Bachelor Degree Project

UNIVERSITY
OF SKÖVDE

EVALUATION OF EXOSKELETON USING XSENS SYSTEM INCLUDING SCALEFIT

Bachelor degree project in Product Design Engineering
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Abstract

Although the level of automation in the automotive industry is currently high, real humans are still required for assembly tasks, for example, during overhead tasks. This type of work can cause injuries in workers in this sector, especially musculoskeletal disorders (MSDs), being a cause for the inability to work in developed countries and, in turn, becoming a significant health problem. There is an aim to reduce the risk for these type of injuries during the development processes of this type of assembly operations. Various options are currently being considered where technology and the human factor can be combined. Among them, we find the object of study for this project, an exoskeleton.

The aim of this project is to study the biomechanical effects as well as the ergonomics of a passive exoskeleton called Paexo Shoulder, developed by the company Ottobock, with the aim of relieving tensions in the shoulder joints and upper part of the shoulders, during its use in assembly tasks. For this purpose, an experiment will be designed in which several participants will carry out a series of tasks both with and without the exoskeleton, in such a way that the effects of its use and how they affect the users of the product can be observed. For this purpose, an experiment was designed to evaluate the effects of the use or non-use of this exoskeleton on 10 participants when performing a task similar to an overhead task in an assembly line. For the evaluation of the product, the Xsens motion capture system, in particular the Awinda model, was used together with the ScaleFit software to evaluate the results obtained through the motion capture recordings. In addition, in order to improve Digital Human Modelling (DHM) tools, the same task was simulated with the IPS-IMMA software, where the results were later analysed and compared with the motion capture results through ScaleFit.

The results showed relatively large improvements in the respective moment reduction at the shoulder joint when using the exoskeleton. However, it was also observed that due to the upward force exerted by the exoskeleton on the arms, participants spent less time in low-risk areas evaluated by ScaleFit and therefore, this effect needs to be studied further.

Keywords: Exoskeleton, overhead tasks, musculoskeletal disorders, ergonomic assessments, Xsens system, ScaleFit, IPS-IMMA.

Preface

Many thanks to all the people who have supported us throughout this project, especially to our colleagues in Sweden for helping us to carry out the project, to our supervisor Erik Brölin and our assistant supervisor Francisco Garcia for helping us throughout the project, to our examiner Ari Kolbeinsson for the feedback on the report that has allowed us to improve the project and finally, we would also like to thank Volvo Cars experts Dan Lämkull and Tony Wenlert for the great help they have given us regarding ergonomics and the industry in general. And finally, many thanks to our family and friends in Spain who have supported us from afar throughout the whole process.

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1 Introduction

This chapter introduces the description of the project and its goals, the problem statement and finally, the implementation plan to be followed.

1.1 Description of the project

From a product development point of view, the use of CAD and simulation tools provides value to engineers working in product and production development by enabling virtual testing in early design phases (Becker et al., 2005).

Nowadays, it is getting easier and easier to see the pace at which production is being digitised and automated, but despite the acceleration in the development of modern technologies, there are many jobs in the industry that still require manual handling tasks (Theurel et al., 2018). For instance, automotive and aerospace industries in different manufacturing jobs (Yin et al., 2020a). In particular, it is worth mentioning the work carried out on assembly lines in the automotive sector. This type of task requires many overhead operations. They can cause work-related musculoskeletal disorders (WMSDs)(Maurice et al., 2019), which are the most common cause for inability to work in developed countries; more than 40% of the workers in the European Union continue to suffer from back and shoulder pains (Bosch et al., 2014), and therefore they have become a major health issue and a significant cost factor for companies (Maurice et al., 2020).

These days, robots, as well as handling manipulators, have been used to solve these problems (Schmalz et al., n.d.), and they have been rapidly adopted to perform tasks that require heavy load lifting. Even though they have been proven beneficial in some areas, they are not as agile, versatile and intelligent as a human in order to solve problems (Yin et al., 2020a). In recent years, as an alternative to deal with WMSDs, exoskeleton technology has attracted the attention of manufacturing industries. Exoskeletons are defined as wearable, mechanical structures that enhance the strength of a person; occupational exoskeletons have been designed to physically assist workers in performing their tasks and thus reduce their exposure to the associated physical demand (Theurel et al., 2018).

Some studies have already reported the effects of exoskeleton applications, such as a reduction in shoulder muscle activity when performing various overhead tasks with commercial exoskeleton vests, the increase of productivity or a boost in task performance and a decrease in perceived discomfort (Yin et al., 2020a). A decrease in physical workload of the targeted limb or increased productivity are, however, not sufficient to demonstrate the reliability and safety of an industrial exoskeleton, especially the passive ones (de Looze et al., 2016), several other factors may affect the system's effectiveness. Exoskeletons may restrict and/or modify movements kinematics such as the load transfer or the weight of the system, which can lead to an increment of biomechanical strains elsewhere in the body (Maurice et al., 2020).

This project aims to evaluate a passive upper extremity exoskeleton (Paexo), developed by Ottobock SE & Co. KGaA and commercialized together with Volkswagen AG. In this research, Xsens motion capture system Awinda (a wireless human motion tracker) with ScaleFit (a biomechanical measuring system) as well as subjective ratings and participant feedback will be analysed to evaluate the effects of Paexo while operating overhead tasks.

Furthermore, in order to improve DHM tools, the results extracted from the experimentation will be implemented in IPS-IMMA, where we will try to simulate the task performed with motion capture.

1.2 Problem statement

The purpose of the research presented in this thesis is to evaluate the use of exoskeletons in the automotive industry, more specifically in assembly plants, where workers perform overhead tasks most of the time. The Viva project (https://www.his.se/en/research/virtual-engineering/user-centred-product-design/viva/)intends to investigate ergonomic aspects and usage of exoskeletons in order to find possible advantages that the use of these technologies have to reduce physical load and also to improve Digital Human Modelling (DHM) systems to enable evaluations of different technical aids, for example exoskeletons. The question is, how can biomechanical load when wearing an exoskeleton be assessed and predicted by ergonomics evaluation methods? Also, what functionalities are needed to do similar evaluations when simulating a task using DHM systems?

Thus, it is of vital importance to know the advantages and disadvantages of implementing this type of technology, so attention will be put on possible limitations that the exoskeleton may present, such as the range of motion of workers while using it. Exoskeletons used in overhead operations are usually implemented to reduce the static load by giving support to the upper limbs when raised over the head, even during longer periods of time. However, using exoskeletons could lead to other issues such as injuries and discomfort for the workers wearing them. For this purpose, different overhead tasks will be performed with and without the exoskeleton, so that the results can be compared and a conclusion can be drawn. The exoskeleton under study is the Paexo developed by Ottobock SE & Co KGaA together with Volkswagen AG.

The interpretation of the tests will be carried out using Xsens technology, a provider of 3D motion capture products and sensors based on inertial sensor technology, as well as human motion visualization tools. In addition, the ScaleFit system will be implemented to assess the biomechanical load, as the software is able to visually indicate frame by frame the state of the joints involved in the relevant processes of the automotive workspace.

The objectives involved in the development of the present study are as follows:

- From a product development point of view, we will provide engineers working in fields related to product and production development by improving DHM tools through the use of motion capture technology and ergonomics evaluation tools.
- Evaluate the biomechanical effect of wearing an exoskeleton when performing overhead operations in order to reduce work-related musculoskeletal disorders as well as improving the workers' performance while doing overhead tasks.
- Finding ergonomic assessment methods that can be implemented into IPS IMMA to study the ergonomic changes of wearing an exoskeleton.

1.3 Implementation plan

This project focuses on studying how the use of a passive upper extremity exoskeleton (Paexo) affects the biomechanical load of workers while performing overhead tasks.

As it is shown in the diagram process (*Figure 1*), the project will start by describing and formulating the main problem that the study aims to achieve, followed by some literature research where relevant information for the project related to topics involved (ergonomics, exoskeletons, overhead work, musculoskeletal disorders) will be collected. After that, the Paexo exoskeleton will be tested in a lab, where it will be easier to control the experimentation with the exoskeleton, a lab test will also allow an in-depth investigation of the diverse effects that an exoskeleton could cause, and it avoids possible interferences that could happen with other workers or restricted space. Finally, as a way of global validation of the results obtained in the lab, the exoskeleton should be tested in ecological conditions; however, due to the current situation that the world is facing these days, this project will just focus on analysing the results obtained while testing the exoskeleton in the lab with the Awinda Xsens motion capture system and ScaleFit. This study will be studying the results obtained during the experimentation and finding ergonomic assessment methods which could be implemented into IPS IMMA in order to finally study the ergonomic changes of wearing an exoskeleton.

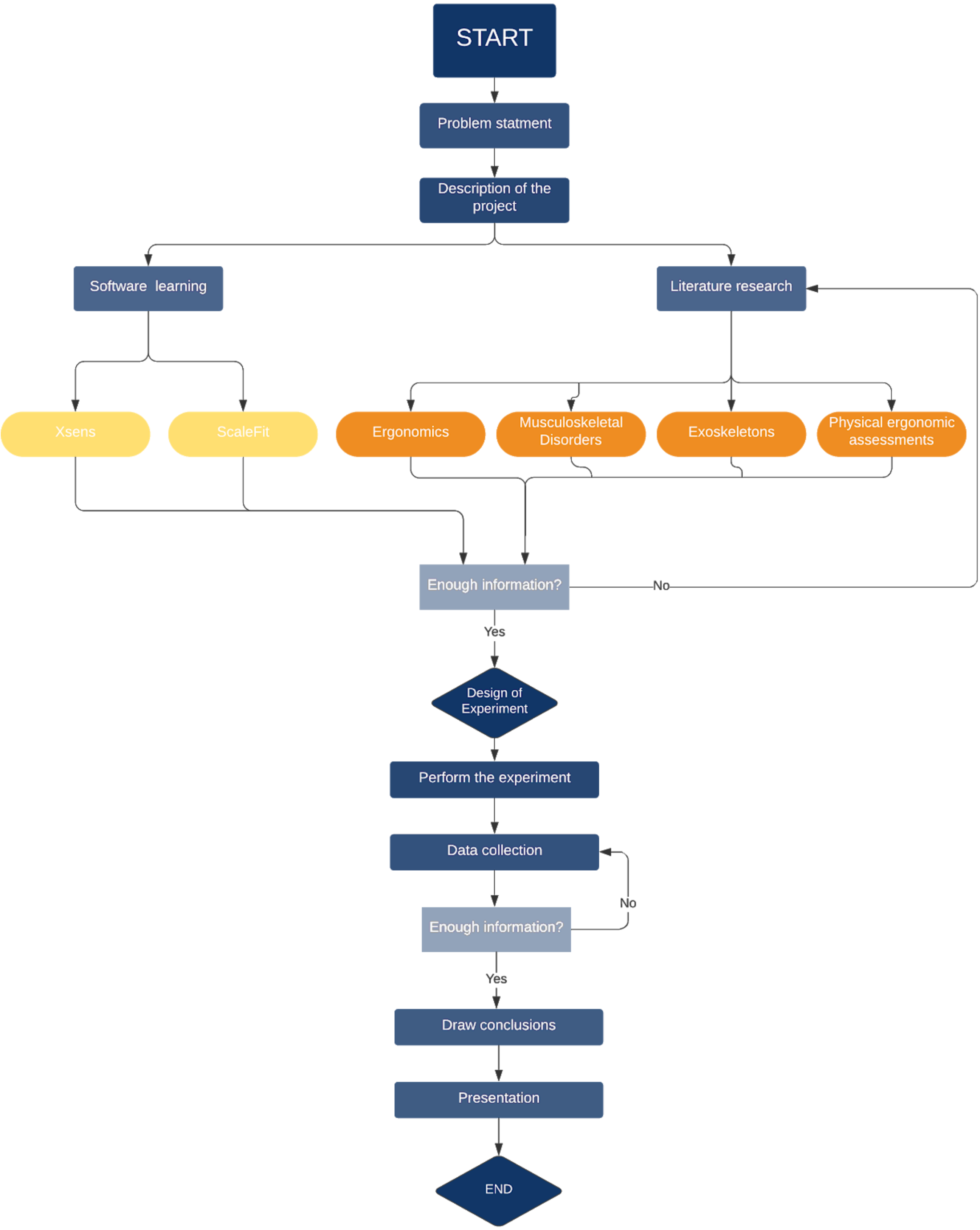


Figure 1. Project process diagram.

2 Literature study

This chapter includes different relevant and useful information extracted from various studies related to the field of studies, such as ergonomics, musculoskeletal disorders, exoskeletons, and ergonomic assessments.

2.1 Ergonomics

According to the International Ergonomics Association (IEA), "*Ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimise human well-being and overall system performance*" (https://iea.cc/definition-and-domains-of-ergonomics/). Ergonomics emerged from the problems and needs of humans as a research field to efficiently interact with the ever more advanced and demanding technology and industry in the mid-20th century (Pheasant and Haslegrave, 2005). This research field has been evolving through the years, and nowadays, it is divided into three different domains of specialization depending on the human attributes or human characteristics interaction (Berlin and Adams, 2017):

- Physical ergonomics: concerned with human anatomical, anthropometric, physiological and biomechanical characteristics (physical activity).
- Cognitive ergonomics: Concerned with mental processes, such as perception, memory, reasoning and motor response (mental processes).
- Organisational Ergonomics: Concerned with the optimisation of sociotechnical systems, including their organisational structures, policies and processes (sociotechnical systems).

The focus of ergonomics is the optimisation of the interaction between humans and machines, which should not be just seen as industrial machines but also workplaces, system´s tools, products and public spaces (Wiley, 2012). Improving ergonomics within different processes will not only increase human performance and productivity but also reduce the level of risk factors in the workplace, which could lead to musculoskeletal diseases (Dombrowski and Wagner,2014).

Hence good ergonomics is achieved when the capabilities of humans match the demands given by the machine or tasks. Meeting this objective can be achieved through a human and user centred design process that aims at making systems more usable by focusing on the use of the system and applying ergonomics and usability knowledge and techniques (ISO,2009).

When talking about ergonomics, concepts related to anthropometry come up automatically. Anthropometrics is the branch of the human sciences dealing with measurements of the size, weight and proportions of the human body to achieve comfort, fit and usability. (Hanson et al., 2008). It is known that humans are different from each other (proportions, dimensions, etc.), and user-centred design requires an understanding of this variability. (Pheasant and Haslegrave, 2005). Due to these variations in the individual human being, it is a challenge to the designers to come up with solutions that will optimally fit the diverse anthropometry of the users and satisfy their task demands, and it is necessary to obtain relevant information or data on task performance, equipment, working posture and environment in order to be able to reach the majority of users intended to use that workspace. (Das and Sengupta, 1996).

2.2 Musculoskeletal Disorders

The following sub-chapters develop in depth the musculoskeletal disorders, defining what they are in a more specific way, their direct relation to overhead tasks, as well as possible solutions to reduce their incidence in the world of industry.

2.2.1 What are Musculoskeletal Disorders (MSDs)?

Based on Musculoskeletal disorders (MSDs) are defined as "injuries or disorders of the muscles nerves, tendons, joints, cartilage and spinal discs", and they are described as Work-related musculoskeletal disorders (WMSDs) when the conditions that cause them are related to the work environment and performance of work or when the conditions mentioned make these injuries persist longer(Bosch et al., 2014). Some examples of MSDs would be sprains, back pain, carpal tunnel syndrome, hernia (*Figure 2*) (Howard, 2004).

Musculoskeletal disorders (MSDs) were recognized as having occupational etiologic factors as early as the beginning of the 18th century. However, it was not until the 1970s that occupational factors were examined using epidemiologic methods, and the work-relatedness of these conditions began appearing regularly in the international scientific literature. Since then, the literature has increased dramatically; more than six thousand scientific articles addressing ergonomics in the workplace have been published. Yet, according to the National Institute for Occupational Safety and Health (NIOSH), the relationship between MSDs and work-related factors remains the subject of considerable debate (https://www.cdc.gov/niosh/docs/97-141/default.html).

The risk for musculoskeletal disorders among workers seems to be ordered along a continuum from typical pain associated with activities for which universal preventive interventions usually are effective to chronic and severe disorders for which only individually designed, intensive, comprehensive, and sustained interventions have any chance of success (Melhorn and Gardner, 2004).

In an interview with the ergonomics manager of Volvo Cars, a company where the use of exoskeletons is being evaluated, he was asked about the most common musculoskeletal disorders. The interview gave that the most common MSDs in the Volvo assembly factories were in the hands, wrists and fingers (34%) and in the neck and shoulders (30%).

Obesity is also a high-risk factor in the development of musculoskeletal problems; a number of studies have reported that obesity is related to a variety of musculoskeletal disorders ranging from osteoarthritis (in both the knee and hip) to joint pain. From a public health perspective, the identification of high-risk individuals using multiple characteristics could be used as a disease management tool for the monitoring and medical intervention of at-risk patients. (Kortt and Baldry, 2002).

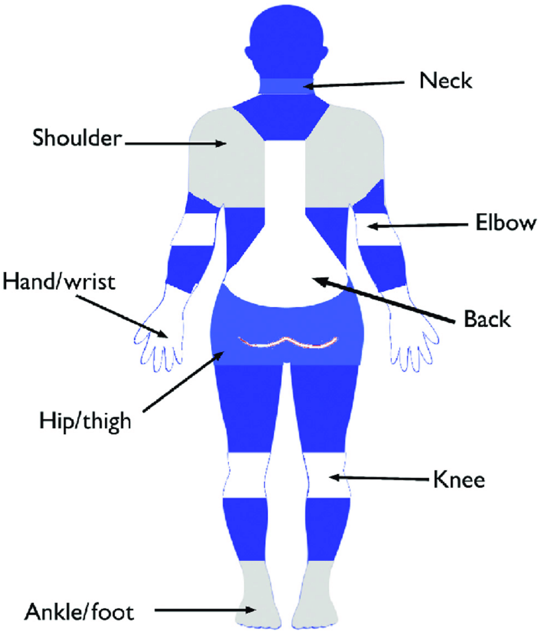


Figure 2: Body map of musculoskeletal regions (Image from https://www.researchgate.net/figure/The-body-map-of-musculoskeletal-regions-based-on-the-Standardized-Nordic-Questionnaire_fig1_315812428)

2.2.2 Overhead tasks and their relation with MSDs

Overhead work is defined as any work that requires the hands in a position above the height of the shoulders, in essence, above the head (Grieve and Dickerson, 2008). It occurs in several work situations and has been recognised as an important risk factor for upper extremity (UE) musculoskeletal disorders (MSDs) (Rashedi et al., 2014).

While risk factors for shoulder MSDs appear to be complex and multifactorial, repetitive overhead work (defined here as working with a hand above the head) appears to be an important specific risk. In fact, several studies have found relationships between the development of musculoskeletal shoulder disorders (MSDs) and work exposures, including static efforts, insufficient recovery or rest and non-neutral postures (Sood et al., 2007).

Furthermore, these Work-Related musculoskeletal disorders (WMSDs) are often accompanied by pain. Working with the arms raised over 90° of anteversion for more than 10% of the working hours increases the risk of WMSDs in the shoulder region by one to two thirds. This leads to the conclusion that these postures are directly related to extremely high stresses in the shoulder joint (Schmalz et al., 2019).

Besides, overhead work creates complex physiological effects on the shoulder area (e.g., increased intramuscular pressure, muscle fatigue) or biomechanical demands (e.g., higher tissue load). However, it is still heavily needed in many industrial manufacturing jobs, such as installation/repair work at the bottom of the vehicle, installation/maintenance inside the aircraft fuselage, and these jobs may not be easily replaced in the workplace. (Yin et al., 2020b)

2.2.3 Possible ways of tackling MSDs related to overhead tasks

If the risks of MSDs related to overhead tasks can be reduced, the health of workers and possibly also the productivity of the company will increase. According to the European Agency for Safety and Health at Work (EU-OSHA), tackling MSDs includes new ways of preventing these injuries as well as rehabilitation, retention, and reintegration of workers who have suffered from these disorders (https://osha.europa.eu/es/about-eu-osha).

Focusing on ways of preventing MSDs, nowadays there are some ergonomic measures such as the use of handling devices (e.g. hand-held manipulators) which have proved that even though they increased the level of "movement effort" and the lack of the necessary flexibility when working, they have proved its benefits in some areas (Schmalz et al., 2019).

There are also some projects going on focused on finding other ways of tackling WMSDs, for example, the Andy Project, which is a research project that aims to study how to prevent this kind of injuries by implementing a human-robot collaboration; this project has received funding from the European Union's Horizon 2020 Research and Innovation Programme. This study focuses on three different scenarios where robots and humans interact actively and safely in the same workspace (*Figure 3*) (https://andy-project.eu/).

- First Scenario: A collaborative robot (robot=corobot) where physically works with the human in order to improve its productivity, health and flexibility.
- Second Scenario: The robot is an exoskeleton (robot=exoskeleton) that provides physical collaboration for improved health, productivity and flexibility.
- Third Scenario: The robot is a humanoid (robot=humanoid) that helps humans with physical collaboration.

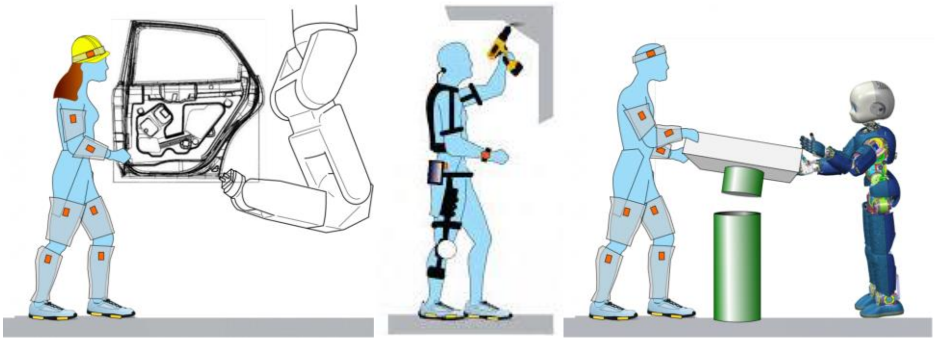


Figure 3. First, second and third scenario from Andy project (Images from Andy project).

2.3 Exoskeletons

The following sub-chapters explain and further develop what exoskeletons are, their uses within the industry and how they affect the range of motion. In addition, the exoskeleton of the Ottobock group, which is the focus of the study, is explored.

2.3.1 What are the exoskeletons

An exoskeleton is a wearable structure or system designed to enhance the wearer's strength or agility through assistive torques and/or structural support (Maurice et al., 2020). They are an example of human-machine physical collaboration, where the device is worn by a person, and the physical contact between the operator and the mechanical structure allows the direct exchange of power and information signals. Even though this technology was originally created for military and rehabilitation purposes, through the years, this technology has been captivating more and more attention by the manufacturing industries since it is a good fusion between human flexibility and robot power enhancement (Spada et al., 2017).

Exoskeletons can be classified into different categories, among which we find aspects such as intended use, power requirements, construction materials, form factors or working principles (Perez Luque et al., 2020). Focusing on working principles, this type of machine can be divided into two different types (Yin et al., 2020):

- Passive exoskeletons: These do not need external power. Instead, they use mechanical actuation and/or springs and dampers for transferring and restoring energy or forces from different parts of the body to other ones.
- Active exoskeletons: Which need at least one actuator to provide energy to the body through actuating the human joints.

