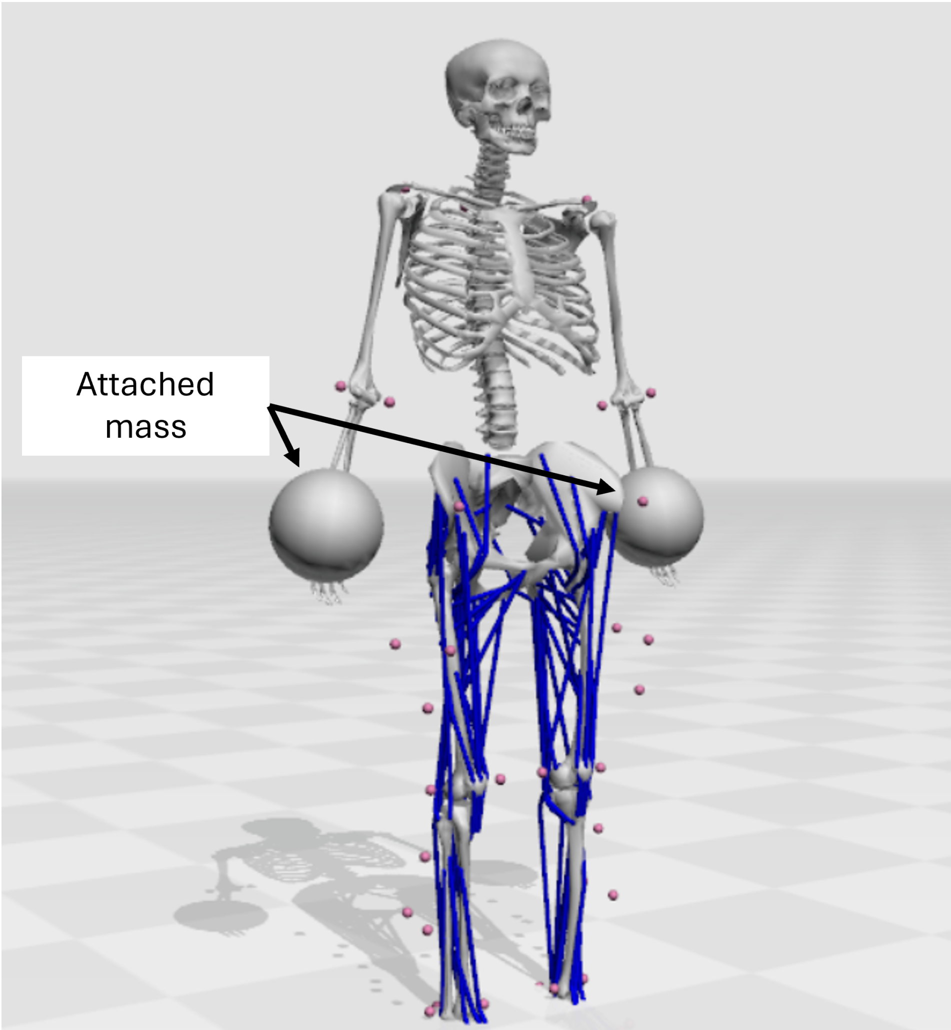


Figure E.1: The LaiUlrich2022shoulder model modified in OpenSimCreator. Each hand has an attached mass. The weight of the mass can be altered for the specific task.