Some investigations related to this field have already proven its benefits on musculoskeletal strains (Theurel et al., 2018). They can reduce the personnel costs of the health system while potentially achieving similar functions and health results. Compared to treadmills or robot-based methods, exoskeletons can provide ground mobility in homes and healthy places for individuals who may not be able to achieve this level of functionality through conventional therapies. However, these devices are still in the early stages of development, and there is a lack of strong evidence regarding clinical and cost-effectiveness, and suppliers are exploring the best ways to utilize these technologies for clinical and financial feasibility. (Heinemann et al., 2018).

2.3.2 Ways exoskeletons contribute to the industry

It is known that in industrial manufacturing processes, robotic solutions can perform tasks requiring large forces; however, they do not provide manipulation ability, dexterity, flexibility, problem-solving capacity and quality, which are proper of human beings (Spada et al., 2017).

Furthermore, many activities in the automotive industry should be done by humans, and exoskeletons present beneficial functionalities that might address industrial ergonomic needs like postural load compensation, upper limb request or adaptability in task choice (*Figure 4*) (Nahema et al., 2014).

There are a lot of experiments that have been done on the question of how beneficial it is to use an exoskeleton; in Theruel et al. (2018), the observed reductions of muscle activity in the low back region illustrate the good potential of the passive exoskeleton to reduce the internal muscle forces and (reactive) spinal forces in the lumbar region. From these, it can be concluded that a passive exoskeleton might form an effective strategy to reduce the risks of developing work-related low back pain in forwarding bent work (Bosch et al., 2014).

Several studies showed that the use of an exoskeleton could reduce normalized fatigue levels in the arm muscles, e.g. Maximum fatigue reduction by 45% and drilling task time reduced by almost 20%. The results showed that the use of exoskeletons could reduce the physical strain on the user's body when working overhead and, in some cases, improve work efficiency (Yin et al., 2020b).

Although the field of study is the application of exoskeletons in the automotive industry, it is applicable and useful in other industries such as construction and any other sectors involving human effort that can lead to muscular problems.

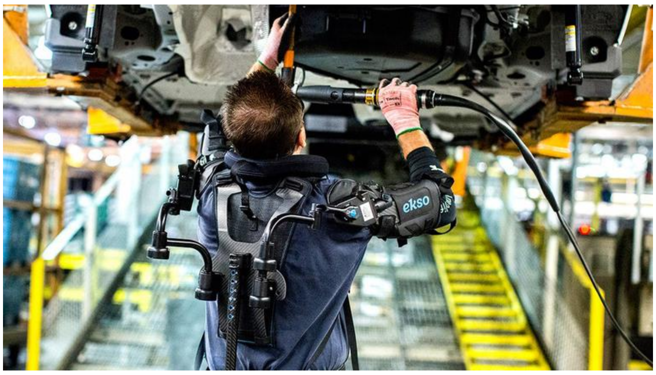


Figure 4. Manufacturing worker with an exoskeleton (Image from https://www.machinedesign.com/article/21836235/manufacturing-workers-become-more-than-human-with-exoskeletons)

2.3.3 Paexo exoskeleton

The Paexo exoskeleton developed by Ottobock SE & Co. KGaA in collaboration with Volkswagen AG commercialized (*Figure 5*), is a 1.9 kg upper-limb passive exoskeleton that provides support to the people’s arms, especially while developing tasks where they have to lift their arms for long periods of time (Maurice et al., 2019), this device mitigates strain on the shoulder joints and upper arms, for this reason, this exoskeleton is useful while performing overhead tasks on assembly lines and in the building trade (https://paexo.com/).

The Paexo Shoulder was designed for use in industrial applications, for example, by automobile manufacturers, aeroplane hangars and shipyards, trade enterprises or logistics companies. In these settings, Paexo Shoulder supports people who carry out physically demanding tasks on a daily basis, such as overhead work in assembly.

Workers wear Paexo Shoulder close to their body, similar to a backpack. When they raise their arms, the forearm pads transfer this weight to the hips thanks to mechanical cable pull technology. This provides noticeable relief for the muscles and joints in the shoulder region.

The assistive structure of the exoskeleton, designed to create a support moment that varies with the arm elevation angle, where the maximum support moment results when the upper arm is at an angle of 90°, provides support for the user's arm by transferring part of the weight of the arm to the pelvis through the hip belt (Maurice et al., 2020). More kinematic details related to the Paexo structure as well as an analysis of the mechanical design are presented on the exoskeleton product webpage https://paexo.com/paexo-shoulder/?lang=en .

Figure 5. Paexo shoulder exoskeleton by Ottobock (Image obtained from https://paexo.com/?lang=en)

2.4 Physical ergonomics assessments

Ergonomic assessment is an objective measurement of the risk factors that may lead to musculoskeletal diseases or injury to workers in the work environment. The main goal of an ergonomic assessment is to identify and quantify these risk factors so that you can make measurable improvements in the work environment. In addition, the ergonomics assessment methods give results in some action categories, often related to the traffic light scale (green, yellow and red) relying on a visual system.

In recent years, even work environments that are considered low risk of injury have begun to undergo comprehensive ergonomic assessments. This is because although impact injuries and other serious injuries suffered in the workplace have decreased, musculoskeletal diseases (MSD) related to repetitive stress have increased (Proactive, 2019).

In ergonomics, the posture and movement of workers are important information for determining the risk of musculoskeletal injuries in the workplace. Different methods and tools have been developed to assess risk factor exposure for work-related musculoskeletal diseases (MSD) (Plantard et al., 2017).

The Rapid upper limb assessment or RULA is a popular postural analysis method for industrial applications. An advantage of this method is that the scoring sheet is simple, intuitive and straightforward. This advantage contributed to making RULA easy to use for the novice as well as experienced ergonomists (Nahavandi and Hossny, 2017).

Another popular assessment method is OWAS (Ovako Working Posture Analysing System) which is a simple observation method for postural analysis (Kivi and Mattila, 1991).

However, it must be borne in mind that the use of these ergonomic assessments, even experienced ergonomists will make different assessments that could even lead to different results (Forsman et al., 2002).

At the University of Sherbrooke, with workers from three industrial sectors, it was concluded that it is really important for the practitioner to collect ratings from more than one employee, if possible, for each analysed job position and to check whether these respondents reported pain in the previous seven days. The findings also indicate that, from an MSD prevention perspective, the judgment of an ergonomic expert may be more appropriate for detecting vulnerable workplaces (Chiasson et al., 2015).

For this reason, using the language incorporated in the Xsens and Scalefit software would be a direct measuring method that is more objective and potentially more accurate since they use standards such as DIN EN 1005-4 and ISO 11226:2000 related to ergonomics evaluations.

3 Method

3.1 Approach

An experimental study was designed to assess the ergonomics of wearing an exoskeleton while performing overhead operations during assembly tasks. The experiment included three tasks to be performed using the Paexo Shoulder exoskeleton and then without it. The tasks were performed in a simulated workspace to be as representative as possible. Using the technology provided by Xsens and Scalefit, as well as a set of subjective questions to people who performed the tasks, data was collected to evaluate the ergonomics of the exoskeleton. In addition, a simulation will be carried out using the IPS IMMA software, in which the representation scenario will be recreated as well as the task to be executed. By creating manikins based on two of the test participants, we will compare the results obtained with the simulation and those obtained in Scalefit and Xsens.

3.2 Group of study

The object of study is workers in production plants in the automotive industry. These workers are carrying out tasks that cannot be replaced by robots or machines since it is practically artisan assembly work.

As they cannot be replaced, it is vitally important to provide the workers with some sort of relevant lifting aids, as many of these tasks are performed in unnatural positions that place high demands on the joints, especially overhead tasks. The solution that is being studied and continues to be developed is to implement the use of exoskeletons which reduce the loads and strains that these workers must carry out.

For the execution of this experiment, a sample representing the intended or actual user group shall be recruited to take part in the test. The sample of users shall be selected to model the distribution of relevant user characteristics within the specified user group (the characteristics that differentiate the people in the selected user groups is explained in ISO 20282-1). Once the study group has been identified, tests and experiments will be carried out with volunteer participants, and the conclusions drawn will be applied to the automotive atmosphere and assembly lines.

3.2.1 Participants

As for the participants in the experiment, several questions (*Appendix A*) of interest were put to the Global Strategy Manager Ergonomics at Volvo Car. Data were provided on the percentage of men and women currently working in the assembly plants, which was 69.9% male and 30.1% female. The age of the workers was also discussed, ranging from 18 years old to over 50, with an average of 38 years old. In the end, the experiment was carried out on ten subjects, seven men and three women. As for the age range, due to the current pandemic, the experiment was carried out with cohabitants, so the final range was from 20 to 25 years old. Furthermore, the physical fitness of the participants was taken into account; all of them have an active life and healthy habits. As for the dominant hand, there were eight right-handed and two left-handed subjects, which affected the way the experiments were carried out slightly due to ergonomic issues. The average height was 175.5 centimetres. Finally, it should be noted that none of the participants was familiar with the task or the tools used in order to obtain the fairest possible results.

3.3 Analysis criteria

In this project, an operation performed by workers in assembly lines (overhead tasks) will be analysed. For that, the postures adopted by the participants during the experimentation while doing these tasks will be captured through motion capture sensors, where a high level of fidelity to the postures adopted in real environments is expected.

For this study, there will be some key parameters that will be analysed in order to observe the possible advantages or disadvantages of performing a task with and without an exoskeleton.

- Arm elevation
- Shoulder moment
- Time performing the task
- Overall effects in the body
- Weight analysis

3.3.1 Key parameters

Arm elevation:

In order to prevent musculoskeletal disorders, according to ISO standards (ISO 11226:2000), it is important not to exceed 60°, this being a limit angle. For this reason, the amount of time the arms are raised above 60° in this task and how this may affect the appearance of musculoskeletal disorders will be studied with a 0 kg weight in order to make the lifting of the arm the only conditioning factor of the movement.

Shoulder moment:

Shoulder injuries account for 30% of all injuries in the assembly plants of Volvo Car; therefore, to determine the moment exerted when operating with overhead tasks, the shoulder moment with and without the use of the exoskeleton will be analysed to quantify the possible assistance provided by the Paexo Shoulder. These parameters will also be studied with a 0 kg load in order to find out the minimum moment that a worker could be facing while operating overhead tasks.

Time performing a task:

For the purpose of analysing whether task performance has been altered with the use of the exoskeleton, the time each participant needed to perform the operation will be analysed to check whether productivity or task performance was degraded with the use of this device. As a relatively novel object, the exoskeleton could either hinder the participants' ability to navigate the scenario, or its mechanical properties could speed them up and reduce the time taken to perform the task. In addition, this information corroborated with the response of Volvo Cars' Ergonomics Manager on this issue, *"The task time is not in general significantly affected"*.

Overall effects on the body:

Another of the most pronounced aspects during overhead work is the trochlear area and the back. Therefore, special attention should be paid to disc compression as well as trunk inclination. The trunk's ability to move when wearing the exoskeleton and without it will also be analysed in order to conclude on the limitations it may present in terms of movement limitation as well as to assess if wearing an exoskeleton does increase biomechanical strain in this other part of the body or not.

Weight analysis:

The data analysis should study how weight-bearing affects the performance of the participants, more specifically, how it affects the moment during the task and how the assistance of the exoskeleton influences depending on the load that the participant is holding.

3.4 Scenario

The experiments are going to be carried out in ASSAR (*Figure 6*), an Industrial Innovation Arena in Skövde (Sweden). ASSAR is a research centre where several companies develop projects with the aim of solving problems related to the world of industry.

Figure 6. ASSAR Industrial Innovation Arena (Image from https://businessregionskaraborg.se/automotive-motor-for-utveckling/)

For the realization of the task, this experiment will try to simulate a real workplace scenario for overhead operations. Using information provided by Volvo Cars, a company where the use of exoskeletons is being evaluated, a replica as similar as possible to an assembly operation area will be created. In real conditions, the worker performs the assembly task under a statically elevated car at the height of 175 cm from the ground.

The test scenario consists of a 90 x 95 cm (width x length) wooden board (*Figure 7*) placed on top of a shelf 198.5 cm above the floor; the participant performs the task under this badge, this elevation also helped us for testing the use of the exoskeleton in extreme conditions. On the shelf described below, the tools used to develop the experiments are located in several spaces at different heights, and during the development of the task, these tools are deposited on an auxiliary round table (70 cm in diameter) with 103 cm height located to the right of the board.

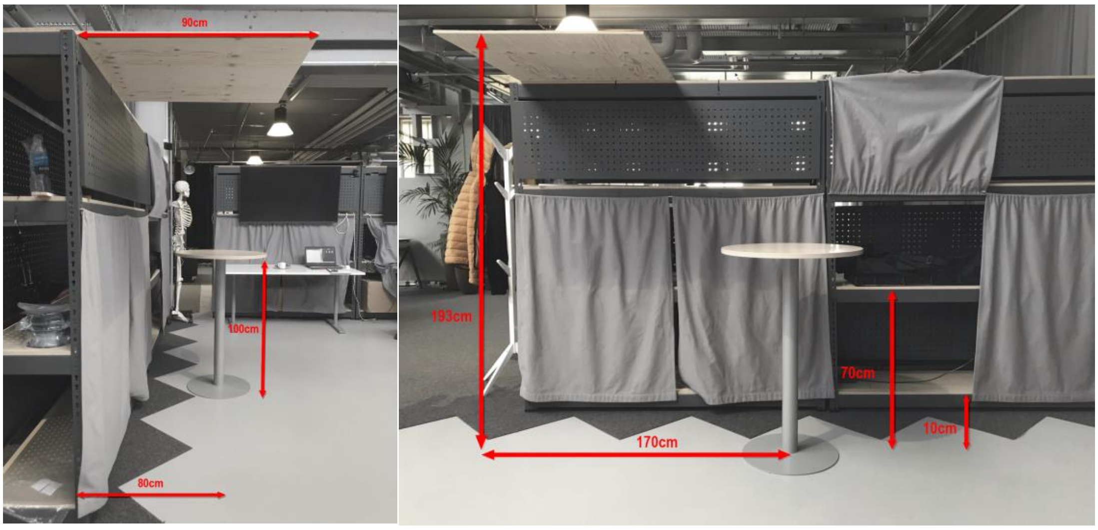


Figure 7. Dimensions of the testing area.

3.5 Experimental tasks

This subchapter will describe the common procedure in a real overhead task as well as the task to be performed in the experiment as a simulation of these tasks.

3.5.1 Description of an overhead task in natural conditions

Based on information from papers as well as an interview with an expert in virtual manufacturing and ergonomics at Volvo Cars in Gothenburg, a description was given about the actual working conditions in overhead tasks at the company where the use of exoskeletons in the assembly plants is evaluated (*Figure 8*).

Although it may vary depending on the manufacturing plant, a worker usually rotates tasks every 30 minutes. Therefore, one operator changes between 4-6 different tasks during one working shift. The natural operation in the factory consists of the attachment of plastic plates underneath the car station. The cars are statics and raised to a height of 1.75 cm from the floor, and at that specific height, the task is performed.

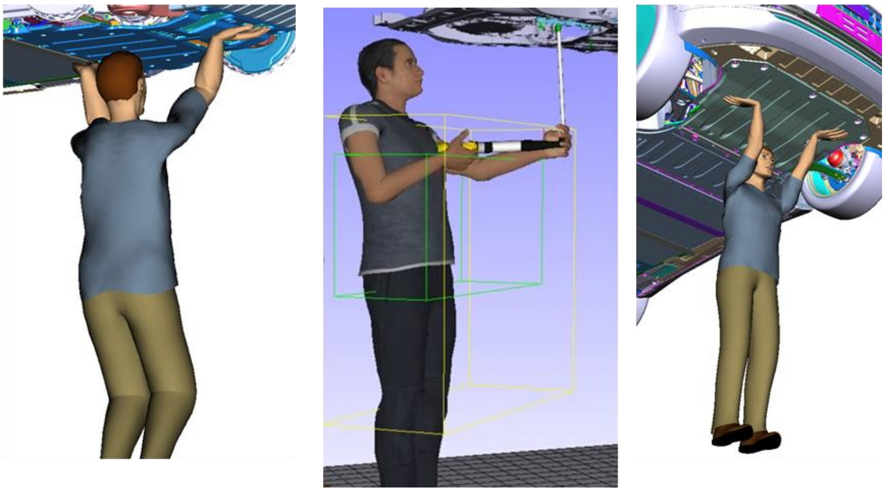


Figure 8. Overhead task simulation (Image provided by Volvo Cars)

3.5.2 Pilot task

Before undertaking the definitive task to test the use of the exoskeleton, two pilot tests were performed in order to have an overall understanding of the data as well as relevant parameters to focus on while doing the experimentation; these pilot tasks also served for having a better understanding of how the development of the experiment was going to be and how the different instrumentation was going to be used. These tasks were conducted by two different participants in order to confirm that the results observed were true.

Description of Pilot Task 1:

- Description of the task: This task consists of screwing four screws in different nuts located on a wooden board at the height of 198.5 cm and where the operator must stand underneath it to complete the operation (overhead task).
- Number of workers involved: 1
- Instruments used during the task performance: Electric screw drill "Meec Multiseries 18V" (Approx. 1.3kg), screws (4 units of indoor screws).
- Task character: This task is considered a semi-static condition (SSC) operation due to a minor level of alterations in the region of the shoulder and elbow joint angles.
- Task duration: Approx. One and half minutes
- Estimated workload: Low

Description of Pilot Task 2:

- Description of the task: In this task, two plates that will simulate the crankcase of a car will be screwed to the wooden board. To do this, the operator will first fix the screw between the plate and the board and then proceed to screw; this process will be executed four times.
- Number of workers involved: 1
- Instruments used during the task performance: Electric screw drill "Meec Multiseries 18V" (Approx. 1,3kg), screws (4 units of indoor screws, 2 wooden plates (simulating the crankcase)
- Task character: This task is considered a semi-static condition (SSC) operation due to a minor level of alterations in the region of the shoulder and elbow joint angles.
- Task duration: Approx. 2 minutes
- Estimated workload: Low

3.5.3 Experimental task description

From the two pilot tasks, a new task was developed containing the positions performed in both overhead tasks as well as low tasks, the purpose of which is to better study the effects of an exoskeleton in extreme working conditions (moment and range of motion) and to condense all the data into one task. At the same time, this task also seeks to evaluate certain parameters such as the height (which in the experiment is somewhat higher than the real one) or the range of movement of the operator (in normal conditions, he must only make a slight movement/turn to reach the tools and in this case, he must take a few steps to reach them) are modified.

Figure 9. Experimental Overhead task.

DESCRIPTION OF THE TEST TASK:

- Description of the task: The task (*Figure 9*) includes both low and high positions and consists of collecting the screws and wooden plates from a storage system with different heights (one of them located close to the floor). Once the necessary materials have been collected, they will be placed on an auxiliary table where the user will maintain an optimal distance from the main wooden board located 198,5 cm high to perform the task of screwing the plates to the board. Each plate has two holes and a total of 4 screws need to be screwed in to finish the task.
- Number of workers involved: 1
- Instruments used during the task performance: Electric screw drill "Meec Multiseries 18V" (Approx. 1,3kg), screws (4 units of indoor screws), 2wooden plates (simulating the crankcase)
- Task character: This task is considered a semi-static condition (SSC) operation due to a minor level of alterations in the region of the shoulder and elbow joint angles.
- Task duration: Approx. 2 minutes
- Estimated workload: Low

3.6 Instrumentation and data processing

This subchapter explains the different instruments and data record that is going to be used during the experiment to collect different data about the biomechanical effects of wearing an exoskeleton or not during overhead operations.

3.6.1 Xsens motion capture system

Xsens is a provider of 3D motion capture systems based on inertial sensor technology. The Xsens MVN product line has two hardware versions: MVN Link and MVN Awinda (*Figure 10*). MVN Awinda uses 17 wireless sensors, which are fitted on the body with adjustable straps, whereas with MVN Link, the wired sensors are fitted on the body with a Lycra suit. Finally, for the execution of the experiment, we will use the Awinda version, which is an easy to integrate wireless human motion tracker for real-time applications. The patented Awinda protocol ensures highly accurate time-synchronized data sampling (within 10 µs) in all connected MTw's, which is essential for accurate joint angles. It can be used in multiple situations and for different purposes like ergonomics, health and safety, sports, research, virtual reality or human machine interaction.

Figure 10. Awinda Motion Capture Tracker.

3.6.2 ScaleFit

ScaleFit is a biomechanical measuring system that can visualize the physical workload in real-time under actual conditions. ScaleFit helps identify different load types such as force, awkward posture and repeated load in diverse body regions, evaluating them according to biomechanical and ergonomic standards. ("Home - scalefit englisch," n.d.) ScaleFit is able to animate graphically and assign body postures and joint forces detected by Xsens IMU sensors and through synchronised recordings between both systems in order to detect health hazards, identify exposure risks or prevent musculoskeletal disorders (*Figure 11*).

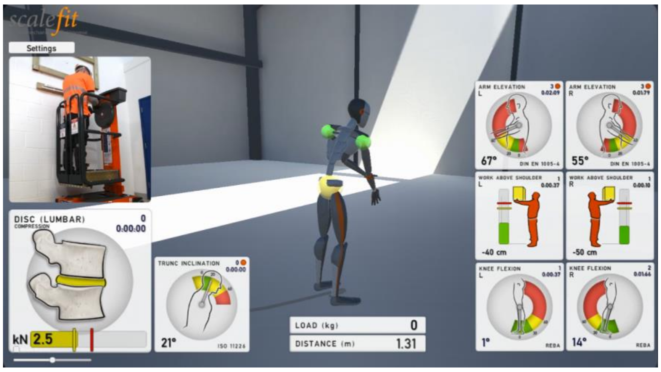


Figure 11. ScaleFit software (Image from https://www.scalefit.de/).

For this project, the ScaleFit measuring system will be used together with the Xsens motion capture system, specifically, Awinda human motion tracker. During the experiment, the participants will perform different activities with and without the exoskeleton while wearing IMU sensors of the Awinda human motion tracker. The movements of the participant will be recorded and using ScaleFit; those postures will be analysed through graphic animations (*Figure 12*).

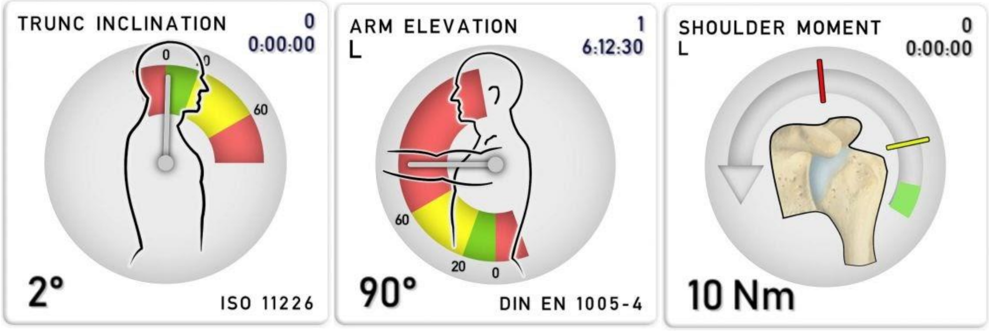


Figure 12. Examples of ScaleFit parameter boxes.

3.6.3 IPS-IMMA

IPS IMMA enables the simulation of assembly work with a digital human body model. The software is able to simulate collision-free assembly movement of humans and objects to be assembled and taking into account the diversity of humans (*Figure 13*). The comfort function of the manikin is designed to minimize the biomechanical load and provide users with the convenience of not having to place all joints individually. This type of computer analysis contributes to a more effective assembly planning process and could possibly lead to a reduced number of injuries and a higher level of quality. To implement this software in our project, a scenario will be created with the use of CAD software and the task will be simulated on two manikins that have the same measurements as two of the participants who carried out the real experiment. Finally, the data will be exported and analysed and compared with the data extracted from the other tools to be used.

Figure 13. Example of a simulation with IPS IMMA (Image obtained from https://industrialpathsolutions.se/).

3.7 Testing procedures

Following the ISO standard on "Usability of consumer products and products for public use - Part 2: Summative test method" (ISO/TS 20282-2:2013, IDT), as well as the Swedish standard on "Safety of machinery - Human physical performance - Part 1: Terms and Definitions" (SS-EN 1005-1+A1:2008); a procedure for testing the use of exoskeletons during overhead operations, will be carried out in order to corroborate the following hypotheses and sub-hypotheses:

Main hypothesis:

H1: The ergonomics when using an exoskeleton is better than the ergonomics when not using an exoskeleton for assembly work.

H0: The ergonomics when using an exoskeleton is worse or equal than the ergonomics when not using an exoskeleton for assembly work.

Sub-hypothesis:

SH1A: The biomechanical load when using an exoskeleton is lower than the load when not using an exoskeleton for overhead assembly work.

SH0A: The biomechanical load when using an exoskeleton is higher or equal than the load when not using an exoskeleton for overhead assembly work.

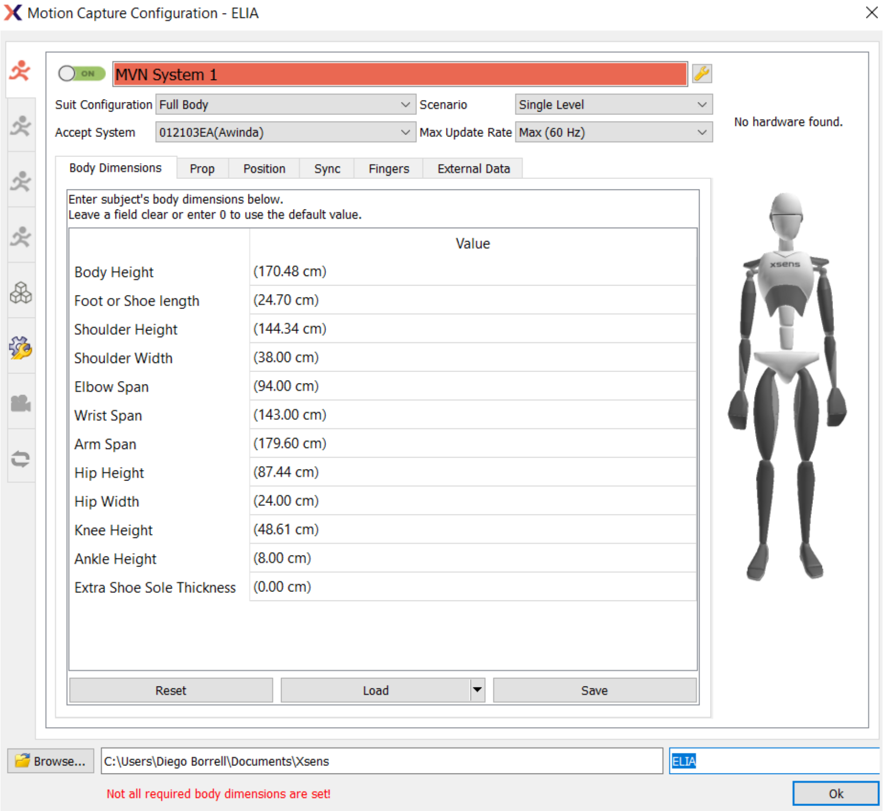
SH1B: The total time when using an exoskeleton is higher than the time when not using an exoskeleton.

SH0B: The total time when using an exoskeleton is shorter or the same as the time when not using an exoskeleton.

The experiment is divided into two weeks, where the procedure carried out in each of them will be explained below.

During the first week, the main focus was on initial preparations before starting to test the final task with participants. For this purpose, once in ASSAR, the instrumentation required to carry out the test was prepared, the necessary measures were taken to carry out the task and the test scenario was checked to ensure that it was in good condition. Once the initial preparations were ready, as mentioned in section 3.6.2, in order to obtain a general understanding of the parameters to be obtained and how the experiment was to be conducted, two short tasks containing parts of the general task were developed with only two participants. Finally, the data obtained in ScaleFit through these operations were studied.

In the second week, the evaluation of the overall task was performed. Before starting the experiment, each participant was briefed on how to proceed while answering possible questions about the task to be performed. To conduct the experiment, the measurements of each user were first taken and entered into the Xsens program (*Figure 14*); once the measurements were entered into the software, the participant was helped to place the sensors on the determined points of the body and later the person was calibrated with Xsens, depending on the subject, the calibration varied between starting in T-pose or N-pose until an acceptable result was obtained. When performing the task, all the participants had to start and end each task in a standing position (N-pose) and as a control for the experiment, the order of task performance with and without the exoskeleton was varied between participants to ensure that participants were not influenced by the use of the exoskeleton during task performance. At the same time, during the experiment, participants rested for approximately 5 minutes between tasks to prevent fatigue from being a factor that altered the results; after the break, the remaining task was carried out. Once both tasks were completed, each subject was asked to fill in two questionnaires (NASA TLX), one about their performance with and one without the exoskeleton.



MVN System 1

Suit Configuration: Full Body
Scenario: Single Level
Accept System: 012103EA(Awinda)
Max Update Rate: Max (60 Hz)

No hardware found.

Enter subject's body dimensions below.
Leave a field clear or enter 0 to use the default value.

	Value
Body Height	(170.48 cm)
Foot or Shoe length	(24.70 cm)
Shoulder Height	(144.34 cm)
Shoulder Width	(38.00 cm)
Elbow Span	(94.00 cm)
Wrist Span	(143.00 cm)
Arm Span	(179.60 cm)
Hip Height	(87.44 cm)
Hip Width	(24.00 cm)
Knee Height	(48.61 cm)
Ankle Height	(8.00 cm)
Extra Shoe Sole Thickness	(0.00 cm)

C:\Users\Diego Borrell\Documents\Xsens

ELIA

Not all required body dimensions are set!

Figure 14. Manikin dimensions (N-pose) in Xsens.

3.8 Data collection and analysis

For the analysis of the data obtained in the experiments, qualitative and quantitative information will be used to evaluate how the use of the exoskeleton affects overhead tasks. For this purpose, information from the experiment will be collected by different means, such as observation and videos during the performance of the task, questionnaires to the participants or motion capture records.

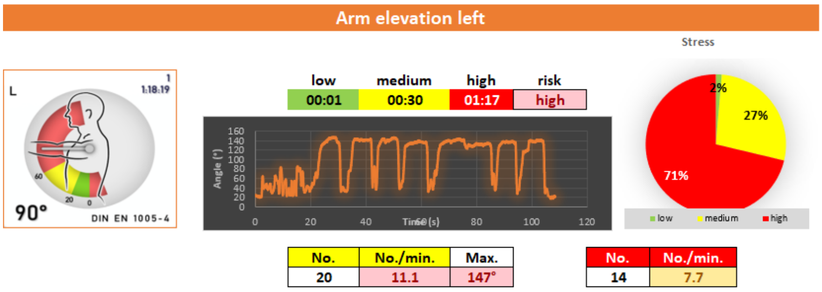
To obtain the subjective rating, we will make use of the videos and observations made during the experiment; however, since this information is not accurate enough to determine how the use of the exoskeleton affects the participants, we will also make use of questionnaires, which will be the main source of information for obtaining a subjective rating, since they provide direct information on the opinions of the users of this device. The type of questionnaire to be used in this study is called NASA Task Load Index (TLX); this method allows to easily find out the possible difficulties or insecurities that a user may have encountered during the performance of a task, each question is scored on a scale which minimum would be "very low" and the maximum score would be "very high". The questions that constitute this questionnaire are:

- Mental demand (How mentally demanding was the task?)
- Physical demand (How physically demanding was the task?)
- Performance (How successful were you in accomplishing what you were asked to do?)
- Effort (How hard did you have to work to accomplish your level of performance?)
- Frustration (How insecure, discouraged, irritated, stressed and annoyed were you?)

Two questionnaires were completed for each participant, one for the task performed with the exoskeleton and one for the task performed without the exoskeleton, resulting in a total of twenty questionnaires. Among the questions mentioned above, special attention was paid to the questions on physical demand, effort and frustration, as these provided more information when differentiating between the tasks performed with and without the exoskeleton.

In order to obtain the quantitative data, use was made of the Awinda motion capture system from Xsens from which the task recordings were obtained, as well as the ScaleFit programme. Although the ScaleFit software allows you to add a load and locate it on the right or left hand, the experiment focuses on the ergonomics and postures of the human body and will therefore be disregarded. This is due to a possible alteration of the experiment, so no external factors will be added. Subsequently, the analysis will be carried out on two of the subjects with the most relevant results with a load of 1 kg to test the assistance provided by the exoskeleton under different loads. Using the recordings obtained with the Xsens motion capture system, parameters such as arm elevation, shoulder moment, working time and other parameters in different parts of the body in general were evaluated using ScaleFit (*Figure 15*). As a result, an excel document is obtained in which each of the parameters of the programme is studied by means of graphs according to DIN EN 1005-4 or ISO 11226. In this way, two different documents are obtained for each participant, one where the results of the task where the exoskeleton has been used are analysed and another for the task where no exoskeleton has been used. In turn, because the programme is not able to detect when the exoskeleton is being used (and the generic exoskeleton provided by the programme does not coincide with the exoskeleton under study), ScaleFit is not able to detect the moment caused in the shoulders in a reliable way, therefore, in the excel documents where the results are analysed in the tasks where this device has been used, an extra sheet was added in which, based on a formula developed by a researcher at the University of Skövde (Perez Luque et al., 2020), it was possible to obtain from the data collected in the recordings the predicted real moment that originates in the shoulders when using the Paexo exoskeleton, thus obtaining a more realistic comparison, which is also shown graphically in the aforementioned documents.

Besides that, with the help of fellow students at the University of Skövde, the experiment will be simulated in IPS IMMA. From this simulation, the data of joint angles and shoulder moment will be extracted and adapted to the ScaleFit analysis format to evaluate if such ergonomics assessments method could be implemented into IPS IMMA.



low	medium	high	risk
00:01	00:30	01:17	high

No.	No./min.	Max.
20	11.1	147°

No.	No./min.
14	7.7

Figure 15. Example of a graphic evaluation by ScaleFit.

4 Results

This chapter describes all the information gathered during the experimentation.

4.1 Motion capture

As mentioned above, the Xsens devices and ScaleFit software are used to capture the movement and analyse it (see *Sections 3.6.1 and 3.6.2*). *Figure 16* shows all the parameters captured by Xsens. By placing the strips that come with the hardware as shown in *Figure 10*, the model of the test subject is defined and generated in the Xsens software. Once the experiment is about to start, it is recorded, and the programme exports all the data in different formats. The Microsoft Excel compatible format is chosen as it will be the software with which all the relevant analyses and comparisons will be carried out. The programme exports every 0.03 seconds information about the motion capture, which allows a very precious analysis of the different points of interest that are discussed below.

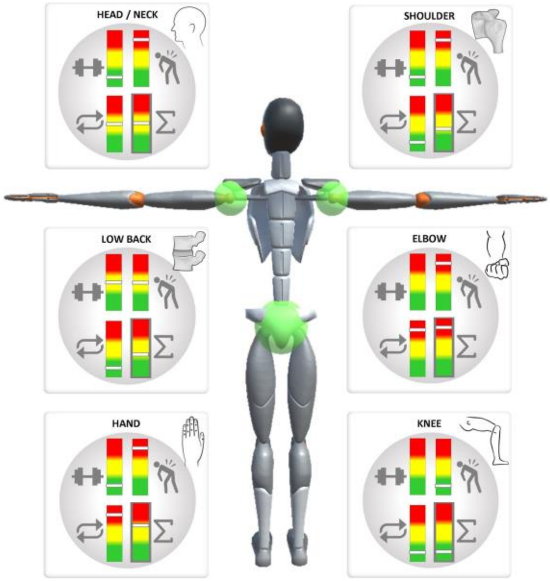


Figure 16. ScaleFit analyser parameters.

4.1.1 Arm elevation

Based on the data obtained in ScaleFit on the elevation of the arms of each of the participants, the percentage of time in which they keep their arms elevated (joint angle) in each of the risk zones established both by DIN EN 1005-4 and ISO 11226:2000 was studied. In addition, a comparison was also made about the maximum and average joint angles obtained from the participants.

In the figures below (*Figure 17 and 18*), a comparison has been made between the different analyses of a participant performed with ScaleFit for the lifting of the arms, the purpose of this was to compare the results obtained in the recording of the task performed with the exoskeleton and the task performed without it. The graphs obtained for the elevation of the arms show in the vertical column (y-axis) the angle (°) produced in the joint shoulder throughout the task and in the horizontal column (x-axis) the duration of the task in seconds. In addition, for each of the recordings (with an exoskeleton and without exoskeleton), there is a pie chart showing the percentage of time in which the participant is in each of the risk zones; finally, under each chart, there is a small table showing the maximum angle that has been reached, the number of times and how many times this angle has been repeated per minute.

LEFT ARM ELEVATION

Non-Exoskeleton

low	medium	high	risk
00:22	00:24	01:04	high

No.	No./min.	Max.
13	7.1	118°

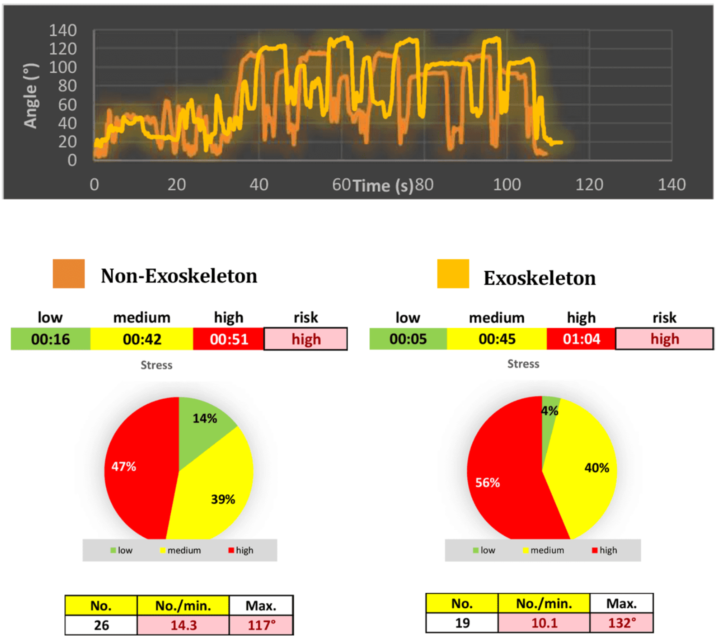
Exoskeleton

low	medium	high	risk
00:13	00:32	01:07	high

No.	No./min.	Max.
9	4.8	130°

Figure 17. Left arm elevation results of Participant 7.

RIGHT ARM ELEVATION



Non-Exoskeleton

low	medium	high	risk
00:16	00:42	00:51	high

No.	No./min.	Max.
26	14.3	117°

Exoskeleton

low	medium	high	risk
00:05	00:45	01:04	high

No.	No./min.	Max.
19	10.1	132°

Figure 18. Right arm elevation results of Participant 7.

Based on the above information, using Microsoft Excel software, a comparative table (*Table 1*) was made with each of the percentages of time spent in each of the risk zones for each of the participants. The subjects remained in the high risk zone 55% of the total task time when not using the exoskeleton and 59.5% when performing the task with the exoskeleton. For the left arm, during the task without an exoskeleton, each participant remained 62% of the total time in the high risk zone and 63.4% when performing the task without the exoskeleton. On the other hand, regarding the low risk zone, on average (*Table 2*) for the right arm, it was observed that during the operation performed without an exoskeleton, the percentage of time in this area was 9.3%, and when the task was performed with an exoskeleton, this percentage decreased to 5.4%, for the left arm, the average percentage of time in the low risk zone was 9.3% when not wearing an exoskeleton and 5.5% when working with an exoskeleton.

Table 1. Non-exoskeleton arm elevation comparison between participants

ARM ELEVATION (% of time in risk positions)	**Non-Exoskeleton**					
	RIGHT ARM			LEFT ARM		
	LOW RISK	MEDIUM RISK	HIGH RISK	LOW RISK	MEDIUM RISK	HIGH RISK
Participant 1 (male)	0	29	72	2	27	71
Participant 2 (male)	6	37	57	3	34	63
Participant 3 (male)	8	38	54	8	26	66
Participant 4 (male)	4	36	60	1	27	72
Participant 5 (male)	4	36	60	0	44	56
Participant 6 (female)	1	35	35	1	35	64
Participant 7 (female)	14	39	47	20	22	58
Participant 8 (male)	28	32	40	21	19	60
Participant 9 (male)	21	11	68	29	18	53
Participant 10 (female)	7	36	57	8	35	57
AVERAGE	9.3	32.9	55	9.3	28.7	62

Table 2. Exoskeleton arm elevation comparison between participants.

ARM ELEVATION (% of time in risk positions)	**Exoskeleton**					
	RIGHT ARM			LEFT ARM		
	LOW RISK	MEDIUM RISK	HIGH RISK	LOW RISK	MEDIUM RISK	HIGH RISK
Participant 1 (male)	0	34	66	0	34	66
Participant 2 (male)	0	37	63	6	27	67
Participant 3 (male)	13	37	50	0	37	63
Participant 4 (male)	0	47	53	0	38	62
Participant 5 (male)	0	38	62	1	38	61
Participant 6 (female)	0	23	68	10	22	68
Participant 7 (female)	4	40	56	12	29	59
Participant 8 (male)	17	45	38	13	28	59
Participant 9 (male)	20	9	71	13	27	60
Participant 10 (female)	0	32	68	0	31	69
	5.4	34.2	59.5	5.5	31.1	63.4

Regarding the joint angles obtained during the development of the task (*Table 3*), when the operation was carried out without exoskeleton, on average, a maximum angle of 125.57° was obtained with the right arm, with an average angle of 72.8°, and for the left arm, a total of 134.3° was obtained, with an average angle of 82.5°. Concerning the exoskeleton task, an average maximum angle of 131.9° and an average elevation of 77.9° was achieved for the right arm, for the left arm, an average maximum angle of 139° and an average elevation of 88.3° was achieved.

Table 3. Maximum and average angles between participants.

ANGLE (°)	Non-Exoskeleton				Exoskeleton			
	RIGHT		LEFT		RIGHT		LEFT	
	MAX	AVERAGE	MAX	AVERAGE	MAX	AVERAGE	MAX	AVERAGE
Participant 1 (male)	147.0	95.3	147.3	101.3	140.0	82.4	163.4	106.2
Participant 2 (male)	109.6	64.8	130.3	83.9	122.4	73.9	125.4	83.1
Participant 3 (male)	125.6	69.2	130.1	86.0	106.8	59.9	143.3	94.0
Participant 4 (male)	108.1	65.2	130.5	91.0	115.3	66.3	132.1	87.2
Participant 5 (male)	139.4	76.6	147.3	84.7	151.0	85.3	153.1	92.6
Participant 6 (female)	139.0	80.1	157.8	102.0	152.8	95.0	152.8	102.9
Participant 7 (female)	116.5	64.0	118.4	75.6	132.3	73.0	130.0	79.7
Participant 8 (male)	92.7	44.1	103.0	63.8	101.2	46.9	106.0	69.1
Participant 9 (male)	116.2	78.8	126.6	60.0	130.2	84.7	133.4	70.1
Participant 10 (female)	161.6	89.9	152.1	76.8	166.8	111.5	156.1	97.9
AVERAGE	125.57	72.8	134.34	82.51	131.88	77.89	139.56	88.28

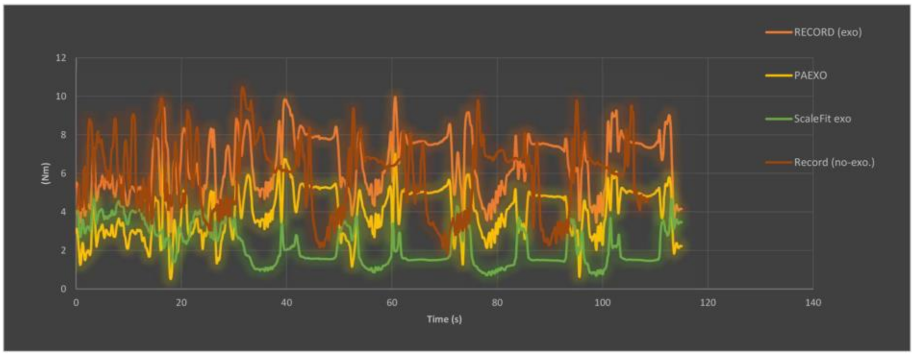
4.1.2 Shoulder moment

For the evaluation of the biomechanical changes wearing an exoskeleton, it was analysed how the use of this device affected the moment of the shoulders. This was done in order to check if it provided physical relief and assistance to this joint as the exoskeleton has been designed for. With this objective in mind, it was analysed for each participant how the shoulder joint moment varied when they performed the task without the exoskeleton and when the task was performed with the exoskeleton, obtainingfour4 different graphs as a result:

- Record (Non-Exo.): This graph shows the variation of the moment at the shoulder when the subject performs the task without the exoskeleton.
- Record (Exo.): This graph shows how the moment varies in the task where the exoskeleton is used; however, as the ScaleFit program is not able to detect the assistance of the Paexo exoskeleton, the moment is supposed to be similar to the previous graph.
- Paexo: From the recording where the exoskeleton was worn, the formula developed at the University of Skövde was used to calculate from the data obtained in the recording the assistance offered by Paexo at each instant and therefore the real moment caused in the shoulder joint.
- ScaleFit exoskeleton: The ScaleFit software has the option of incorporating a fictitious exoskeleton into the recording, which follows an ease-in-out characteristic with maximum support of 80% arm weight in 90° arm elevation. We also wanted to find out how much support this type of exoskeleton offered and from the data obtained from the simulation where the participant operated with the exoskeleton to be studied.

These four variants were analysed on both the right and left shoulder (*Figures 19 and 20*). The comparative graph, which was made from the ScaleFit results of one of the participants, shows in the vertical column (y-axis) the moment (Nm) caused at each instant of the task in the shoulder joint, in the horizontal column (x-axis,) the time in seconds of the task. Below the graph is a comparative table with the maximum moments in each of the analyses and finally an analysis of the risk of the task according to the moment reached in the task.

RIGHT SHOULDER MOMENT

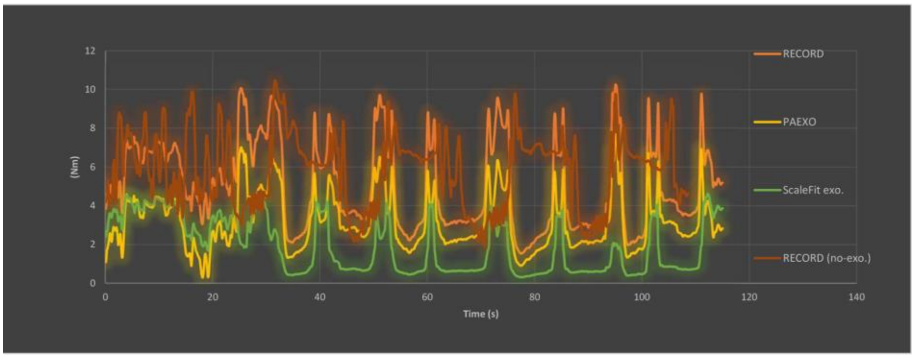


No.	No./min.	Max. Exo. Record	Max. PAEXO	Max. ScaleFit exo.	Max. No-exo. Record
0	0.0	10 Nm	7 Nm	5 Nm	10 Nm

low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

Figure 19. Participant 1 right shoulder moment comparison.