E.2. Data filter script

Listing E.1: Filtering Kinematics Data

```matlab
clc
clear all
close all

%% Settings for used subject, kinematics and filtering
% specify the name of the subject, this is used in the name of the output
% file
subject='monteur1'

% Specify the path to the raw (unfiltered) kinematics files
path_directory='All_kinematics/Kinematics_monteur1_trimmed';
% Find all files in the directory that end with .mot
original_files=dir([path_directory '/*.mot']);

% Setup filter parameters
fc = 2;
fs = 60;
n_order =4;
window = 10;

%setup filter
[b,a] = butter(n_order,fc/(fs/2));
c = 1/window*ones(window,1);

%start loop for filtering every file seperately and saving in different
%folder
for k=1:length(original_files)
    filename=[path_directory '/' original_files(k).name];
    outputname = original_files(k).name;
    outputFile = strcat(outputname(1:end-4),'_',subject,'_filtered.mot');
    outputfolder = strcat('Kinematics_',subject,'_filtered_',string(fc),'_Hz\');
    if not(isfolder(outputfolder))
        mkdir(outputfolder);
    end
    %% Filter data
    % Read the .mot file
    [data,labels] = readStoFile(filename);

    %setup empty data frame
    data_fil = zeros(length(data(:,1))-window*2,length(data(1,:)));
    data_fil(:,1) = data(window+1:end-window,1);

    for i= 2:length(labels)
        fil1 = filtfilt(b,a,data(:,i));     % butterworth filter
        fil2 = filter(c,1,fil1);            % window filter
        data_fil(:,i) = fil2(window+1:end-window);
    end

    % Write the filtered data to a new .mot file
    writeStoFile(data_fil,labels,strcat(outputfolder,outputFile))

    %% Save the script in the output folder

    scriptFile = mfilename('fullpath');  % Get the full path of this script
    [~, scriptName] = fileparts(scriptFile);  % Extract file name without extension

    % Add .m extension to the script file name and copy it
    copyfile([scriptFile, '.m'], outputfolder);

```

```
end
```

E.3. External force create script

Listing E.2: Filtering Kinematics Data

```
clc
clear all
close all

%% Define input  markers kinematics and amount of force
markerfolder = 'marker_files/';
marker_kinematics = 'ratel_hoog2.mat';

inputfile = strcat(markerfolder,marker_kinematics);

load(inputfile);

% specify amount of force (N)
forcefactor = 10;

figure();
plot(markers.C7_study(:,1));

%% filtering marker data

% Define parameters for the Butterworth filter
order = 4;    % Filter order
cutoff = 2; % Normalized cutoff frequency (adjust as needed)
fs = 60;    % Sampling frequency (adjust as needed)
nfft = 1024

% Create the Butterworth filter
[b, a] = butter(order, cutoff / (fs / 2), 'low');

%% check cuttof power

for j = 1:3
    R_elbow_fil(:, j) = filtfilt(b, a, markers.RElbow(:, j));
end

P_fil_but = sum(abs(R_elbow_fil).^2) / nfft;
P_raw = sum(abs(markers.RElbow).^2) / nfft;

Elbow_perc_but = P_fil_but/P_raw*100


%%
% Example structure with 63 fields containing 3D arrays
% Let's assume the structure is called "dataStruct" and each field is an array with size (Nx3)
% where N is the number of samples and 3 corresponds to x, y, z coordinates
% Get the list of field names
fieldNames = fieldnames(markers);

% Loop through each field in the structure
for i = 1:length(fieldNames)
    fieldName = fieldNames{i};  % Get the current field name (e.g., 'neck', 'shoulder', etc.)

    % Access the current 3D array
```

```
    currentField = markers.(fieldName);

    % Apply the Butterworth filter to each column (x, y, z) separately
    for j = 1:3
        currentField(:, j) = filtfilt(b, a, currentField(:, j));
    end

    % Save the filtered data back to the structure
    dataStruct.(fieldName) = currentField;
end

figure()
plot(dataStruct.C7_study(:,1))

forcefactor_string = 30;

%% Find direction for force while doing contact wire tensioning task

middel_elbow = (dataStruct.r_lelbow_study+dataStruct.r_melbow_study)/2;

vector1 = middel_elbow-dataStruct.r_mwrist_study;
vector2 = middel_elbow-dataStruct.r_lwrist_study;

forcedirection = cross(vector1,vector2) ;


magnitudes = sqrt(sum(forcedirection.^2, 2));

forcedirection_norm =(forcedirection)./magnitudes;

%% plot for visual
n=20;
figure()
% plot(time,forcedirection(:,2))
% quiver3(0,0,0,forcedirection_norm(n,1),forcedirection_norm(n,2),
    forcedirection_norm(n,3))
hold on
% quiver3(0,0,0,1,0,0,'r')
% quiver3(0,0,0,0,1,0,'g')
% quiver3(0,0,0,0,0,1,'b')
title(time(n))
xlim([-1 1])
ylim([-1 1])
zlim([-1 1])

forcedirection_norm(n,1)
forcedirection_norm(n,2)
forcedirection_norm(n,3)
plot3(forcedirection_norm(:,1),forcedirection_norm(:,2),forcedirection_norm(:,3))

%% Determine when to excert force and when not
% Define the time intervals as a matrix [start_time, end_time]

% ratel_normaal1
% time_intervals = [1.92, 2.40; 2.87, 3.35; 3.88,
    4.30;4.87,5.25;5.73,6.15;6.62,7.0;7.50,7.75];
% ratel_normaal2
% time_intervals =
    [0.65,1.05;1.52,1.9;2.28,2.68;3.13,3.47;3.92,4.27;4.72,5.12;5.53,5.95;6.37,6.8];

```

```
% ratel_ver1
% time_intervals = [0.73,1.22;1.68,2.15;2.58,3.07;3.52,4.0;4.45,4.98;5.48,5.85;6.38,6.83;7.32,7.87];
% ratel_ver2
% time_intervals = [0.78,1.22;1.6,2.03;2.42,2.9;3.25,3.65;4.15,4.53;4.97,5.38;5.77,6.08];

% ratel_hoog1
% time_intervals = [1.62,1.96;2.45,2.82;3.22,3.58];
% ratel_hoog2
time_intervals = [1.5,1.92;2.37,2.73;3.2,3.6;4,4.42;4.85,5.25;5.72,6.08;6.48,6.87;7.35,7.75];


% Initialize the output array with zeros
output_array = zeros(size(time));

% Transition length
transition_length = 5; % Number of time steps for transition

% Loop through the time intervals
for i = 1:size(time_intervals, 1)
    % Get the start and end times for the current interval
    start_time = time_intervals(i, 1);
    end_time = time_intervals(i, 2);

    % Find the start and end indices in the total time vector
    start_index = find(time >= start_time, 1);
    end_index = find(time >= end_time, 1);

    % Ensure the indices are within bounds
    if start_index <= length(time) && end_index <= length(time)
        % Transition from 0 to 1 over the specified time steps
        % If the duration is shorter than the transition length, adjust it
        actual_transition_length = min(transition_length, end_index - start_index);

        % Create a transition from 0 to 1
        transition = linspace(0, 1, actual_transition_length);

        % Set values in the output array for the transition
        output_array(start_index:start_index + actual_transition_length - 1) = transition;

        % Set remaining values to 1 after the transition
        output_array(start_index + actual_transition_length:end_index) = 1;
        % Transition back to 0 over the specified time steps after the interval
        if end_index + actual_transition_length - 1 <= length(time)
            transition_down = linspace(1, 0, actual_transition_length);
            output_array(end_index:end_index + actual_transition_length - 1) = transition_down;
        end
    end
end

% Display the output array
% disp(output_array);

figure()
plot(time,output_array)

```

```
%% Write force file

Fx = forcedirection_norm(:,1) * forcefactor .* transpose(output_array);
Fy = forcedirection_norm(:,2) * forcefactor .* transpose(output_array);
Fz = forcedirection_norm(:,3) * forcefactor .* transpose(output_array);
Mx = zeros(length(Fx),1);
My = zeros(length(Fx),1);
Mz = zeros(length(Fx),1);

extractedData.t = transpose(time);
extractedData.Fx = Fx;
extractedData.Fy = Fy;
extractedData.Fz = Fz;
extractedData.Mx = Mx;
extractedData.My = My;
extractedData.Mz = Mz;

array = struct2array(extractedData);
writeStoFile(array, ["time", "Fx", "Fy", "Fz", "Mx", "My", "Mz"], strcat('
    force_files/',marker_kinematics(1:(end-4)), '_force','_',string(forcefactor), '
    .mot'));
```

E.4. Batch inverse dynamics script

Listing E.3: Filtering Kinematics Data

```
% Add OpenSim libraries to MATLAB
import org.opensim.modeling.*

% Define paths to the model file, the directory with the kinematic files, and the
    output directory
modelFile = 'C:\Users\douwe\OneDrive - Delft University of Technology\Documents\
    Afstuderen\OpenSim\ID_batch_opensim\Model\