LEFT SHOULDER MOMENT



No.	No./min.	Max. Exo. Record	Max. PAEXO	Max. ScaleFit exo.	Max. No-exo. Record
0	0.0	10 Nm	8 Nm	5 Nm	10 Nm

low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

Figure 20. Participant 1 left shoulder moment comparison.

In order to ensure that the arm with which each participant performed the test did not alter the result, the moment produced in the dominant arm (which held the instruments and screwed the plates) and the moment produced in the non-dominant arm (which mainly held the plates suspended above the participant) were analysed.

As a result of this analysis, the data obtained in both recordings, as can be appreciated in the table below (*Table 4 and 5*), showed that on average, the maximum moment was close to 9.8 Nm in both shoulders and on average, the dominant hand had a moment of 6.1 N,m and the non-dominant hand had a moment of about 5.4 Nm. At the same time, in the graph where the moment with the ScaleFit exoskeleton is analysed, it is observed that the maximum moment produced is 5.2 Nm in both arms, obtaining an average moment that is reduced to less than half that of the recordings where the device is not taken into account, this average being approximately 2 Nm in both arms. Finally, when analysing the effect produced by Paexo, it can be seen that the maximum average moment between participants is around 7 Nm in both arms and respect the average moment produced at the shoulder joint, it is also observed that in the dominant arm the average moment produced is 3.7 Nm with a standard deviation of 0.3 and the non-dominant arm has an average moment throughout the task of 3.3 Nm with a standard deviation of 0.5.

Table 4. Maximum shoulder moments (Nm).

Maximum shoulder moment [Nm]	Non-Exoskeleton		Exoskeleton (RECORD)		Scalefit exoskeleton formula		PAEXO FORMULA	
	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant
Participant 1 (male)	10.4	10.1	10.0	10.2	4.7	4.6	7.0	7.7
Participant 2 (male)	9.8	10.5	9.8	10.4	6.0	5.6	7.8	8.4
Participant 3 (male)	10.7	9.8	9.0	10.4	5.3	5.1	5.8	7.4
Participant 4 (male)	9.4	8.8	9.0	9.0	4.8	5.1	5.8	5.8
Participant 5 (male)	10.1	10.1	10.1	10.4	4.6	4.7	7.1	7.5
Participant 6 (female)	10.1	10.4	10.5	8.8	4.6	4.9	7.6	6.2
Participant 7 (female)	9.6	8.9	9.8	9.7	4.5	4.6	6.7	6.8
Participant 8 (male)	9.7	10.4	9.6	9.7	5.6	5.1	6.6	6.6
Participant 9* (male)	10.0	9.7	10.3	9.7	7.2	5.7	7.2	6.7
Participant 10* (female)	8.9	8.8	9.6	9.6	4.6	4.7	6.4	6.4
Average	9.9	9.8	9.8	9.8	5.2	5.0	6.8	7.0
Std.dev	0.5	0.7	0.5	0.6	0.9	0.4	0.7	0.8

* Left dominant arm

Table 5. Average shoulder moments (Nm).

Average shoulder moment [Nm]	Non-Exoskeleton		Exoskeleton (RECORD)		Scalefit exoskeleton formula		PAEXO FORMULA	
	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant	Dominant	Non-dominant
Participant 1 (male)	5.8	5.0	6.5	5.0	2.3	1.9	4.0	3.2
Participant 2 (male)	6.8	5.6	5.4	4.3	2.0	1.5	3.3	2.6
Participant 3 (male)	6.0	5.4	5.9	4.6	2.5	1.8	3.4	2.8
Participant 4 (male)	6.0	5.1	6.3	5.2	2.5	2.1	3.5	3.1
Participant 5 (male)	6.3	5.3	6.3	5.0	2.3	2.0	3.9	3.2
Participant 6 (female)	6.9	5.2	6.5	5.1	2.0	1.8	4.1	3.5
Participant 7 (female)	6.1	5.9	6.3	5.7	2.3	1.8	3.8	3.6
Participant 8 (male)	6.1	6.8	6.4	6.8	3.1	2.3	3.9	4.3
Participant 9* (male)	6.1	5.6	6.1	5.9	2.3	1.9	3.7	3.8
Participant 10* (female)	5.3	4.3	5.5	4.1	1.9	1.5	3.3	2.5
Average	6.1	5.4	6.1	5.2	2.3	1.9	3.7	3.3
Std.dev	0.4	0.6	0.4	0.8	0.3	0.2	0.3	0.5

* Left dominant arm

4.1.3 Time

As can be seen in *Table 6*, there is an increase of 4 seconds in the average duration when wearing the Paexo Shoulder exoskeleton while doing the experimental task.

Table 6. Comparison of the time completing a task.

Task performance time (h:min:sec)	TIME Non-Exoskeleton	TIME Exoskeleton
Participant 1 (male)	0:01:49	0:01:55
Participant 2 (male)	0:01:27	0:01:31
Participant 3 (male)	0:02:08	0:02:19
Participant 4 (male)	0:02:02	0:02:00
Participant 5 (male)	0:01:37	0:01:29
Participant 6 (female)	0:01:57	0:01:55
Participant 7 (female)	0:01:49	0:01:53
Participant 8 (male)	0:01:43	0:01:40
Participant 9 (male)	0:01:59	0:02:32
Participant 10(female)	0:02:49	0:02:41
AVERAGE	0:01:56	0:02:00

4.1.4 Weight analysis results

As discussed above (see *Section 3.8*), two of the participants will be tested by adding a constant load to their dominant hand using the functionality in ScaleFit. In other words, how weight-bearing affects the performance of the participants, more specifically, how it affects the moment during the task and how the assistance of the exoskeleton influences depending on the load that the participant is holding. The participants chosen were the male participant number 3, who has the highest values for the shoulder moment, and the female participant number 10, whose dominant arm is the left arm and also has relatively low values in terms of the moments studied before. The experiment is recorded in ScaleFit, with and without the exoskeleton, to compare the support provided by the exoskeleton when carrying a 1kg load in their dominant arm, which is approximately the weight of the screwdriver carried in the task.

In the tables below (*Table 7 and 8*), a comparison has been made with the maximum and average moment of the participants mentioned when the weight in question is 0 kg and when the weight is 1 kg.

Table 7. Maximum moment comparison for 0 kg and 1 kg load.

MAXIMUM SHOULDER MOMENT (Nm)		0kg LOAD		1kg LOAD	
		P3	P10	P3	P10
Non-Exoskeleton	Dominant	10.7	8.9	14.5	15.2
	Non-dominant	9.8	8.8	10.4	9.6
Exoskeleton (RECORD)	Dominant	9.0	9.6	14.5	15.2
	Non-dominant	10.4	9.6	10.4	9.6
Scalefit exoskeleton formula	Dominant	5.3	4.6	5.3	9.6
	Non-dominant	5.1	4.7	5.1	4.7
PAEXO FORMULA	Dominant	5.8	6.4	11.4	12.0
	Non-dominant	7.4	6.4	7.4	6.4

Table 8. Average moment comparison for 0 kg and 1 kg load.

AVERAGE SHOULDER MOMENT (Nm)		0kg LOAD		1kg LOAD	
		P3	P10	P3	P10
Non-Exoskeleton	Dominant	6.0	5.3	8.9	7.8
	Non-dominant	5.4	4.3	4.6	4.1
Exoskeleton (RECORD)	Dominant	5.9	5.5	8.9	7.8
	Non-dominant	4.6	4.1	4.6	4.1
Scalefit exoskeleton formula	Dominant	2.5	1.9	2.5	4.2
	Non-dominant	1.8	1.5	1.8	1.5
PAEXO FORMULA	Dominant	3.4	3.3	6.1	5.6
	Non-dominant	2.8	2.5	2.7	2.4

4.1.5 Overall effects in other parts of the body

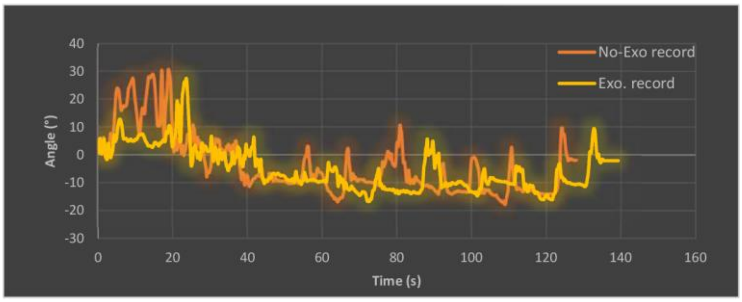
Other key points to assess are spinal disc compression and trunk inclination. To evaluate these two parameters, the recordings of the participants performing the task with and without the exoskeleton will be compared. The purpose of the analysis is to observe whether postural control is reduced, muscle strain is increased or not, and whether end-effectors or joint trajectories change.

For this effect, as can be seen in *Table 9*, the values of trunk inclination have been calculated as well as the average of the maximum disc compression of each of the participants.

Table 9. Maximum trunk inclination and disc compression average

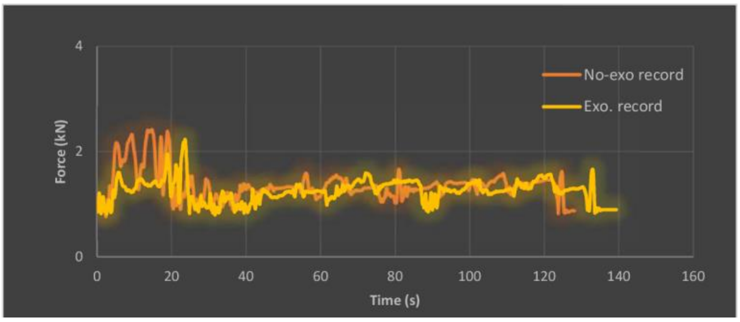
Trunk inclination and Dic compression comparison	Non-Exoskeleton		Exoskeleton (RECORD)		Scalefit exoskeleton formula	
	Trunk inclination (°)	Disc compression (kN)	Trunk inclination (°)	Disc compression (kN)	Trunk inclination (°)	Disc compression (kN)
Participant 1 (male)	47.0	3.1	52.0	3.2	52.0	3.2
Participant 2 (male)	48	3	41.0	2.8	41.0	2.8
Participant 3 (male)	31.0	2.4	28.0	2.2	28.0	2.2
Participant 4 (male)	56.0	3.2	29.0	2.3	29.0	2.3
Participant 5 (male)	56.0	3.3	46.0	3.0	46.0	3.0
Participant 6 (female)	35.0	2.6	38.0	2.8	38.0	2.8
Participant 7 (female)	62.0	3.4	58.0	3.2	58.0	3.2
Participant 8 (male)	49.0	3.1	41.0	2.9	41.0	2.9
Participant 9 (male)	67.0	3.4	83.0	3.4	83.0	3.4
Participant 10 (female)	61.0	3.3	40.0	2.8	40.0	2.8
Average	51.2	3.1	45.6	2.9	45.6	2.9
Std.dev	11.0	0.3	15.2	0.4	15.2	0.4

Besides that, graphs comparing both measurements on the same participant can be observed. In the graph referring to trunk inclination (*Figure 21*), the vertical column (y-axis) refers to the angle (°) at which the back is at each instant of the task, and the x-axis shows the time measured in seconds of the duration of the task. As for the graph on disc compression (*Figure 22*), it can be seen that the vertical column (y-axis) describes the force (kN) at which the disc is compressed at each instant of the task and the horizontal column (x-axis) shows the time in seconds of task duration.



Max. No Exo	Max. Exo record
31°	28°

Figure 21. Trunk inclination comparison of participant 3.



Max. No Exo	Max. Exo record
2.4 kN	2.2 kN

Figure 22. Comparison of the disc compression of participant 3.

4.2 Subjective rating of perceived workload

When the subjective rating was collected, participants were assessed with Nasa TLX. As can be seen in Table 10, the evaluation system has been numerical, from 0 to 10, with 0 being very low and ten being very high. Although the Nasa TLX method includes questions about six different areas, which all were recorded, three aspects are emphasised and documented in this report: Physical demand, mental effort and frustration.

Table 10. NASA TLX comparison results.

	NASA TLX (Non-Exoskeleton)			NASA TLX (Exoskeleton)		
	Physical D.	Effort	Frustration	Physical D.	Effort	Frustration
Participant 1 (male)	4	3	2	4	2	3
Participant 2 (male)	7	5	1	5	4	1
Participant 3 (male)	5	5	1	4	4	1
Participant 4 (male)	5	4	2	4	4	3
Participant 5 (male)	7	7	1	3	3	1
Participant 6 (female)	4	3	1	2	2	1
Participant 7 (female)	7	3	1	5	2	1
Participant 8 (male)	5	5	5	3	4	3
Participant 9* (male)	6	7	5	4	5	2
Participant 10* (female)	8	8	5	6	7	4
AVERAGE	6	5	2	4	4	2

0	**Very Low**
10	**Very High**

4.3 IPS-IMMA simulation

With the assistance of student colleagues in a parallel degree project who are studying the muscle load during the use of an exoskeleton, the experiment was analysed using the DHM tool IPS IMMA. The scenario was recreated using Rhinoceros CAD software (Rhino 3D, version7) and then exported to IPS IMMA (FCC Chalmers, version 3.10). Once the 3D environment was imported, the simulation of the task began to develop. This was done in a simplified way since in order to extract the points of interest such as maximums or sequences where the participant works in the low area, it was not necessary to implement all the movements in the simulation.

To create the manikins, the necessary anthropometric measurements was defined using the data collected for the Xsens calibration. Participant 3 and participant 10 were taken as a sample to have some difference in moment values and both male and female. On the one hand, participant 3 has the highest values for the shoulder moment, which is interesting to evaluate in IPS IMMA. On the other hand, participant 10 have relatively low should moment values and is a female user whose dominant hand is left-handed. So these two participants cover a wide range within the ten possible users.

The task is to be simulated without the use of the exoskeleton, as the focus is on the angles and moments of the shoulder as well as trying to recreate some similarity between the task performed through motion capture and the simulation with IPS-IMMA (*Figure 23*).

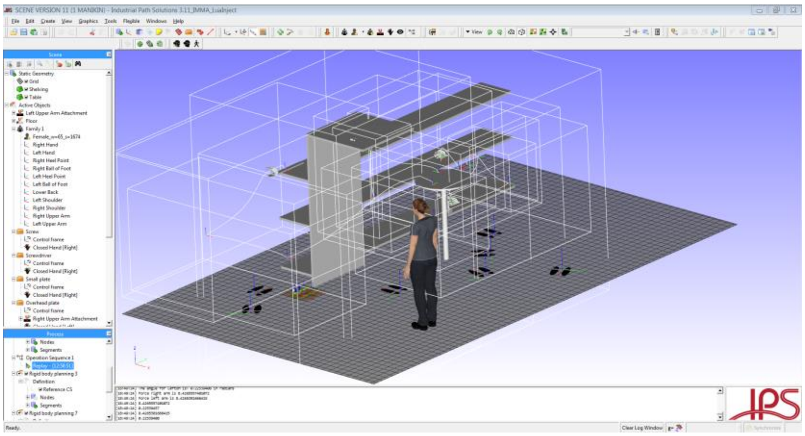


Figure 23. IPS-IMMA recreation of the real task scenario.

4.3.1 Data export from IPS-IMMA

The data to be exported from IPS IMMA are the shoulder moment and the joint angle. These two values are the most useful to compare with the data obtained in ScaleFit; besides, simulation of the task reflects the maximum moment of these values. To implement the simulation with both manikins, the body measurements of each of the participants are exported from Xsens to IPS IMMA and the simulation proceeds so that both manikins reproduce exactly the same sequence. The time duration is shorter than the task recorded with motion capture, as the focus is on the maximum points, not on the totality of movements that can be reproduced during the task. Before running the simulation, the measurement points of interest are activated, or those that are to be evaluated, in this case, torque and joint angle at shoulders. Once the simulation has been carried out, a single file is obtained in .csv format with the data collected for subsequent interpretation (*Figure 24*).

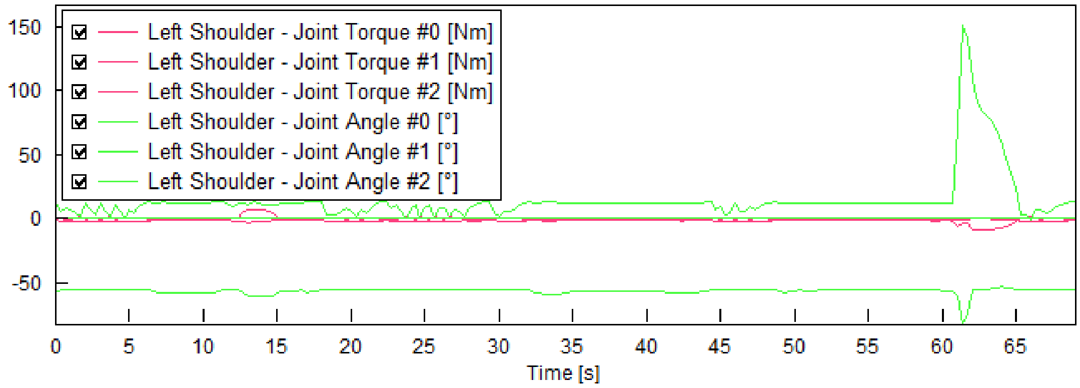


Figure 24. IPS-IMMA simulation results graphic.

4.3.2 ScaleFit evaluation based on IPS-IMMA data

Based on the data obtained from the IPS-IMMA simulation of the task performed during the experimentation with the measurements of participants 3 and 10, these results have been analysed with the ScaleFit software with the aim of evaluating a new way of assessing the results obtained with IPS-IMMA in a more meaningful and informative way in the future.

From the analysis carried out with ScaleFit on the results of the simulation with IPS-IMMA, several graphs were obtained showing the variation of the elevation of the arm during the carried out simulation (*Figures 25 and 26*).

LEFT ARM

low	medium	high	risk	Max.
00:00	01:09	00:06	medium	90°

RIGHT ARM

low	medium	high	risk	Max.
00:05	01:03	00:08	high	66°

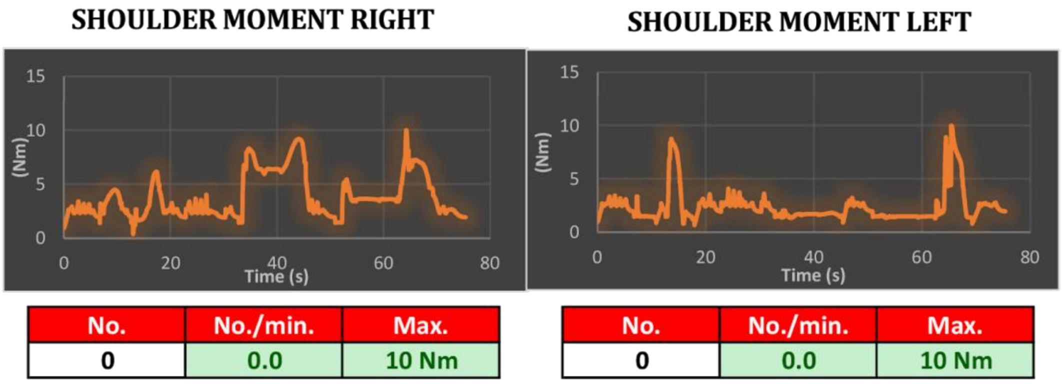
Figure 25. ScaleFit analysis of the arm elevation of the participant 3 from IPS-IMMA.

low	medium	high	risk	Max.
00:06	01:02	00:07	medium	66°

low	medium	high	risk	Max.
00:00	01:08	00:06	medium	78°

Figure 26. ScaleFit analysis of the arm elevation of the participant 10 from IPS-IMMA.

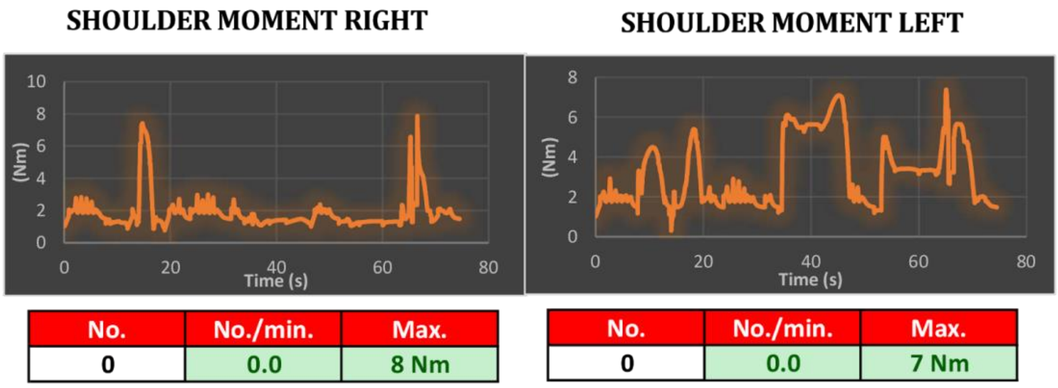
Regarding the maximum moments reached on average by each participant, it has been obtained by means of the ScaleFit software that participant 3 (*Figure 27*) reached a maximum of 10 Nm in both shoulder joints and that participant 10 (*Figure 28*) reached a maximum moment of 8 Nm in the right shoulder and a maximum moment of 7 Nm in the left shoulder.



No.	No./min.	Max.
0	0.0	10 Nm

No.	No./min.	Max.
0	0.0	10 Nm

Figure 27. ScaleFit analysis of the shoulder moment of the participant 3 from IPS-IMMA.



No.	No./min.	Max.
0	0.0	8 Nm

No.	No./min.	Max.
0	0.0	7 Nm

Figure 28. ScaleFit analysis of the shoulder moment of the participant 10 from IPS-IMMA.

4.4 Comparison of evaluation from motion capture and IPS-IMMA

Based on the data obtained from motion capture and IPS-IMMA with the ScaleFit analysis of participants 3 and 10, a comparison was made to analyse both the maximum moments and the maximum elevation angles of the arms (Table 11). On this occasion, the analysis of risk zones was omitted because the simulated task with IPS-IMMA was shorter and was limited to evaluating the extreme positions and not the time in them; therefore, the time in risk positions is considerably lower, as has been observed previously.

Table 11. Comparison results from motion capture and IPS-IMMA.

COMPARISON BETWEEN MOTION CAPTURE AND IPS-IMMA	**MAX,ARM ELEVATION (º)**				**MAX,SHOULDER MOMENT (Nm)**			
	Motion capture		IPS-IMMA		Motion capture		IPS-IMMA	
	Left	Right	Left	Right	Left	Right	Left	Right
Participant 3 (male)	143.0	107.0	90.0	66.0	10.4	9.0	10.0	10.0
Participant 10*(female)	156.0	167.0	66.0	78.0	9.6	9.6	7.0	8.0

*Left dominant arm

5 Analysis of results

5.1 Motion capture

Once the recordings obtained with the movement sensors of the Xsens Awinda suit were analysed and analysed with ScaleFit, relevant parameters in the evaluation of the use of the exoskeleton such as arm elevation, shoulder moment, time, weight or effects produced on the trunk were analysed. In this way, a series of graphs were obtained that evaluated these parameters according to the aforementioned standards used by ScaleFit (see *Section 3.6.2*), and later, a comparison was made with the different results to observe relevant changes when the task was performed with and without the exoskeleton.