    LaiUhlrich2022_shoulder_scaled_withweights_R_5kg.osim'; % Replace with your
    model file path
kinematicsDir = 'C:\Users\douwe\OneDrive - Delft University of Technology\
    Documents\Afstuderen\OpenSim\ID_batch_opensim\Kinematics_monteur1_filtered_1_Hz
    /'; % Replace with the directory containing kinematic files
outputDir = 'C:\Users\douwe\OneDrive - Delft University of Technology\Documents\
    Afstuderen\OpenSim\ID_batch_opensim\ID_results_Monteur\'; % Replace with your
    output directory
resultsDir = fullfile(outputDir, 'InverseDynamicsResults\');
% define the model that should be used for all inverse dynamic runs
mod = 'Model_5kgR'
% define the set of tasks that you want to be processed
trials = 'monteur2_1Hz'
currentDir = pwd();

outputfolder = [currentDir,'\','ID_',mod,'_',trials]

if ~exist(outputfolder, 'dir')
    mkdir(outputfolder);
else
    % If the directory exists, stop the script with an error message
    error('The output directory already exists: %s\nStopping the script.',
        outputDir);
end


% Load the OpenSim model
model = Model(modelFile);
```

```
model.initSystem();

% Get list of kinematic files
kinematicsFiles = dir(fullfile(kinematicsDir, '*.mot')); % Assuming .mot files
nFiles = length(kinematicsFiles);

% Define the specific time point for the analysis (e.g., 1.5 seconds)
targetTimePoint = 1.5; % Change this to the time point you want

% Loop through each kinematic file and run inverse dynamics
for i = 1:nFiles
    % Get the full path to the kinematic file
    kinematicFilePath = fullfile(kinematicsDir, kinematicsFiles(i).name);

    % Read the kinematic file to determine the time range
    kinematicsData = importdata(kinematicFilePath);
    timeColumn = kinematicsData.data(:,1); % Assuming time is in the first column
    startTime = timeColumn(1);  % First time point
    endTime = timeColumn(end);  % Last time point

    % Create an InverseDynamicsTool object
    idTool = InverseDynamicsTool();

    % Set the model for the tool
    idTool.setModel(model);

    % Set the kinematic file
    idTool.setCoordinatesFileName(kinematicFilePath);


    % Set the start and end time for the entire duration of the kinematic file
    idTool.setStartTime(startTime);
    idTool.setEndTime(endTime);

    % Set the external loads file (if you have one, otherwise comment it out)
    % externalLoadsFile = 'path_to_external_loads_file.xml'; % Optional
    % idTool.setExternalLoadsFileName(externalLoadsFile);

    % Set the output directory and file names

    outputFileName = ['ID_', kinematicsFiles(i).name(1:(end-4)),'_results.sto'];


    idTool.setOutputGenForceFileName(outputFileName);

    % disp([output])
    % Run the inverse dynamics tool
    idTool.run();

    movefile(outputFileName, outputfolder)
    % Display a message to indicate progress
    fprintf('Processed %d/%d: %s\n', i, nFiles, kinematicsFiles(i).name);
end

fprintf('Batch processing completed!\n');
```

E.5. Combine STO files script

Listing E.4: Filtering Kinematics Data

```
clc
close all
clear all
% MATLAB Script to Combine Two .sto Files Based on Specific Time Ranges

% Specify the file paths for the two .sto files
ID_folder1 = 'ID_Model_NoWeight_monteur1_1Hz\'
ID_folder2 = 'ID_Model_5kg_monteur1_1Hz\'
ID_folder3 = 'ID_Model_10kg_monteur1_1Hz\'
ID_folder4 = 'ID_Model_2.5kgR_monteur1_1Hz\'
ID_folder5 = 'ID_Model_5kgR_monteur1_1Hz\'

Movement = 'ID_klem_paal2_monteur1_filtered_results.sto'

file1 = strcat(ID_folder1,Movement);
file2 = strcat(ID_folder2,Movement);
file3 = strcat(ID_folder3,Movement);
file4 = strcat(ID_folder4,Movement);
file5 = strcat(ID_folder5,Movement);

currentDir = pwd();

outputfolder = [currentDir,'\','ID_mont1_combined']
% outputfolder = 'ID_mont1_combined'
outputFile = strcat(Movement(1:(end-4)),'_combined.sto');  % Output file name

if ~exist(outputfolder, 'dir')
    mkdir(outputfolder);
else
    % If the directory exists, stop the script with an error message
    % error('The output directory already exists: %s\nStopping the script.', outputDir);
end

output = strcat(outputfolder,'\',outputFile)