5.1.1 Arm elevation

The results obtained with ScaleFit concerning this parameter are analysed according to DIN EN 1005-4 and ISO 11226:2000. These standards distinguish between the following differentiated zones (*Figure 29*), in which a higher range generates a higher probability of developing musculoskeletal disorders:

- Low risk zone (Zone 1): Comprised between 0° and 20°.
- Medium risk zone (Zone 2): Between 20° and 60°.
- High risk zone (Zones 3 and 4): Between <0° and >60°.

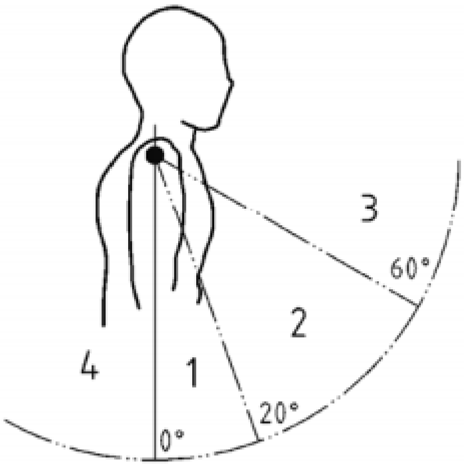


Figure 29. Areas for arm elevation (DIN EN 1005-4).

Among the participants, it was observed that time spent in the high risk zone hardly varied, despite being the area where they spent the most time (around 60% of their time). However, there was a notable decrease in the percentage of time spent in the low risk zone when performing the task with the exoskeleton. This time decreased to almost half of the time when the participant was conducting the task with the exoskeleton, thereby increasing the time spent in the medium risk zone. Initially, as this is a task lasting approximately 2 minutes, the task would not be considered a risky one; however, depending on the number of times in a working day, this could be harmful to health.

With regard to the maximum and average angles obtained by comparing data of each of the participants, it can be seen that when they used the exoskeleton during the average task, they kept their arms higher and that, in turn, the maximum angles obtained in these recordings increased by an average of 5° with respect to the recordings made without the exoskeleton.

5.1.2 Shoulder moment

From the analysis carried out for this parameter, it was found that the moment at the shoulder joint hardly changed in the recordings made with and without the exoskeleton. As mentioned in section 4.1.2, ScaleFit is not able to detect the assistance of the exoskeleton and therefore analyses the movements as if no exoskeleton is used. However, there is a notable difference between the ScaleFit results based on the recordings and the results obtained in the charts where the provided exoskeleton assistance is predicted. The results in this area showed that the Paexo exoskeleton, despite not offering as much assistance as that supposedly offered by the ScaleFit exoskeleton, contributed to a considerable reduction in the moments produced at the shoulder joints thanks to the assistance it provides when the arms are raised and reaching its maximum assistance when the arms are raised at a 90° angle. It is also worth noting that because the moments in the arms when the arms are unweighted never exceed 12Nm and the duration of the task is approximately 2 minutes, the risk in this area is low according to ScaleFit's assessment.

5.1.3 Time

Since the time variation between tasks when using or not using the exoskeleton is minimal, it is not considered that the use of this device greatly alters the pace of the task, which can still be completed in two minutes, thus confirming the testimony given by the Volvo Cars expert (*Appendix A*) where he mentioned that the time was hardly altered.

5.1.4 Weight

As a result of the comparison, it can be seen that in both participants, when performing the task with 1 kg of load, the maximum moment produced in the dominant arm increases considerably. With respect to the average moment throughout the task, an increase in the moment of the dominant arm is observed while hardly any variation is observed in the non-dominant arm.

With this analysis, it can be confirmed that the help offered by the exoskeleton incorporated by ScaleFit is greater as it manages to reduce the moment produced in the joint shoulders by almost half. Paexo, the exoskeleton to be evaluated, also provides considerable help as it also succeeds in reducing the moment produced when the task is performed with weight.

5.1.5 Overall effects in other parts of the body

In general, a slight reduction of both values (disc compression and trunk inclination) when the exoskeleton is in use is seen, and although it cannot be very precise about the trunk tilt since, in each task, the participant does not reproduce exactly the same movements, this result could mean that the exoskeleton limits the movements a little bit. In the same way, the compression of the disc also decreases, which could mean that the use of the exoskeleton could help reduce the load in the workers' back. Although, as mentioned above, these results are indicative because it is uncertain if the ScaleFit software considers the additional load that is put on the body, from the weight of the exoskeleton, and which might increase the spinal disc compression.

About the graphs (*Figures 22 and 23*), it can be observed that the most critical point and where the maximums are collected are located at the beginning of the task, specifically at the moment in which the participant has to work in the lower zone.

5.2 Subjective rating of perceived workload

From the aspects to be analysed in the NASA TLX questionnaire, the first was the physical demands of the experiment; this is a very convenient and direct way of assessing whether the participants perceived a reduction or increase in physical demand when doing the experiment with the exoskeleton. As it was observed, there was a reduction in the average value of 2 points when using the Paexo Shoulder. The second aspect being analysed was the mental effort involved in the experiment, as the use of the exoskeleton may or may not lead to an improvement. This aspect was selected to assess whether or not the exoskeleton could reduce mental stress in the workplace and there was a minimal reduction by using the exoskeleton. Finally, the frustration of the participants in performing the task was taken into account, as none of them was familiar with the development of overhead tasks. For many of them, inserting the screw correctly into the hole and then making good use of the drill may have been more strenuous. However, it can be observed that the use of the Paexo Shoulder was irrelevant in that respect.

5.3 IPS-IMMA

5.3.1 ScaleFit evaluation based on IPS-IMMA data

Due to the fact that the task carried out with IPS-IMMA, a DHM tool, is not as long as the real one carried out in experimentation and that the arms do not completely reproduce the natural movement that was done by the test participants during the real task, mainly the maximum angles of the shoulder joint and the risk areas in which the manikin works in throughout the task according to the DIN EN 1005-4 standard will be studied.

From the IPS-IMMA simulation, it can be seen that the results obtained are very similar between participants, as both carry out the same exercise with the difference of the dominant hand. It is obtained that they spend an average of 87% of the time in the risk zone, 27 percentage points more than the data extracted using motion capture. This is due to unnatural or unrealistic movements made by the manikin in this type of software.

The data obtained for participant 3, taking into account that his dominant hand is the right hand, show that both arms were kept mostly in a medium risk zone; however, it is observed that due to the fact that this participant kept his right arm elevated for longer in a risky position, this task turns out to have a high risk for his dominant arm; regarding the maximum angles, we found that the maximum angle reached by the right arm is 90° and the right arm is elevated to a maximum angle of 66°, both higher than 60° (the angle that delimits the medium risk zone). As for participant 10, taking into account that she is left-handed, it is worth noting that both arms remained on average in a medium risk zone and that the maximum angles reached were 66° and 78° for the left and right arm, respectively.

5.4 Comparison of evaluation from motion capture and IPS-IMMA

As *Table 11* showed, there is a great difference between the angles of elevation of the arms obtained with motion capture and those obtained with IPS-IMMA. The motion capture results were much higher than those obtained with IPS-IMMA for arm elevation. On the other hand, when analysing the shoulder moment, values much closer to those obtained by motion capture can be observed. In this IPS-IMMA simulation, it can be seen that the highest values for the shoulder moments were obtained while the manikin was screwing the wooden plate.

6 Discussion

This chapter will discuss the results obtained from experimentation, the methodology used and possible applications of the information gathered.

6.1 Method

With the aim of evaluating the biomechanical effects produced by the use of an exoskeleton during overhead operations, an experiment was designed to simulate the real conditions that assembly line workers face during the performance of overhead tasks. Below we will discuss how the experimental phase of the study was conducted and the manner in which the data was collected.

6.1.1 Experiment

The experiment was intended to simulate a real scenario where overhead tasks were carried out in which more extreme movements were added in order to evaluate how the exoskeleton affects a wider range of movements and positions. The fact that the stage (the height of the wooden plank) where the work was carried out at ASSAR was already set up at certain heights also influenced the decision to analyse the behaviour of the exoskeleton under extreme conditions. The initial intention was to analyse the pilot tasks and extract the necessary information to evaluate the exoskeleton from them, however during the first recordings of the tasks, it was observed that there was too much information to analyse, and for this reason, a single task was created that condensed all the information from both tasks and used the recordings already made with Xsens as a pilot test to discover possible relevant data to look out for during the recordings of the general task. Furthermore, after conducting the experiments and attending a visit to Volvo Cars' engine assembly facility in Skövde, where more ergonomic risk factors were explained, it was noted that the experiment was more extreme than what the workers actually face in reality. This fact affects the ecological validity, which examines whether the research results can be generalized to real life. In view of future tests in addition to the one conducted in this experiment, the procedure and ergonomics used in the Volvo Cars assembly lines should be taken into account to reproduce a task even more similar to the real one.

Another notable fact, due to the situation caused by the Covid-19 virus that the world is currently facing, was that the participants in the experiments could not be real operators. Therefore, ASSAR colleagues volunteered to help with the experimentation. Thanks to their collaboration, we were able to have a number of 10 people in which there were seven men and three women, which simulated a small sample of the proportion of operators that exist in reality in Volvo's company. Also noteworthy is that because the participants were also working on their own theses and the scenario and exoskeleton were shared with other fellow students, the experiment took longer than expected as it had to fit in with the participants' schedules and free time. This fact affects the external validity, which checks whether the research results can be generalized to other contexts. The research is conducted on a sample, and if the sampling is random, the sample represents the population, so the research results can be effectively extended to the population of the sample. To conclude, if there had been an opportunity to provide completely external participants, the results could have been more objective and will be taken into account in future studies.

As mentioned above, the lack of participants due to the current pandemic was a problem. Therefore, we also participated in the experiment. With the awareness that this meant, we tried to be as neutral and objective as possible, as we started from the same basis as the other participants. This fact affects the internal validity, which checks whether the design, implementation and analysis methods of the study can provide reliable answers to the research questions in the study. Add something about how this could be solved with additional tests in the future.

6.1.2 Data analysis

To obtain the necessary information in motion capture, we first used Xsens technology and later ScaleFit to analyse the biomechanical effects on the operators in order to evaluate the effects and alterations produced by the use of an exoskeleton during overhead operations on assembly lines. Due to the initial lack of knowledge about how ScaleFit worked and where the load was placed during the recording, it was decided to start the analysis by evaluating only movements and without the weight factor, however in the last weeks, it was finally figured out how to place the weight on a certain point of the body during the recordings, but due to the short time frame, only the two participants who had shown the most significant data in the non-weight analysis were studied. However, limitations have been found in the function of adding loads and weights to localised areas of the body in Scalefit. That it is not possible to have the weight just during a certain part of the recording. Therefore, the main and most comprehensive analysis has been carried out without including loads of any kind.

Regarding the information obtained with IPS-IMMA, due to the short time frame for this analysis, we made use of the simulation carried out by students in a parallel degree project, who carried out a similar task in the experimentation of their project to evaluate different aspects of the exoskeleton. Thanks to their contribution, it was possible to analyse two subjects with relevant results in the IPS-IMMA simulation and thus later proceed to evaluate the data obtained in this programme once again with ScaleFit.

6.2 Results

Despite possible errors and details to be considered in future research, the results obtained from the study have proved to be very interesting and open the door to new factors to be studied in the near future.

With regard to the results obtained using motion capture, there are a number of aspects that should be highlighted, such as the fact that the task is considered a low-risk task according to the arm elevation, but in the case of such a task being carried out in a normal work shift, where the same task is repeated for around 30 minutes before changing to a different task and that the same operator performs 4 to 6 different tasks during an eighth shift, the amount of time this task is repeated during the day should be monitored, as holding these positions for more than 10% of the working time could increase the probability of developing WMSDs in the shoulders by one to two thirds (Schmalz et al., n.d.). Another point to take into account regarding arm elevation would be the fact that many of the participants mentioned the fact that they had to exert downward force to maintain relaxed posit; it, it would be interesting to investigate how this aspect is affected in tasks with a longer time span, as this effect could perhaps cause adverse effects to those expected with the use of the exoskeleton.

As for the results obtained on the moment produced in the shoulders, it was observed that initially, the moment obtained in both recordings did not change because the software was not able to detect the assistance of the exoskeleton to the participants; however, this fact served to corroborate that the momentum when no formula was added to calculate the assistance of any exoskeleton was similar in both recordings. When analysing the results of the moments produced in the shoulders when wearing an exoskeleton, a formula developed at the University of Skövde (Perez Luque et al., 2020a) was used, and to compare the results with other exoskeletons, the generic exoskeleton that ScaleFit allows to add to the recordings was also used (*Figure 30*).

Figure 30. ScaleFit exoskeleton (Image from https://paexo.com/paexo-back-scalefit-analysis/?lang=en)

Regarding the evaluation performed with ScaleFit to assess possible adverse effects on other parts of the body when performing overhead tasks with and without an exoskeleton, the possible effects on the trunk (disc compression and trunk inclination) were analysed since, as mentioned above, this area accounts for about 40% of cases caused by MSDs (Yin et al., 2020a) and this parameter was easy to analyse with ScaleFit. However, as later results showed when comparing the recordings made with and without the exoskeleton, there was hardly any variation between the trunk tilt angles of the two recordings, and because ScaleFit is not able to detect the load of the exoskeleton when the participant is wearing it, and there is no known formula to calculate the variation of the compression on the disc, no significant change was observed in this aspect either. However, since the musculoskeletal disorders in these parts of the body when performing such tasks are still very high, it would be advisable to study somehow the effects of the exoskeleton on the trunk as well as on the neck or wrists (*Appendix A*).

In addition to the quantitative results, qualitative results obtained from observations and the NASA TLX questionnaire indicated that a positive assessment for the use of the exoskeleton, as it is generally concluded that it reduced the effort required and did not alter either the stress or the mental effort required by the participants to perform the task.

From the results obtained during the experiments with the aim of evaluating the effects of using an exoskeleton in overhead tasks, the following hypothesis and sub-hypothesis can be corroborated:

- Main Hypothesis: Since the analysis has shown very similar results in terms of positions and postures with the use or non-use of the exoskeleton during the task but has also shown a decrease in the time participants spend in the low risk zone when using the exoskeleton, it was considered that before either of the two possible hypotheses could be confirmed or disproved with enough certainty, a more in-depth study should be carried out to obtain the effects on the effort participants make to keep their arms down in front of the exoskeleton trying to propel them upwards.

- Sub-hypothesis A: Considering that the evaluation has shown that with the use of exoskeleton, the moment in the shoulder has been reduced but not knowing if it is also reduced in the rest of the body, the sub-hypothesis SH1A cannot be fully supported: *The biomechanical load when using an exoskeleton is lower than the load when not using an exoskeleton for overhead assembly work.*
- Sub-hypothesis B: The time of the task is not altered to any great extent when performed with the exoskeleton, and therefore, the null-hypothesis of the second sub-hypothesis cannot be rejected, SH0B: The total time when using an exoskeleton is shorter or the same as the time when not using an exoskeleton.

About the simulation carried out using the IPS IMMA software, quantitative data on arm lift and shoulder moment were extracted without considering the use of the exoskeleton because currently the software does not have this option and there was not enough time to study how to implement one in these simulations. For this purpose, as with motion capture, the results obtained with IPS-IMMA were analysed with ScaleFit. When comparing the results obtained with both methods, it was observed that although the resulting shoulder moments were very close, in the elevation of the arms, the results were very disparate. This result could be due to the fact that the manikin offered by the software performs movements with the arms that are somewhat forced, which could alter these results.

6.3 Application and alignment with the goals of the 2030 Agenda for a sustainable development

Through the experiment, it has been found that the shoulder moment is reduced when wearing an exoskeleton and can therefore be considered a device to be taken into account to alleviate the problems such as MSDs related to arms and shoulders developed while doing overhead operations. For this reason, related to the Sustainable Development Goals of the 2030 Agenda, the use of exoskeletons could contribute to improving the health of those who use them in this type of operations and at the same time counteracting possible occurrences of MSDs, thus favouring decent work. Therefore, this work can be aligned with Goals 3 (Good Health and Well-being) and 8 (Decent Work and Economic Growth) (*Figure 31*).

Figure 31. Objectives 3 and 8 from the Agenda 2030 (Image obtained from https://sdgs.un.org/2030agenda)

In turn, it is also necessary to take into account how the world of the automotive industry is evolving today, as new proposals are beginning to be seen in the assembly lines that propose to carry out the work in the area in front of the worker, that is to say, the car is placed vertically. But the economic impact of such a change for a company may be too high, so the exoskeleton could be a solution to be considered until the transition can be allowed, thus eradicating most of the critical positions. For this reason, incorporating the use of technologies such as exoskeletons in the field of the industry could contribute to Goal 9 (Industry, Innovation and Infrastructure) (*Figure 32*).

Figure 32. Objectives 9 from the Agenda 2030 (Image obtained from https://sdgs.un.org/2030agenda)

Furthermore, by incorporating the use of the exoskeleton in assembly lines, it could incentivise diversity and gender equity in factories, as more women may be interested in working in factories and industry if they have teams to assist in these kinds of tasks. This advantage could align with Goal 10 (Reduced inequalities), as, for example,e the exoskeleton could contribute to gender gaps in this area, also increasing access and opportunities for both genders (*Figure 33*).

Figure 33. Objectives 10 from the Agenda 2030 (Image obtained from https://sdgs.un.org/2030agenda)

Regarding the cognitive issue, by implementing exoskeletons in factories, workers could feel more cared for by the company, as the company would be contributing to improve their health and influence cognitive ergonomics to reduce fatigue or stress (Hollnagel, 1997). This thought could again be associated with Objective 8 (Decent Work and Economic Growth).

6.4 New suggestions related to DHM Tools

When proposing new suggestions for the development of DHM tools, first of all, it is necessary to analyse the functions that are not yet working properly. One of them is the export of files extracted from motion capture software to DHM. In this case, it is a matter of importing a recording file from Xsens into the IPS IMMA software in version 3.11, an experimental version that is able to read such files. The software was able to import the measurements as well as the recording of the task, but the participant remains static in the same place, i.e. does not move on the axes. In addition, the values of the shoulder moment or angles are not able to be provided.

On the other hand, unlike motion capture programmes, problems have been encountered in analysing the data extracted from IPS IMMA, as the mean values, when the participant is not performing the task at its maximum, are still very artificial, angles that clearly do not correspond to those of the participant in reality, which makes the DHM tool user look exclusively at specific points or maxima/minima and not at the whole experiment. This is why perfecting the reading and importing of files from motion capture programmes would be something that would help and greatly improve this type of software in order to create a simulation and analysis of how performing different tasks affects the participant through an experiment.

6.5 Future Work

In terms of future work to be developed, several duties have already been mentioned, especially in the area of IPS IMMA software, but this is not the only thing on the agenda.

The most critical point that has been found in the study is the force that the exoskeleton exerts on the arms, which takes them into risky positions, causing the user to make an extra effort to bring his arms back to normal positions, or out of risk. Therefore, a more exhaustive study of this aspect should be carried out.

On the other hand, it is also necessary to continue with the investigation of possible adverse effects on the different parts of the body, such as the wrists, arms, neck, trunk, with an evaluation software other than ScaleFit, as this does not present major differences as it is not capable of detecting the exoskeleton.

Finally, in order to continue with the evaluation of these devices, it is considered essential to carry out a study of these characteristics in natural conditions, with the workers who will later use these devices, to check that the results obtained in laboratories are true and to draw new conclusions due to the use of these devices in a different environment to the one tested.

7 Conclusion

The objectives of the present thesis were:

- Assess the biomechanical effects of wearing an exoskeleton when performing overhead tasks with the aim of reducing the occurrence of MSDs.
- Suggest improvements in DHM tools through motion capture technology and ergonomic evaluation tools.
- To find ergonomic assessment methods that can be implemented in IPS-IMMA in order to study ergonomic changes when wearing exoskeletons in the future.

The first objective, to study the biomechanical effects produced by the use of the exoskeleton, which was considered the most important point to study, consisted of analysing how this device affected the range of motion, shoulder moments and arm elevation among others. In terms of ergonomics, it has been observed that the mere fact of adjusting the exoskeleton to the user's body has caused problems, but even so, all the participants in the experiment have been able to notice a considerable help from the exoskeleton when lifting and working with their arms up. However, as it has already been seen, the exoskeleton also has negative points to be taken into account, which will have to be weighed in the balance in order to conclude about its properties in overhead tasks.

The study itself not only assessed the range of motion in the arm and trunk area but also looked at shoulder moments as well as back disc compression. These areas were of interest as they are the cause of most musculoskeletal injuries and the effects of wearing an exoskeleton such as Paexo should be evaluated as quickly as possible, as there are currently few studies on this new technology.

In other words, the participants were able to observe a noticeable help in terms of working with their arms up. As for the shoulder moment, it has been shown that with the use of the exoskeleton, it decreases, which is a very positive point since, as mentioned above, it is one of the main areas of injury. On the other hand, the results obtained when studying how the device affects the elevation of the arms are not that positive. It has been observed that when using the exoskeleton, more time is spent in higher risk zones than without using it. This is due to the fact that the constant effort that the exoskeleton makes on the participant causes an almost constant raising of the arms unless the participant opposes it. Finally, the results obtained for trunk inclination and disc compression are very similar with and without the exoskeleton, although, in general, the angle of inclination of the trunk decreases slightly with the use of the exoskeleton. Therefore, by working on the ergonomic aspects of such devices, exoskeletons could be considered a viable and fruitful solution to several of the problems that develop today in factories and in jobs that are demanding on the human body.

Concerning the secondary objectives, both were closely related and the methodology used to address them was the same. By means of the simulation carried out with IPS-IMMA, where an attempt was made to recreate the task carried out with motion capture, an ergonomic evaluation was carried out using the ScaleFit software. Although the simulation did not give very similar results with respect to the arm elevation, it did give similar results in the evaluation of moments.

From this analysis, it was corroborated that although certain movements of the manikin still need to be studied by IPS-IMMA, this type of evaluation could be used, or similar ones could be created to help read and understand the results extracted from IPS-IMMA more easily. In addition, in the future, this software could try to be able to read recordings carried out with motion capture, in this way, it would also be possible, for example, to obtain more precise measurements of each subject (since they would be obtained from the measurements obtained in motion capture), in turn, using motion capture, it would be possible to check whether the movements carried out in the simulation are similar to reality or, by contrast, whether the subjects in natural conditions carry out other movements. Thus, the software could carry out movement analysis and more complex simulations, such as analysing the use of exoskeletons for certain tasks, in such a way that first the operations are simulated to observe possible dangers and later the results are checked by means of motion capture.

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Appendix A: Interview

This appendix features an interview conducted with Dan Lämkull, a leading expert in virtual manufacturing and ergonomics at Volvo Cars.

-How is the use of the exoskeleton planned? (time, used in all the activities…)

D:The use of exoskeletons are planned after how the operators are exposed to different risk factors.

There are exoskeletons developed for mitigating different risk factors;

e.g., working above shoulders/head with one/both arms, squatting or kneeling, high pressure forces for finger/fingers.

The exoskeletons are personal protection equipment (PPE) due to personal anthropometric values and sanity reasons.

-What are the usual demographic characteristics of typical assembly workers (Complexion, percentage of male or female, age, description)

D: We have in Torlanda 63 different nationalities in the final assembly plant and the age spans from 18-upper 50 (average age: 38 years; 69,9 % men and 30,1 % women).

In total 1200 persons are working in the Final assembly shop.

-Which is the most challenging/problematic assembly task for workers (Weight, height, duration)

D: High-pressure forces for manual assembly with the hands/fingers are the biggest issue (34 %), second biggest is working under up (30 %).

Most common musculoskeletal problems/disorders

Hand, wrist, finger: 34 %, neck/shoulder: 30 %

-Is there a noticeable increase in task time when wearing an exoskeleton?

D: The task time is not in general significantly affected

-Potential possibility of performing user tests with some operators.

D: Due to the corona pandemic, this is not possible for a considerable time – at least to July 2021

-How much time does it take for a worker to develop only one task, and how many times does the worker repeat it (if the operator has break times between tasks, how much time do they last…). Does he/she do the same task continuously, or does he/she change of task?

D: We have two performance levels of our plants. We have 30 jobs per hour (jph) plants: Charleston and all Chinese plants – so we assemble one car every second minute in these plants.

In our high-volume plants (Torslanda and Gent), we produce 60 jph – in these plants, the operators carry out the same operations 60 times per hour.

The most used remedy for ergonomics issues is work rotation. The worst tasks are only done for 30 minutes, and the operator changes to another task different from the previous one (not exposing the same body parts).

Usually, one operator changes between 4-6 different tasks during one working shift. However, in China, the rotation pattern is completely different – only the absolute worst tasks are related to work rotation.

-Has the exoskeleton been tested in natural conditions (assembly lines)? General perceptions of the workers about the use of the exoskeletons

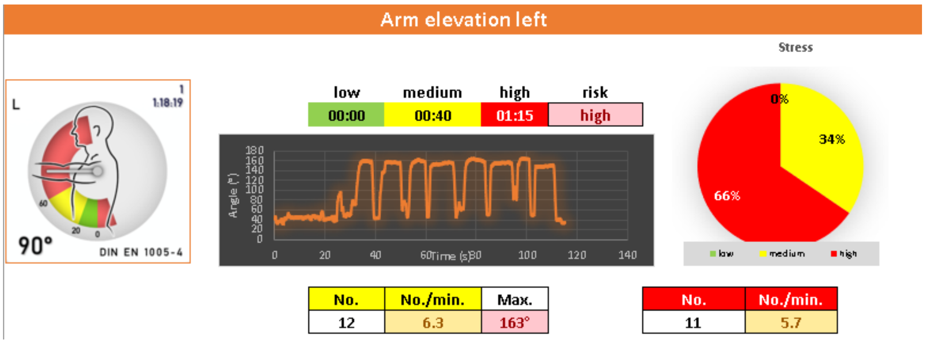
D: Tests have been conducted at the engine plant in Skövde and at Volvo Trucks in Torslanda in a master thesis and in our stamping plant in Olofström.

Appendix B: ScaleFit analysis results

In this appendix is summarized the information evaluated for each participant while recording the tasks with and without the exoskeleton.

7.1 Participant 1

7.1.1 Exoskeleton



Arm elevation left

low	medium	high	risk
00:00	00:40	01:15	high

No.	No./min.	Max.
12	6.3	163°

No.	No./min.
11	5.7

Figure 34. Left arm elevation graph of Participant 1 (Exoskeleton record).

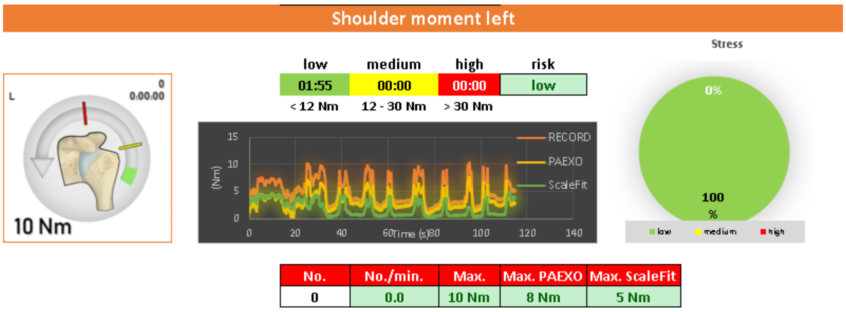
Arm elevation right

low	medium	high	risk
00:00	00:39	01:16	high

No.	No./min.	Max.
17	8.9	140°

No.	No./min.
16	8.3

Figure 35. Right arm elevation of Participant 1 (Exoskeleton record).

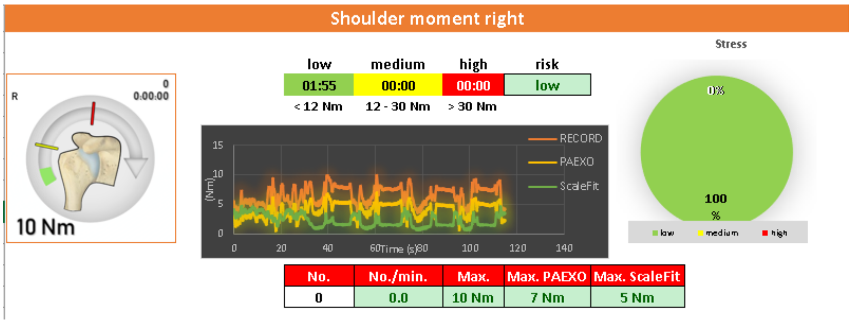


Shoulder moment left

low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	8 Nm	5 Nm

Figure 36. Left shoulder moment graph of Participant 1 (Exoskeleton record).

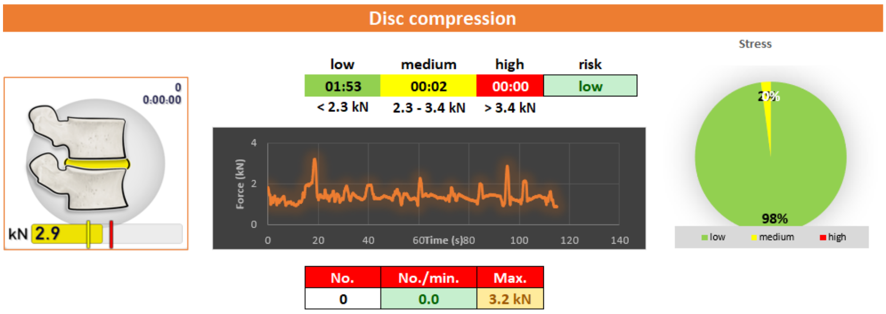


Shoulder moment right

low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	5 Nm

Figure 37. Right shoulder moment graph of Participant 1 (Exoskeleton record).

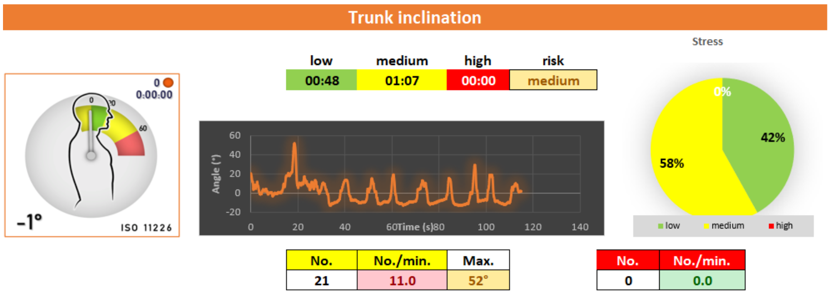


Disc compression

low	medium	high	risk
01:53	00:02	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.2 kN

Figure 38. Disc compression graph of Participant 1 (Exoskeleton record).



Trunk inclination

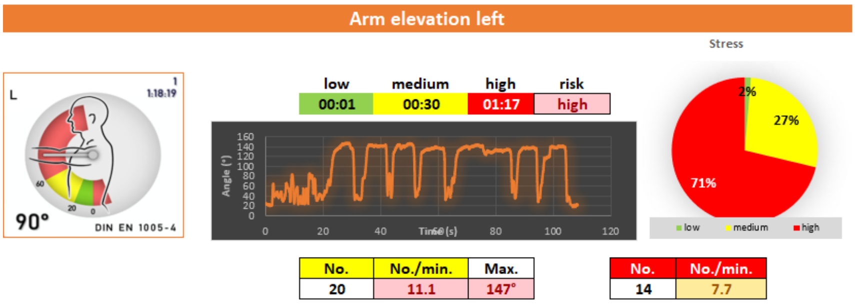
low	medium	high	risk
00:48	01:07	00:00	medium

No.	No./min.	Max.
21	11.0	52°

No.	No./min.
0	0.0

Figure 39. Trunk inclination graph of Participant 1 (Exoskeleton record).

7.1.2 Non-exoskeleton



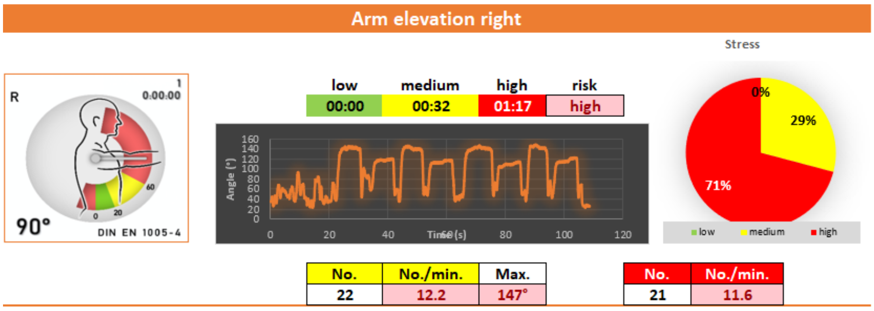
Arm elevation left

low	medium	high	risk
00:01	00:30	01:17	high

No.	No./min.	Max.
20	11.1	147°

No.	No./min.
14	7.7

Figure 40. Left arm elevation graph of Participant 1 (Non-exoskeleton record).



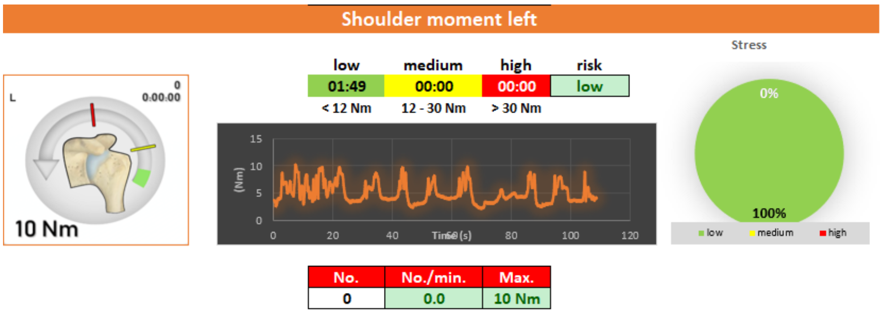
Arm elevation right

low	medium	high	risk
00:00	00:32	01:17	high

No.	No./min.	Max.
22	12.2	147°

No.	No./min.
21	11.6

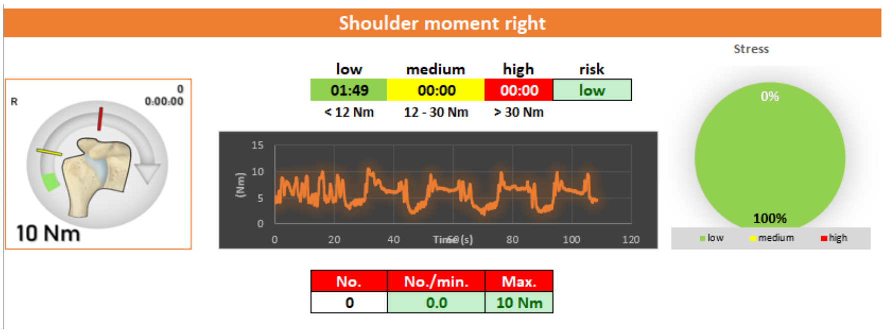
Figure 41. Right arm elevation graph of Participant 1 (Non-exoskeleton record).



low	medium	high	risk
01:49	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	10 Nm

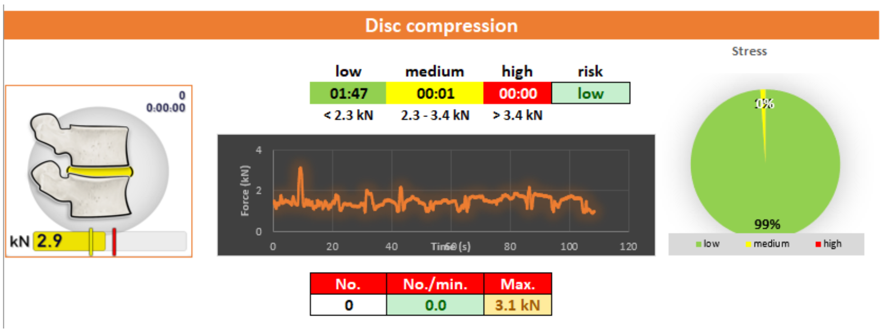
Figure 42. Left shoulder moment graph of Participant 1 (Non-exoskeleton record).



low	medium	high	risk
01:49	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	10 Nm

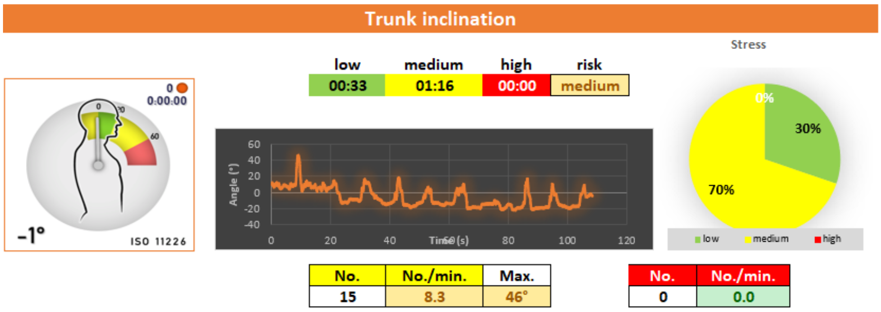
Figure 43. Right shoulder moment graph of Participant 1 (Non-exoskeleton record).



low	medium	high	risk
01:47	00:01	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.1 kN

Figure 44. Disc compression graph of Participant 1 (Non-exoskeleton record).



low	medium	high	risk
00:33	01:16	00:00	medium

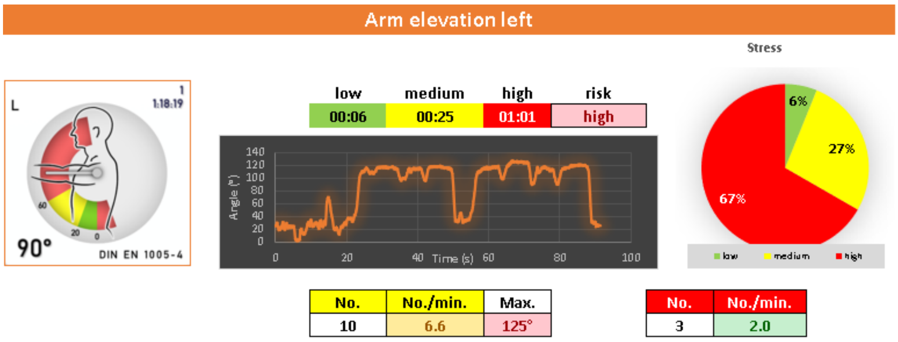
No.	No./min.	Max.
15	8.3	46°

No.	No./min.
0	0.0

Figure 45. Trunk inclination graph of Participant 1 (Non-exoskeleton record)

7.2 Participant 2

7.2.1 Exoskeleton

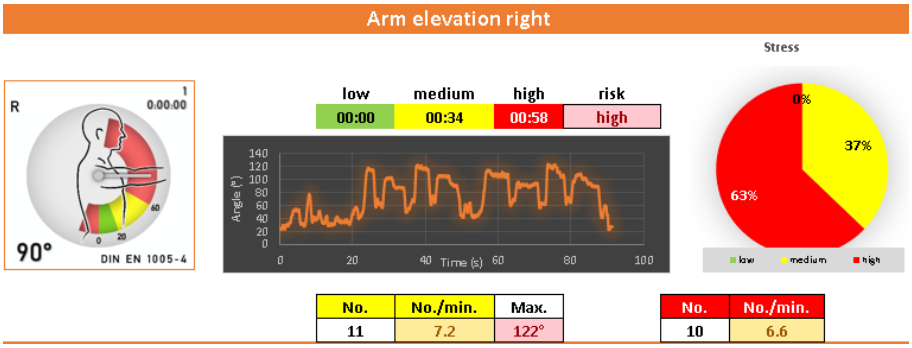


low	medium	high	risk
00:06	00:25	01:01	high

No.	No./min.	Max.
10	6.6	125°

No.	No./min.
3	2.0

Figure 46. Left arm elevation graph of Participant 2 (Exoskeleton record).

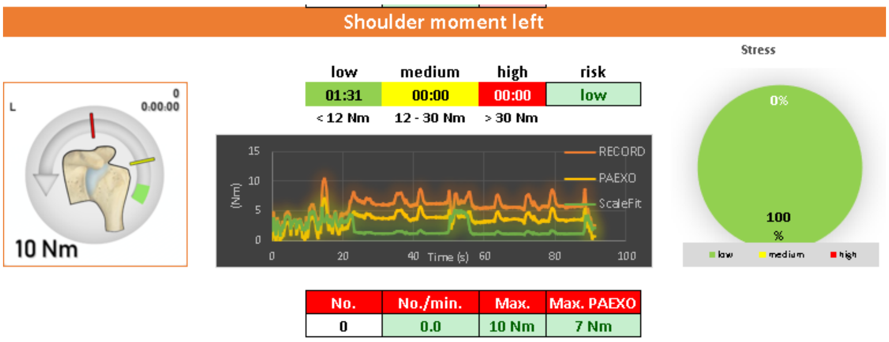


low	medium	high	risk
00:00	00:34	00:58	high

No.	No./min.	Max.
11	7.2	122°

No.	No./min.
10	6.6

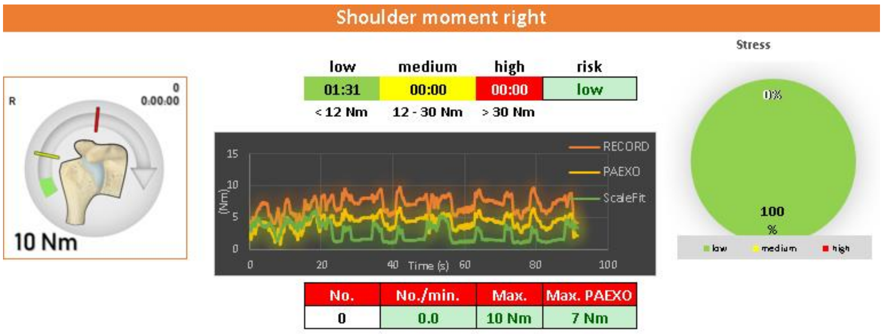
Figure 47. Right arm elevation of Participant 2 (Exoskeleton record).



low	medium	high	risk
01:31	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO
0	0.0	10 Nm	7 Nm

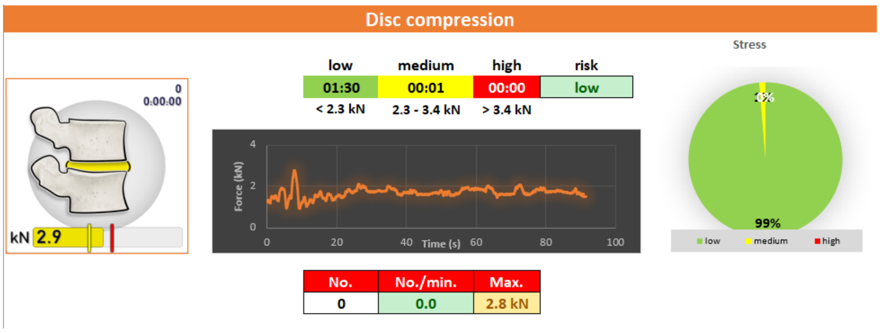
Figure 48. Left shoulder moment graph of Participant 2 (Exoskeleton record).



low	medium	high	risk
01:31	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO
0	0.0	10 Nm	7 Nm

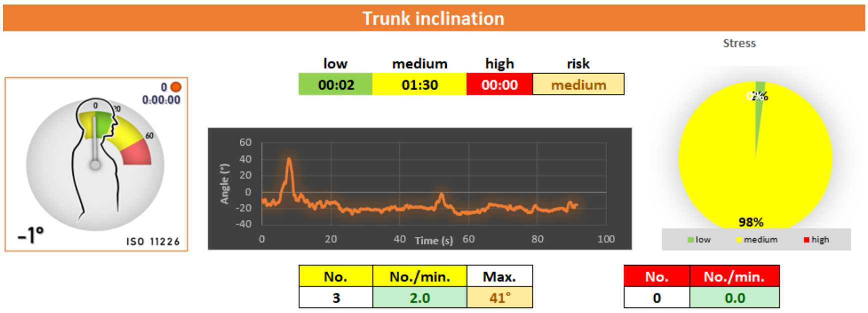
Figure 49. Right shoulder moment graph of Participant 2 (Exoskeleton record).



low	medium	high	risk
01:30	00:01	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.8 kN

Figure 50. Disc compression graph of Participant 2 (Exoskeleton record).



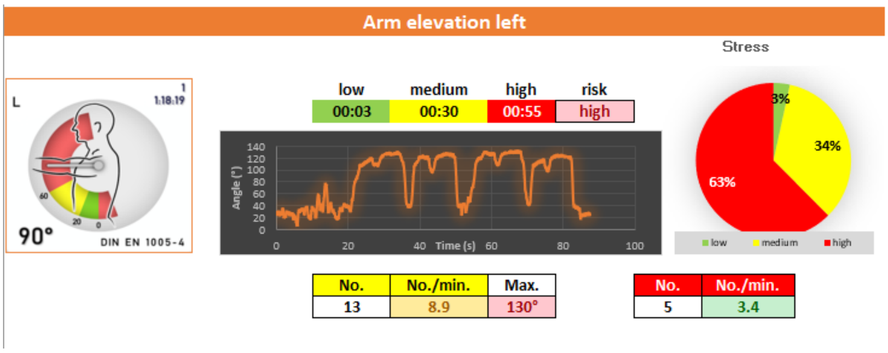
low	medium	high	risk
00:02	01:30	00:00	medium

No.	No./min.	Max.
3	2.0	41°

No.	No./min.
0	0.0

Figure 51. Trunk inclination graph of Participant 2 (Exoskeleton record).

7.2.2 Non-exoskeleton

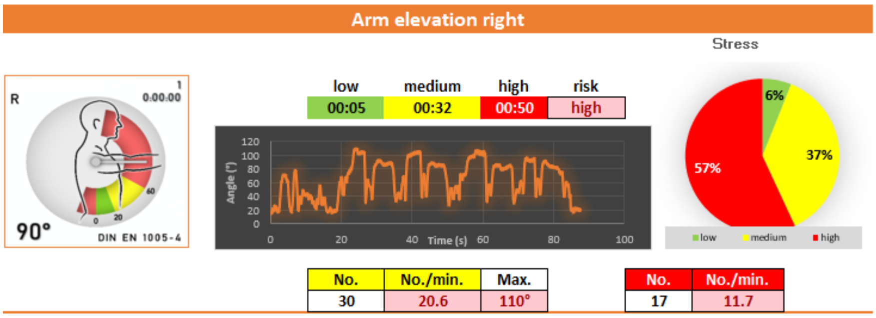


low	medium	high	risk
00:03	00:30	00:55	high

No.	No./min.	Max.
13	8.9	130°

No.	No./min.
5	3.4

Figure 53. Left arm elevation graph of Participant 2 (Non-exoskeleton record).