% Read the data from the two .sto files
[data1, headers1] = readStoFile(file1);
[data2, headers2] = readStoFile(file2);
[data3, headers3] = readStoFile(file3);
[data4, headers4] = readStoFile(file4);
[data5, headers5] = readStoFile(file5);


% Check if the time columns match across the three files
if ~isequal(data1(:,1), data2(:,1)) || ~isequal(data1(:,1), data3(:,1))
    error('The time columns in the .sto files do not match.');
end

% Define time ranges for each file
t1 = 2;   % Start time for file1
t2 = 11.6;   % Switch to file2 at t2
t3 = 14.3;  % Switch to file3 at t3
t4 = 16.25;  % Switch back to file1 at t4
t5 = 16.25;  % Switch back to file1 at t4
% Add more time ranges as needed

% Preallocate combined data
combinedData = zeros(size(data1));

% Loop through the time values and choose data from file1, file2, or file3
```

```
for i = 1:length(data1(:,1))
    time = data1(i, 1);

    if time >= t1 && time < t2
        % Use data from file1 between t1 and t2
        combinedData(i, :) = data3(i, :);

    elseif time >= t2 && time < t3
        % Use data from file2 between t2 and t3
        combinedData(i, :) = data1(i, :);

    elseif time >= t3 && time < t4
        % Use data from file3 between t3 and t4
        combinedData(i, :) = data4(i, :);

    elseif time >= t4 && time < t5
        % Use data from file3 between t4 and t5
        combinedData(i, :) = data1(i, :);
    else
        % Add more conditions if you have more time ranges
        combinedData(i, :) = data1(i, :);  % Default to file1 after t4
    end
end


% Write the combined data to a new .sto file
writeStoFile(combinedData, headers1,output);

disp(['Combined data written to ', outputFile]);
```

E.6. Plotting script

Listing E.5: Filtering Kinematics Data

```
close all
clc
clear all

% TASK 1
% file1 = 'ID_batch_opensim/ID_mont1_combined/
    ID_isolator1_monteur1_filtered_results_combined.sto'
% file2 = 'ID_batch_opensim/ID_mont1_combined/
    ID_isolator2_monteur1_filtered_results_combined.sto'
%
% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/
    isolator1_monteur1_filtered.mot'
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/
    isolator2_monteur1_filtered.mot'

% TASK 2
% file1 = 'ID_batch_opensim/ID_mont1_combined/
    ID_Klem_kolom1_monteur1_filtered_results_combined.sto'
% file2 = 'ID_batch_opensim/ID_mont1_combined/
    ID_Klem_kolom2_monteur1_filtered_results_combined.sto'

% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/
    klem_kolom1_monteur1_filtered.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/
    klem_kolom2_monteur1_filtered.mot';

% TASK 3
```

```
% file1 = 'ID_batch_opensim/ID_mont1_combined/ID_Klem_paal1_monteur1_filtered_results_combined.sto';
% file2 = 'ID_batch_opensim/ID_mont1_combined/ID_Klem_paal2_monteur1_filtered_results_combined.sto';

% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/klem_paal1_monteur1_filtered.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/klem_paal2_monteur1_filtered.mot';

% TASK 4
file2 = 'ID_batch_opensim/ID_mont1_combined/ID_rijdraad_inbinden1_monteur1_filtered_results.sto'
file1 = 'ID_batch_opensim/ID_mont1_combined/ID_rijdraad_inbinden2_monteur1_filtered_results.sto'
% file3 = 'ID_batch_opensim/ID_mont1_combined/ID_rijdraad_inbinden3_monteur1_filtered_results.sto'

kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/rijdraad_inbinden1_monteur1_filtered.mot';
kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/rijdraad_inbinden2_monteur1_filtered.mot';
% kinematics3 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/rijdraad_inbinden3_monteur1_filtered.mot';

% TASK 5.1
% file1 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_normaal1_2Hz_10ff_2/inverse_dynamics.sto';
% file1 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_normaal2_2Hz_10ff_2/inverse_dynamics.sto';

% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_normaal1_monteur1_filtered.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_normaal2_monteur1_filtered.mot';

% TASK 5.2
% file1 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_ver1_2Hz_10ff_2/inverse_dynamics.sto';