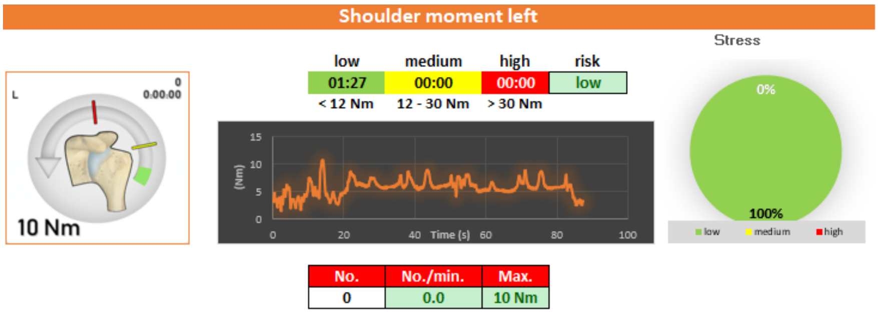


low	medium	high	risk
00:05	00:32	00:50	high

No.	No./min.	Max.
30	20.6	110°

No.	No./min.
17	11.7

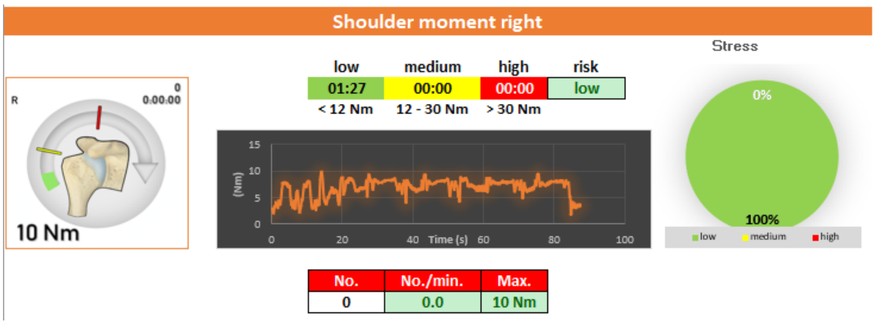
Figure 54. Right arm elevation graph of Participant 2 (Non-exoskeleton record).



low	medium	high	risk
01:27	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	10 Nm

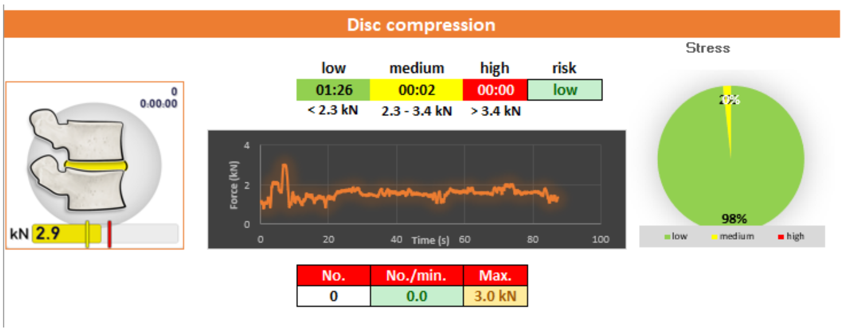
Figure 55. Left shoulder moment graph of Participant 2 (Non-exoskeleton record).



low	medium	high	risk
01:27	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	10 Nm

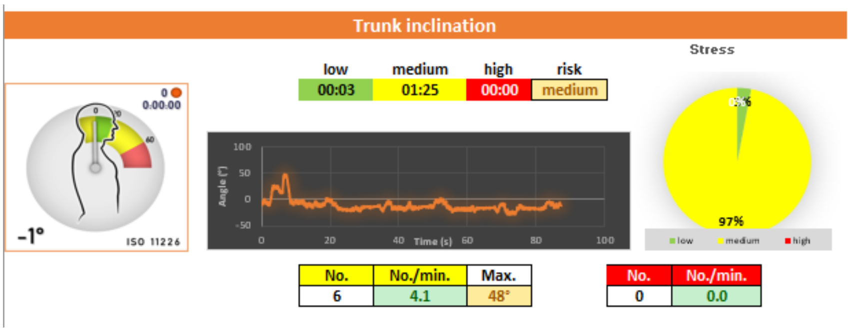
Figure 56. Right shoulder moment graph of Participant 2 (Non-exoskeleton record).



low	medium	high	risk
01:26	00:02	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.0 kN

Figure 57. Disc compression graph of Participant 2 (Non-exoskeleton record).



low	medium	high	risk
00:03	01:25	00:00	medium

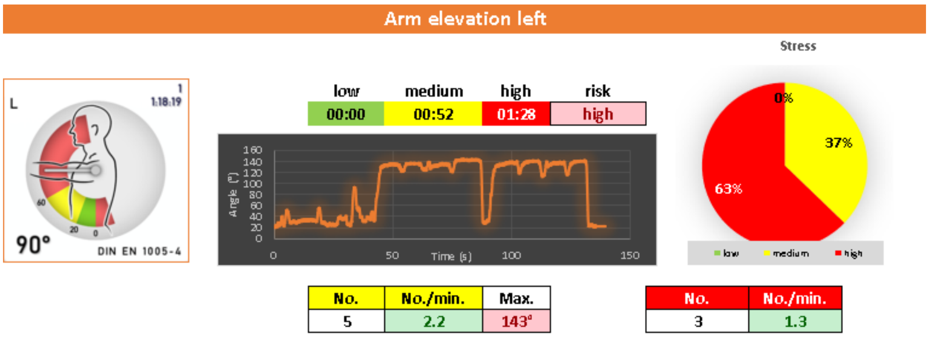
No.	No./min.	Max.
6	4.1	48°

No.	No./min.
0	0.0

Figure 58. Trunk inclination graph of Participant 2 (Non-exoskeleton record)

7.3 Participant 3

7.3.1 Exoskeleton

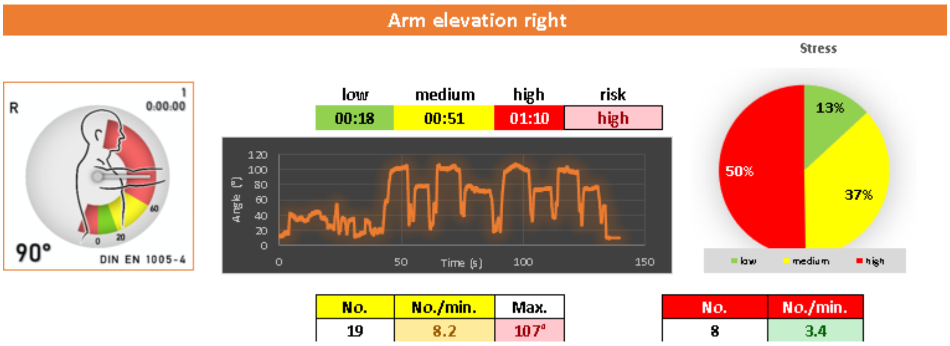


low	medium	high	risk
00:00	00:52	01:28	high

No.	No./min.	Max.
5	2.2	143°

No.	No./min.
3	1.3

Figure 59. Left arm elevation graph of Participant 3 (Exoskeleton record).

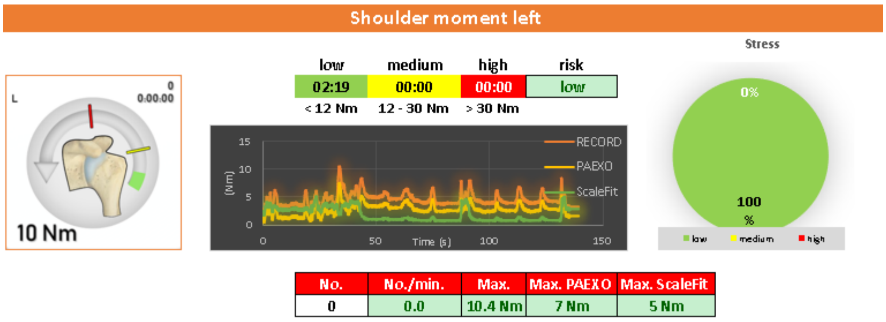


low	medium	high	risk
00:18	00:51	01:10	high

No.	No./min.	Max.
19	8.2	107°

No.	No./min.
8	3.4

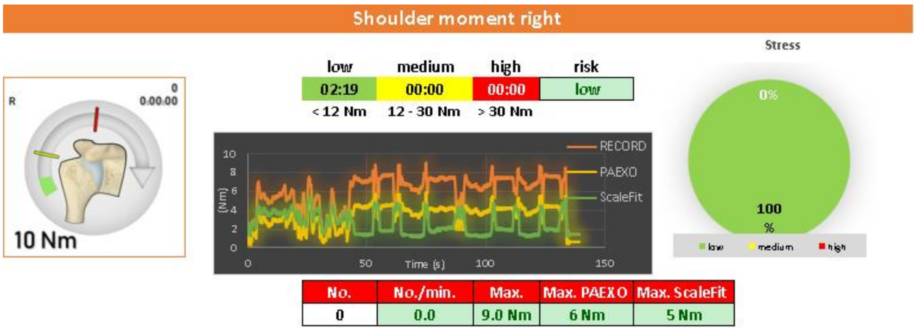
Figure 60. Right arm elevation of Participant 3 (Exoskeleton record).



low	medium	high	risk
02:19	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10.4 Nm	7 Nm	5 Nm

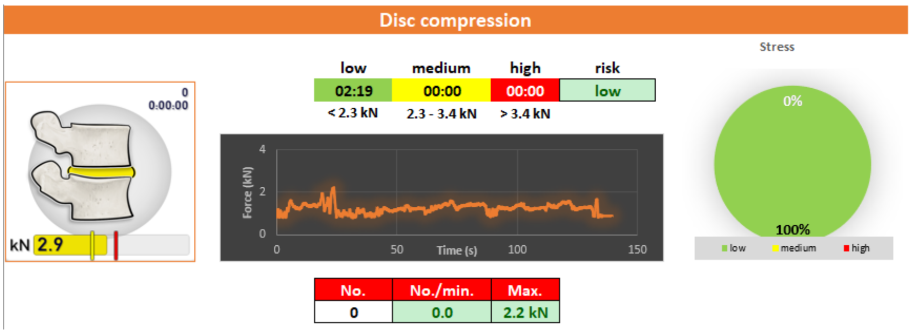
Figure 61. Left shoulder moment graph of Participant 3 (Exoskeleton record).



low	medium	high	risk
02:19	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9.0 Nm	6 Nm	5 Nm

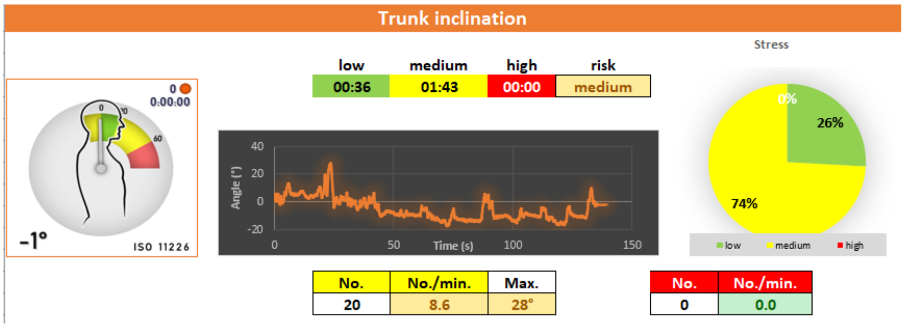
Figure 62. Right shoulder moment graph of Participant 3 (Exoskeleton record).



low	medium	high	risk
02:19	00:00	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.2 kN

Figure 63. Disc compression graph of Participant 3 (Exoskeleton record).



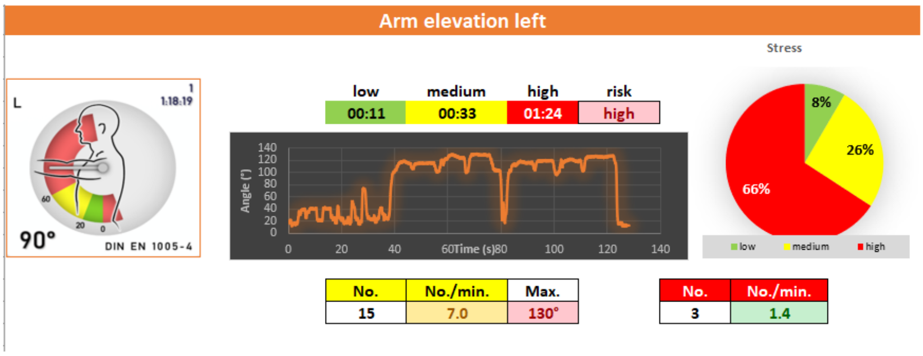
low	medium	high	risk
00:36	01:43	00:00	medium

No.	No./min.	Max.
20	8.6	28°

No.	No./min.
0	0.0

Figure 64. Trunk inclination graph of Participant 3 (Exoskeleton record).

7.3.2 Non-exoskeleton

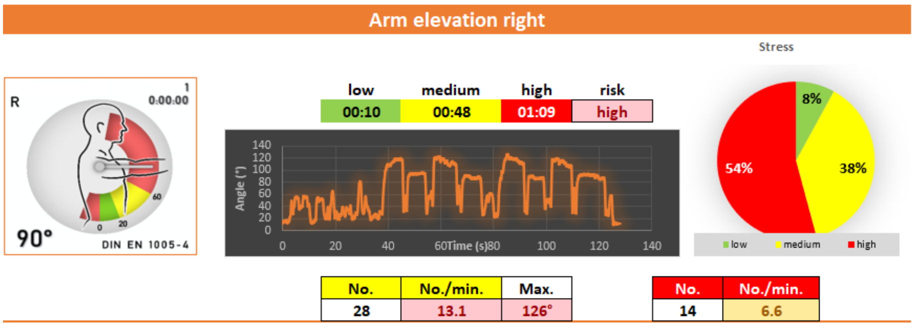


low	medium	high	risk
00:11	00:33	01:24	high

No.	No./min.	Max.
15	7.0	130°

No.	No./min.
3	1.4

Figure 65. Left arm elevation graph of Participant 3 (Non-exoskeleton record).

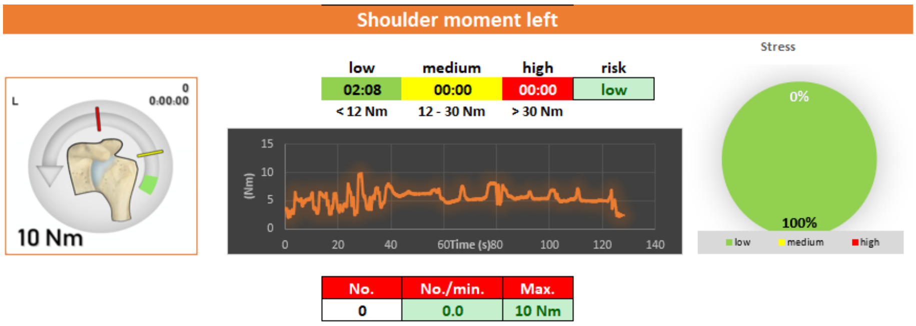


low	medium	high	risk
00:10	00:48	01:09	high

No.	No./min.	Max.
28	13.1	126°

No.	No./min.
14	6.6

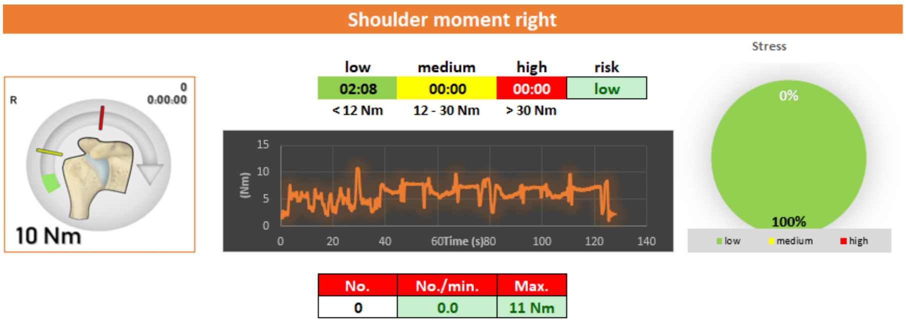
Figure 66. Right arm elevation graph of Participant 3 (Non-exoskeleton record).



low	medium	high	risk
02:08	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	10 Nm

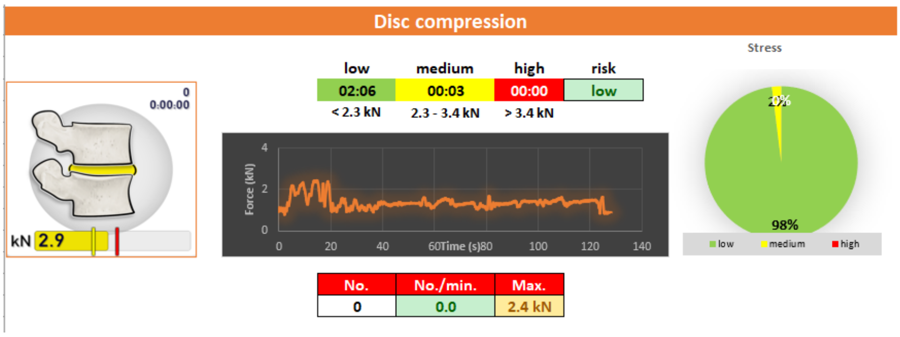
Figure 67. Left shoulder moment graph of Participant 3 (Non-exoskeleton record).



low	medium	high	risk
02:08	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	11 Nm

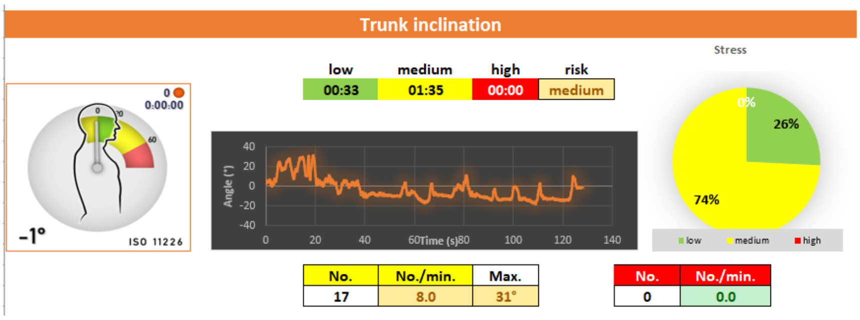
Figure 68. Right shoulder moment graph of Participant 3 (Non-exoskeleton record).



low	medium	high	risk
02:06	00:03	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.4 kN

Figure 69. Disc compression graph of Participant 3 (Non-exoskeleton record).



low	medium	high	risk
00:33	01:35	00:00	medium

No.	No./min.	Max.
17	8.0	31°

No.	No./min.
0	0.0

Figure 70. Trunk inclination graph of Participant 3 (Non-exoskeleton record)

7.3.3 Weight evaluation

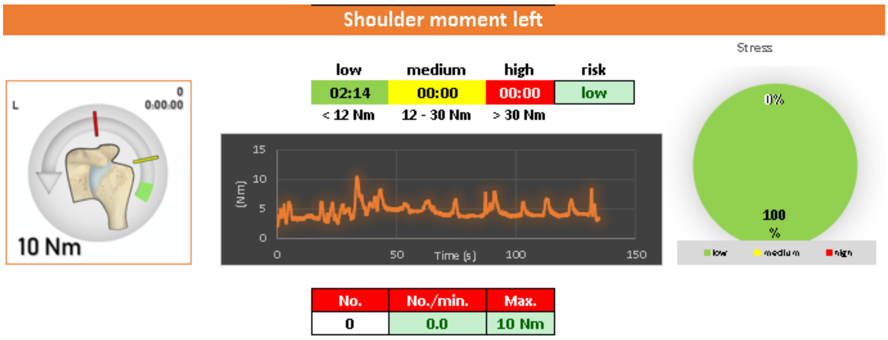


Figure 71. Left shoulder moment graph of Participant 3 (Weight record).

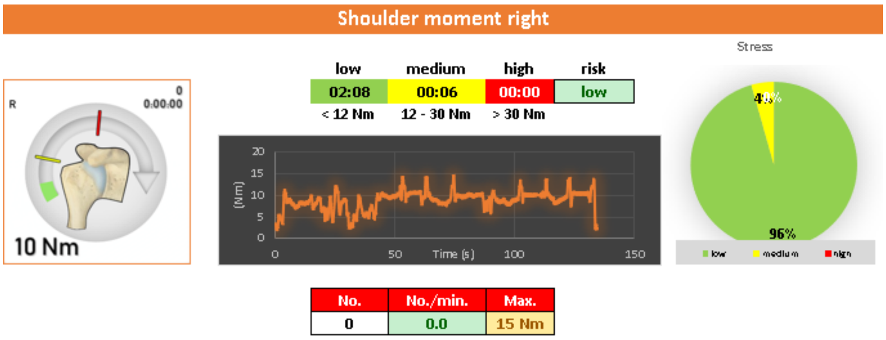


Figure 72. Right shoulder moment graph of Participant 3 (Weight record).

7.3.4 IPS-IMMA evaluation

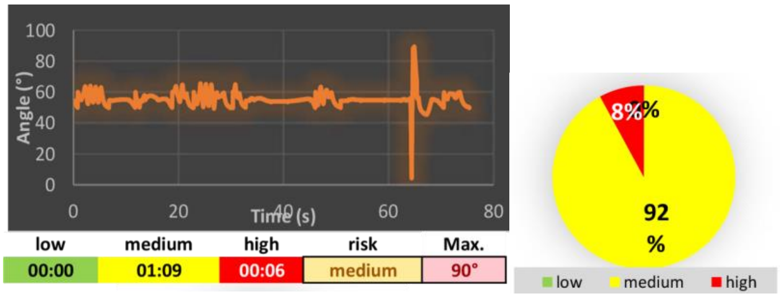


Figure 73. Left arm elevation graph of Participant 3 (IPS-IMMA simulation).

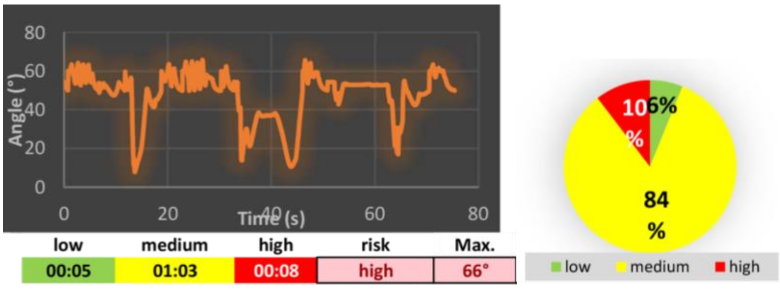
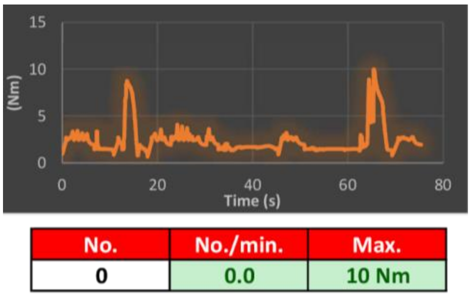
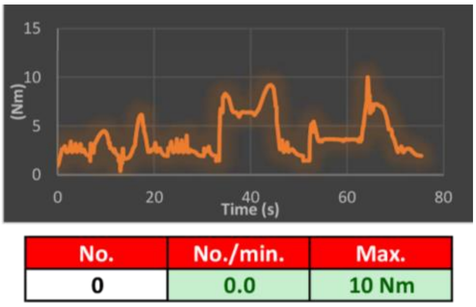


Figure74. Right arm elevation graph of Participant 3 (IPS-IMMA simulation).