% file2 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_ver2_2Hz_10ff_2/inverse_dynamics.sto';

% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_ver1_monteur1_filtered.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_ver2_monteur1_filtered.mot';

% TASK 5.3
% file1 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_hoog1_2Hz_10ff_2/inverse_dynamics.sto';
% file2 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_hoog2_2Hz_10ff_2/inverse_dynamics.sto';

% kinematics1 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_hoog1_monteur1_filtered.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_filtered_2_Hz/ratel_hoog2_monteur1_filtered.mot';

% third file is not plotted
file3 = 'ID_batch_opensim/ID_mont1_combined/ID_ratel_normaal1_2Hz_30ff/inverse_dynamics.sto';
```

```


forcefile1 = 'Create_force_vector/force_files/ratel_hoog2_force.mot';
forcefile2 = 'Create_force_vector/force_files/ratel_normaal2_force.mot';

% COMPARE WITH RAW KINEMATICS
% kinematics1 = 'All_kinematics/Kinematics_monteur1_raw/klem_kolom1.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_raw/klem_paal2.mot';
% kinematics2 = 'All_kinematics/Kinematics_monteur1_raw/ratel_normaal1.mot';

title_name = 'Task 4, Securing the contact wire'

[Mdata1,Mlabels] = readStoFile(kinematics1);
[Mdata2,Mlabels] = readStoFile(kinematics2);

[data1,labels] = readStoFile(file1);
[data2,~] = readStoFile(file2);
[data3,labels] = readStoFile(file3);

[Fdata1,Flabels] = readStoFile(forcefile1);
[Fdata2,Flabels] = readStoFile(forcefile2);

movement1 = file1(40:50);
movement2 = file2(40:50);

% Select which joints are of interest for plotting
% inverse dynamics files
Rn1=30; %shoulder elev right
Rn2=29; %shoulder plane elev right
Rn3 = 31; % Shoulder axial right
Rn4 = 37; % elbow flex right

% kinematics files
R_K_n1=29; %shoulder elev right
R_K_n2=28; %shoulder plane elev right
R_K_n3 = 30; % Shoulder axial right
R_K_n4 = 31; % elbow flex right

% inverse dynamics files
Ln1=33; %shoulder elev Left
Ln2=32; %shoulder plane elev Left
Ln3 = 34; % Shoulder axial Left
Ln4 = 38; % elbow flex Left

% kinematics files
L_K_n1=37; %shoulder elev Left
L_K_n2=36; %shoulder plane elev Left
L_K_n3 = 38; % Shoulder axial Left
L_K_n4 = 39; % elbow flex Left

% total moment from shoulder DoFs added
Total_shoulder_M1 = sqrt(data1(:,Rn1).*data1(:,Rn1)+ data1(:,Rn2).*data1(:,Rn2));
Total_shoulder_M2 = sqrt(data2(:,Rn1).*data2(:,Rn1)+ data2(:,Rn2).*data2(:,Rn2));

%%
% figure()
% subplot(4,1,1)
%
% plot(data1(:,1),data1(:,Rn1))
% hold on
% plot(data2(:,1),data2(:,Rn1))
```

```
% hold on
% plot(data3(:,1),data3(:,Rn1))
% xlim([0 20])
% ylabel('Moment (Nm)')
%
% title('Shoulder elevation moment')
% legend('rijdraad inbinden 1','rijdraad inbinden 2','rijdraad inbinden 3')
% % legend('isolator','klem kolom','klem paal')
%
% % ylim([-150 100])
% % plot(data1(:,1),data1(:,n1)-10*sin(Mdata1(:,29)))
% % plot(Fdata1(:,1),sqrt((Fdata1(:,2).*Fdata1(:,2))+Fdata1(:,3).*Fdata1(:,3)+
    Fdata1(:,4).*Fdata1(:,4)))
%
%
% % figure()
% subplot(4,1,2)
% plot(data1(:,1),data1(:,Rn2))
% hold on
% plot(data2(:,1),data2(:,Rn2))
% hold on
% plot(data3(:,1),data3(:,Rn2))
% xlim([0 20])
% title('Shoulder plane elevation moment')
% ylabel('Moment (Nm)')
% legend('rijdraad inbinden 1','rijdraad inbinden 2','rijdraad inbinden 3')
% % legend('isolator','klem kolom','klem paal')
%
%
% % figure()
% subplot(4,1,3)
% plot(data1(:,1),data1(:,Rn3))
% hold on
% plot(data2(:,1),data2(:,Rn3))
% hold on
% plot(data3(:,1),data3(:,Rn3))
% xlim([0 20])
% title('Shoulder axial rotation moment')
% ylabel('Moment (Nm)')
% legend('rijdraad inbinden 1','rijdraad inbinden 2','rijdraad inbinden 3')
% % legend('isolator','klem kolom','klem paal')
%
% % figure()
% subplot(4,1,4)
% plot(data1(:,1),data1(:,Rn4))
% hold on
% plot(data2(:,1),data2(:,Rn4))
% hold on
% plot(data3(:,1),data3(:,Rn4))
% hold on
% ylabel('Moment (Nm)')
% xlabel('Time(s)')
% xlim([0 20])
% % plot(Mdata1(:,1),Mdata1(:,31))
%
% title('Elbow flexion moment')
% legend('rijdraad inbinden 1','rijdraad inbinden 2','rijdraad inbinden 3')
% % legend('isolator','klem kolom','klem paal')

%% elbow dynamics hoog
% figure()
```

```
%
% plot(Mdata1(:,1),Mdata1(:,31))
% hold on
% % plot(data2(:,1),data2(:,n4))
% hold on
% % plot(Fdata1(:,1),sqrt((Fdata1(:,2).*Fdata1(:,2))+Fdata1(:,3).*Fdata1(:,3)+
    Fdata1(:,4).*Fdata1(:,4)))

%% elbow dynamics normaal
% figure()
%
% plot(Mdata2(:,1),Mdata2(:,31))
% hold on
% plot(data1(:,1),data1(:,Rn4))
% hold on
% plot(Fdata2(:,1),sqrt((Fdata2(:,2).*Fdata2(:,2))+Fdata2(:,3).*Fdata2(:,3)+Fdata2
    (:,4).*Fdata2(:,4)))

%% Exoskeleton potential

% figure()
%
% plot(data1(:,1),data1(:,Rn1)-10*sin(Mdata2(:,29)/180*pi))
% hold on
% plot(data1(:,1),data1(:,Rn1))
% hold on
% % plot(data1(:,1),Mdata2(:,29))
% % plot(Fdata1(:,1),sqrt((Fdata1(:,2).*Fdata1(:,2))+Fdata1(:,3).*Fdata1(:,3)+
    Fdata1(:,4).*Fdata1(:,4)))
% ylabel('Moment (Nm)')
% xlabel('Time(s)')
% legend('Support 10Nm','No support')
% title('Shoulder moment no support vs exoskeleton tijdens klem paal')
%
% figure()
%
% plot(data1(:,1),abs(data1(:,Rn1)-10*sin(Mdata2(:,29)/180*pi)))
% hold on
% plot(data1(:,1),abs(data1(:,Rn1)))
% hold on
% ylabel('Moment (Nm)')
% xlabel('Time(s)')
% legend('Support 10Nm','No support')
% title('Absolute shoulder moment no support vs exoskeleton tijdens klem paal')
%
% sum(abs(data1(:,Rn1)-10*sin(Mdata2(:,29)/180*pi)))
%
% (sum(abs(data1(:,Rn1))))

%% Plot kinematics filtered left and right
figure()
subplot(2,2,1);
plot(Mdata1(:,1),Mdata1(:,R_K_n1))
hold on
plot(Mdata1(:,1),Mdata1(:,L_K_n1))
% xlim([0 8])
title('Shoulder elevation')
ylabel("Joint Angle (degrees)")
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,2);
```

```
plot(Mdata1(:,1),Mdata1(:,R_K_n2))
hold on
plot(Mdata1(:,1),Mdata1(:,L_K_n2))
% xlim([0 20])
title('Shoulder plane elevation')
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,3);
plot(Mdata1(:,1),Mdata1(:,R_K_n3))
hold on
plot(Mdata1(:,1),Mdata1(:,L_K_n3))
% xlim([0 20])
title('Shoulder axial rotation')
ylabel("Joint Angle (degrees)")
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,4);
plot(Mdata1(:,1),Mdata1(:,R_K_n4))
hold on
plot(Mdata1(:,1),Mdata1(:,L_K_n4))
% xlim([0 ])
title('Elbow flexion')
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')

sgtitle(strcat(title_name));

%% Plot joint moments
figure()
subplot(2,2,1);
plot(data1(:,1),data1(:,Rn1))
hold on
plot(data1(:,1),data1(:,Ln1))
% xlim([0 8])
title('Shoulder elevation')
ylabel("Joint Moment (Nm)")
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,2);
plot(data1(:,1),data1(:,Rn2))
hold on
plot(data1(:,1),data1(:,Ln2))
% xlim([0 8])
title('Shoulder plane elevation')
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,3);
plot(data1(:,1),data1(:,Rn3))
hold on
plot(data1(:,1),data1(:,Ln3))
% xlim([0 8])
title('Shoulder axial rotation')
ylabel("Joint Moment (Nm)")
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')
subplot(2,2,4);
plot(data1(:,1),data1(:,Rn4))
hold on
plot(data1(:,1),data1(:,Ln4))
% xlim([0 8])
title('Elbow flexion')
```

```
xlabel('Time (s)')
legend("Right","Left","Location",'northwest')

sgtitle(strcat(title_name));



%% Plot kinematics raw vs filtered
figure()
subplot(2,2,1);
plot(Mdata1(:,1),Mdata1(:,R_K_n1))
hold on
plot(Mdata2(:,1),Mdata2(:,R_K_n1))
% xlim([0 8])
title('Shoulder elevation')
ylabel("Joint Angle (degrees)")
xlabel('Time (s)')
legend("Filtered","Raw","Location",'northwest')
subplot(2,2,2);
plot(Mdata1(:,1),Mdata1(:,R_K_n2))
hold on
plot(Mdata2(:,1),Mdata2(:,R_K_n2))
% xlim([0 8])
title('Shoulder plane elevation')
xlabel('Time (s)')
legend("Filtered","Raw","Location",'southeast')
subplot(2,2,3);
plot(Mdata1(:,1),Mdata1(:,R_K_n3))
hold on
plot(Mdata2(:,1),Mdata2(:,R_K_n3))
% xlim([0 8])
title('Shoulder axial rotation')
ylabel("Joint Angle (degrees)")
xlabel('Time (s)')
legend("Filtered","Raw","Location",'northwest')
subplot(2,2,4);
plot(Mdata1(:,1),Mdata1(:,R_K_n4))
hold on
plot(Mdata2(:,1),Mdata2(:,R_K_n4))
% xlim([0 8])
title('Elbow flexion')
xlabel('Time (s)')
legend("Filtered","Raw","Location",'northwest')

%% plot shoulder joint moments for clamp pole, task 3 run 1

%
% figure()
% subplot(2,1,1)
% plot(data1(:,1),data1(:,Rn1))
% % hold on
% % plot(data1(:,1),data1(:,Rn2))
% hold on
% % plot(data1(:,1),data1(:,Rn4))
% hold on
% % xline(2)
% xline(2,'-',{'Grab','Object'}, 'LabelVerticalAlignment', 'top');
% hold on
% % xline(11.6)
% xline(11.6,'-',{'Release','Object'}, 'LabelVerticalAlignment', 'top');
% hold on
```

```
% % xline(14.3)
% xline(14.3,'-',{'Grab','drill'}, 'LabelVerticalAlignment', 'top');
% hold on
% % xline(16.25)
% xline(16.25,'-',{'Drilling'}, 'LabelVerticalAlignment', 'top');
% title('Shoulder elevation', 'FontSize', 16)
% % xlabel('Time(s)')
% ylabel("Joint Moment (Nm)")
% xlim([0 20])
% ylim([-5 45])
%
%
% subplot(2,1,2)
% plot(data1(:,1),data1(:,Rn4))
% % hold on
% % xline(2)
% xline(2,'-',{'Grab','Object'}, 'LabelVerticalAlignment', 'top');
% hold on
% % xline(11.6)
% xline(11.6,'-',{'Release','Object'}, 'LabelVerticalAlignment', 'top');
% hold on
% % xline(14.3)
% xline(14.3,'-',{'Grab','drill'}, 'LabelVerticalAlignment', 'top');
% hold on
% % xline(16.25)
% xline(16.25,'-',{'Drilling'}, 'LabelVerticalAlignment', 'top');
% title('Elbow flexion', 'FontSize', 16)
% xlabel('Time(s)')
% ylabel("Joint Moment (Nm)")
% xlim([0 20])
% ylim([-5 45])
%% plot shoulder and elbow joint moments for ratel task 5.1 run 1

% figure()
% subplot(3,1,1)
% plot(data1(:,1),(data1(:,Rn1)))
% hold on
% % xline(2)
% xline(1.92,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.4,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.35,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.88,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.3,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.24,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.73,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.15,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.62,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% title('Shoulder elevation', 'FontSize', 16)
% % xlabel('Time(s)')
```

```
% xlim([1 5])
% ylim([-15 20])
% ylabel("Joint Moment (Nm)")
%
% subplot(3,1,2)
% plot(data1(:,1),data1(:,Rn2))
% xline(1.92,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.4,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.35,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.88,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.3,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.24,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.73,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.15,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.62,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% title('Shoulder plane elevation', 'FontSize', 16)
% % xlabel('Time(s)')
% ylabel("Joint Moment (Nm)")
% xlim([1 5])
% ylim([-15 20])

%
%
% subplot(3,1,3)
% plot(data1(:,1),data1(:,Rn4))
% xline(1.92,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.4,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(2.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.35,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(3.88,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.3,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(4.87,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.24,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(5.73,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.15,'-',{'Push'}, 'LabelVerticalAlignment', 'top');
% hold on
% xline(6.62,'-',{'Pull'}, 'LabelVerticalAlignment', 'top');
% title('Elbow moment', 'FontSize', 16)
% xlabel('Time(s)')
% xlim([1 5])
```

```
% ylim([-15 20])
% ylabel("Joint Moment (Nm)")



%% Report max moment in task

% maxMoment_elev = max(abs(data1(:,Rn1)))
% maxMoment_plane_elev = max(abs(data1(:,Rn2)))
% maxMoment_axial = max(abs(data1(:,Rn3)))
% maxMoment_elbow = max(abs(data1(:,Rn4)))


%% Report mean absolute value for moment in task

% MeanMoment_elev = mean(abs(data1(:,Rn1)))
% MeanMoment_plane_elev = mean(abs(data1(:,Rn2)))
% MeanMoment_axial = mean(abs(data1(:,Rn3)))
% MeanMoment_elbow = mean(abs(data1(:,Rn4)))
```