No.	No./min.	Max.
0	0.0	10 Nm

Figure 75. Left shoulder moment graph of Participant 3 (IPS-IMMA simulation).

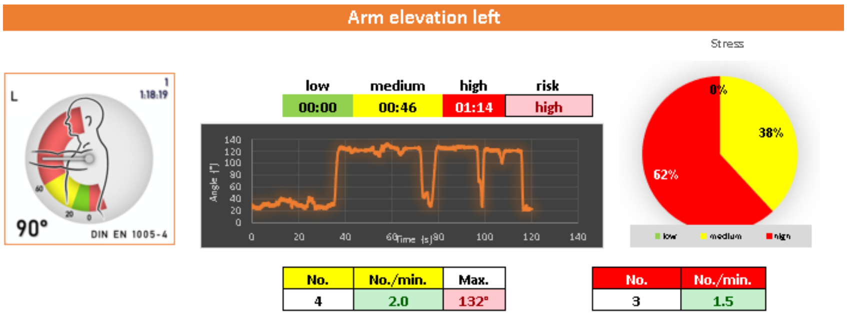


No.	No./min.	Max.
0	0.0	10 Nm

Figure 76. Right shoulder moment graph of Participant 3 (IPS-IMMA simulation).

7.4 Participant 4

7.4.1 Exoskeleton

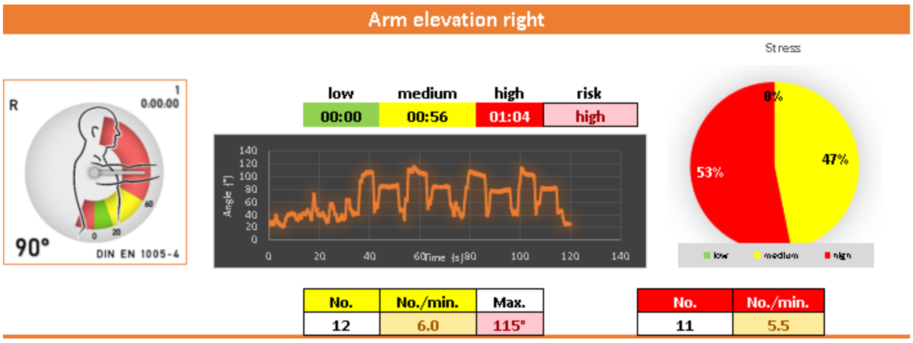


low	medium	high	risk
00:00	00:46	01:14	high

No.	No./min.	Max.
4	2.0	132°

No.	No./min.
3	1.5

Figure 77. Left arm elevation graph of Participant 4 (Exoskeleton record).

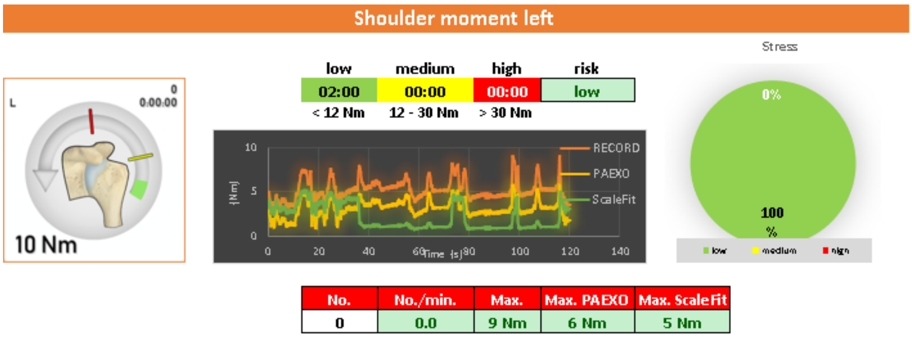


low	medium	high	risk
00:00	00:56	01:04	high

No.	No./min.	Max.
12	6.0	115°

No.	No./min.
11	5.5

Figure 78. Right arm elevation of Participant 4 (Exoskeleton record).



low	medium	high	risk
02:00	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

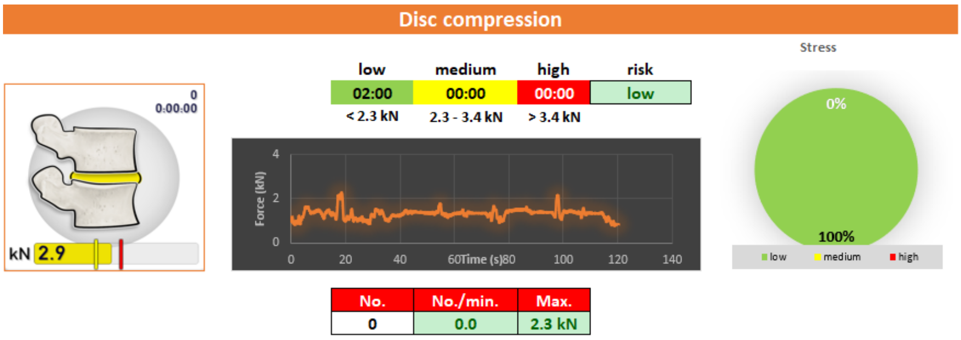
No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9 Nm	6 Nm	5 Nm

Figure 79. Left shoulder moment graph of Participant 4 (Exoskeleton record).

low	medium	high	risk
02:00	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9 Nm	6 Nm	5 Nm

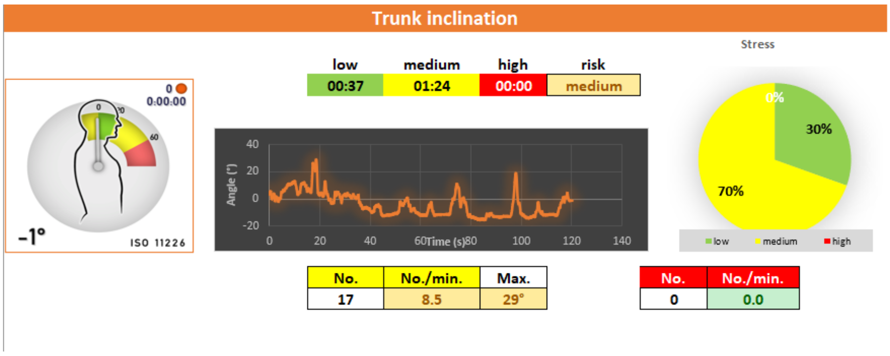
Figure 80. Right shoulder moment graph of the Participant 4 (Exoskeleton record).



low	medium	high	risk
02:00	00:00	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.3 kN

Figure 81. Disc compression graph of Participant 4 (Exoskeleton record).



low	medium	high	risk
00:37	01:24	00:00	medium

No.	No./min.	Max.
17	8.5	29°

No.	No./min.
0	0.0

Figure 82. Trunk inclination graph of Participant 4 (Exoskeleton record).

7.4.2 Non-exoskeleton

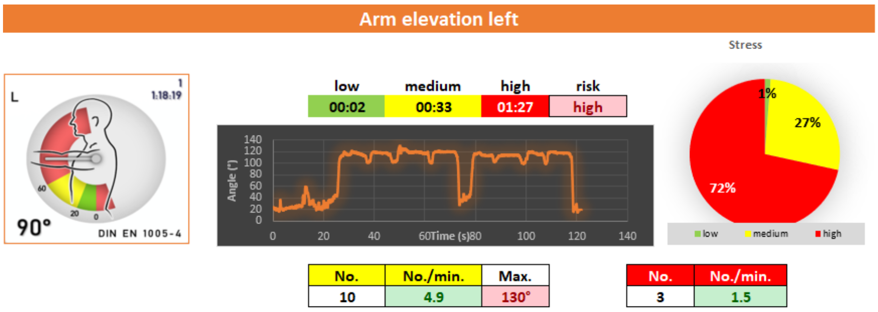


Figure 83. Left arm elevation graph of Participant 4 (Non-exoskeleton record).

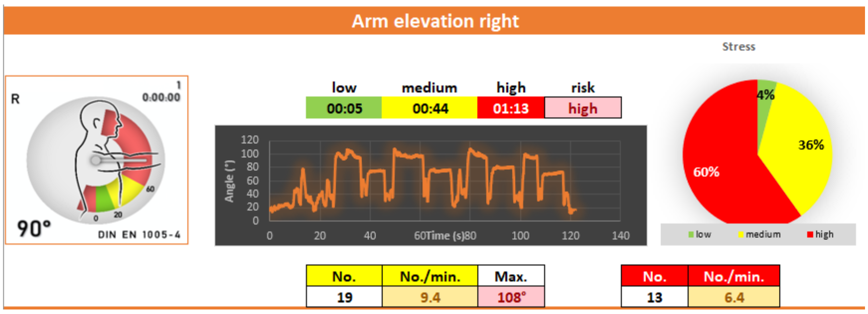


Figure 84. Right arm elevation graph of Participant 4 (Non-exoskeleton record).

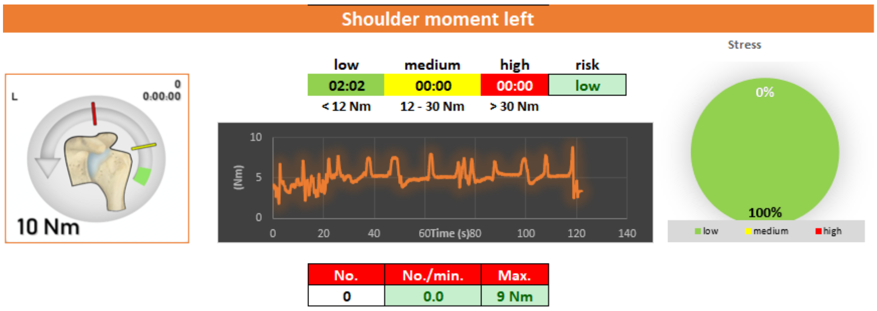


Figure 85. Left shoulder moment graph of Participant 4 (Non-exoskeleton record).

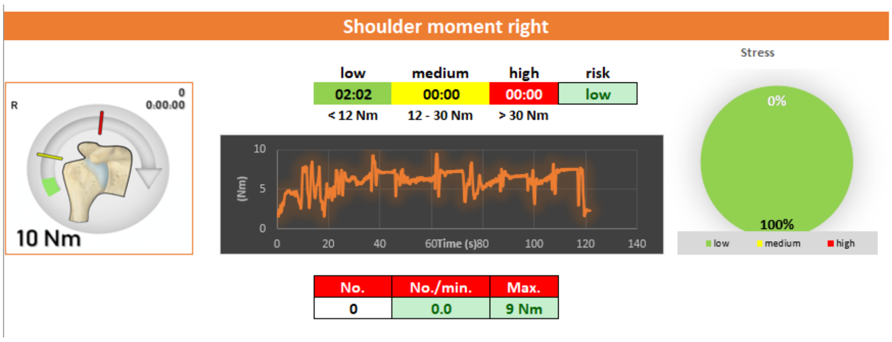
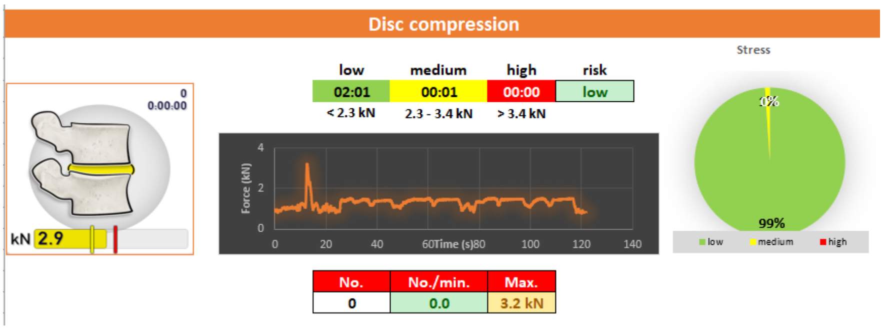


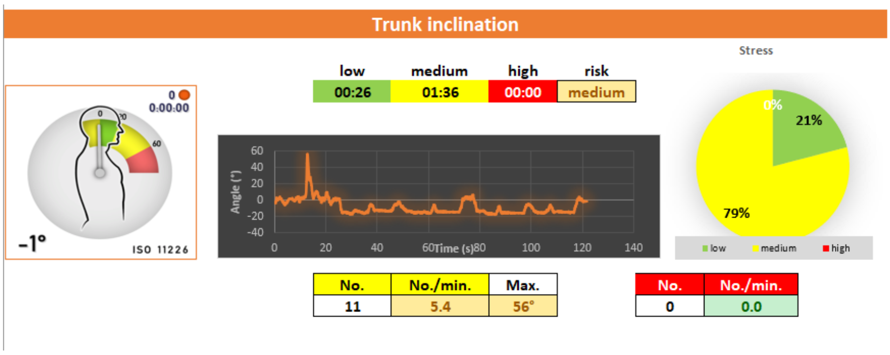
Figure 86. Right shoulder moment graph of Participant 4 (Non-exoskeleton record).



low	medium	high	risk
02:01	00:01	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.2 kN

Figure 87. Disc compression graph of Participant 4 (Non-exoskeleton record).



low	medium	high	risk
00:26	01:36	00:00	medium

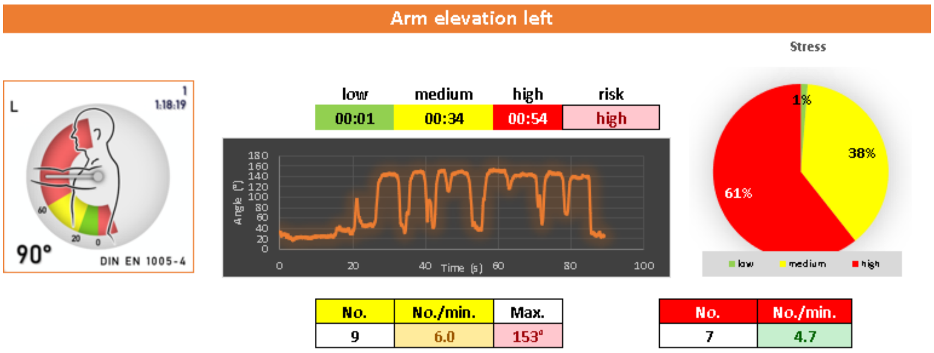
No.	No./min.	Max.
11	5.4	56°

No.	No./min.
0	0.0

Figure 88. Trunk inclination graph of Participant 4 (Non-exoskeleton record)

7.5 Participant 5

7.5.1 Exoskeleton

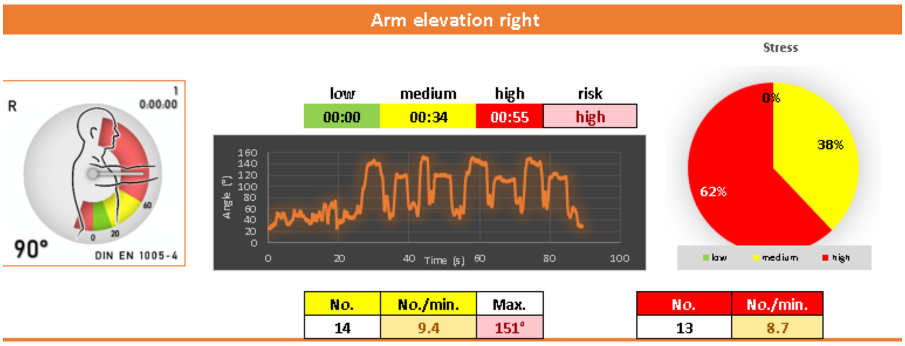


low	medium	high	risk
00:01	00:34	00:54	high

No.	No./min.	Max.
9	6.0	153°

No.	No./min.
7	4.7

Figure 89. Left arm elevation graph of Participant 5 (Exoskeleton record).

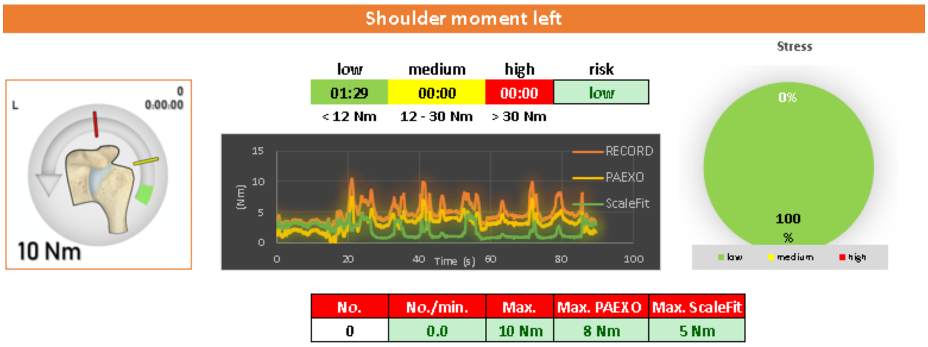


low	medium	high	risk
00:00	00:34	00:55	high

No.	No./min.	Max.
14	9.4	151°

No.	No./min.
13	8.7

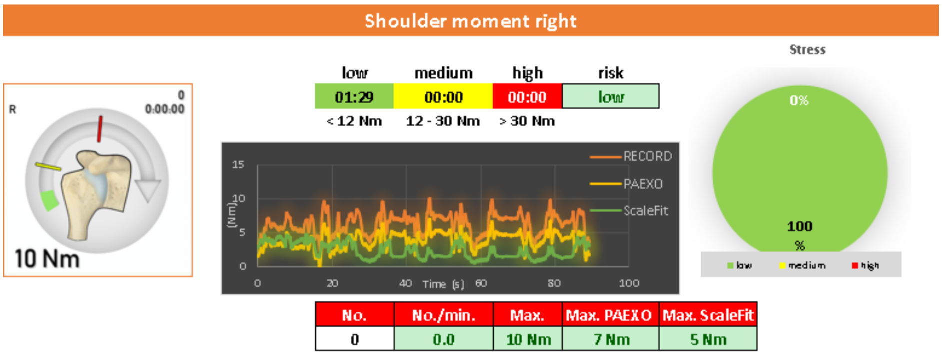
Figure 90. Right arm elevation of Participant 5 (Exoskeleton record).



low	medium	high	risk
01:29	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	8 Nm	5 Nm

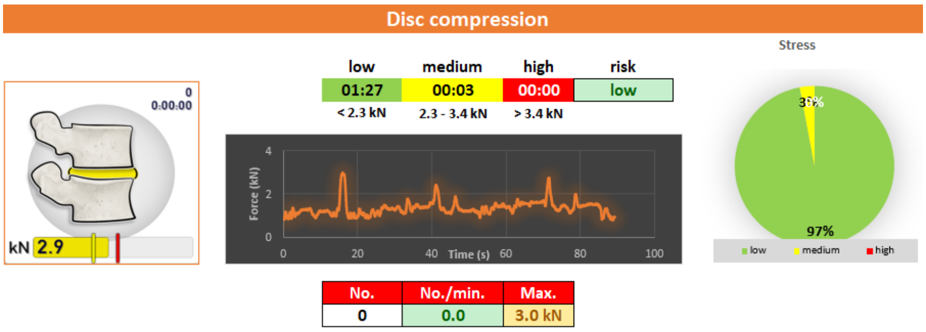
Figure 91. Left shoulder moment graph of the Participant 5 (Exoskeleton record).



low	medium	high	risk
01:29	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	5 Nm

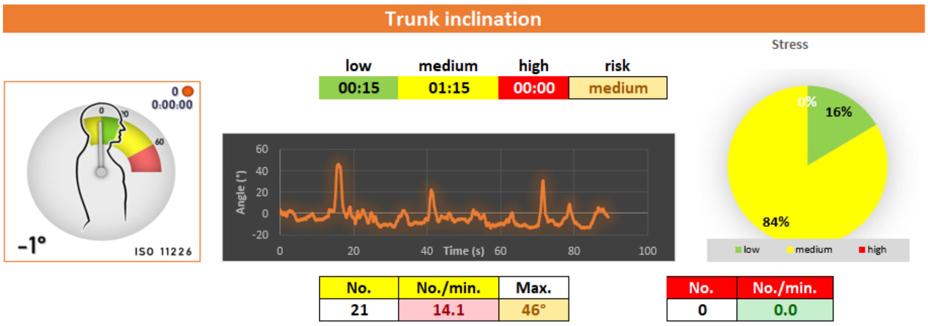
Figure 92. Right shoulder moment graph of the Participant 5 (Exoskeleton record).



low	medium	high	risk
01:27	00:03	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.0 kN

Figure 93. Disc compression graph of Participant 5 (Exoskeleton record).



low	medium	high	risk
00:15	01:15	00:00	medium

No.	No./min.	Max.
21	14.1	46°

No.	No./min.
0	0.0

Figure 94. Trunk inclination graph of Participant 5 (Exoskeleton record).

7.5.2 Non-exoskeleton

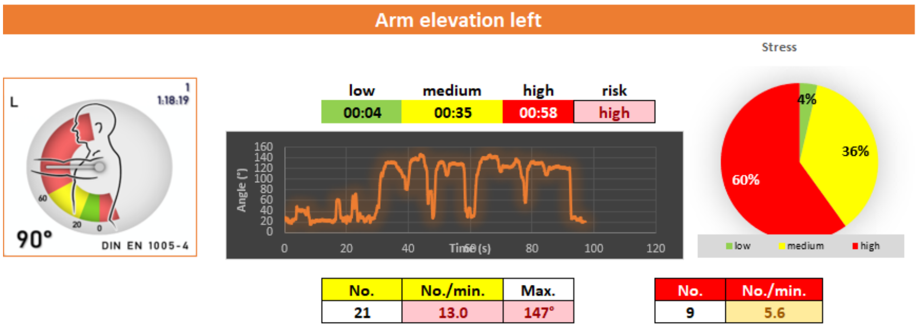


Figure 95. Left arm elevation graph of Participant 5 (Non-exoskeleton record).

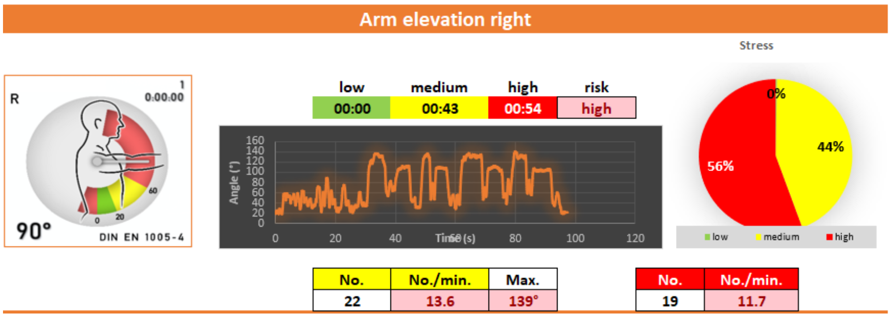


Figure 96. Right arm elevation graph of Participant 5 (Non-exoskeleton record).

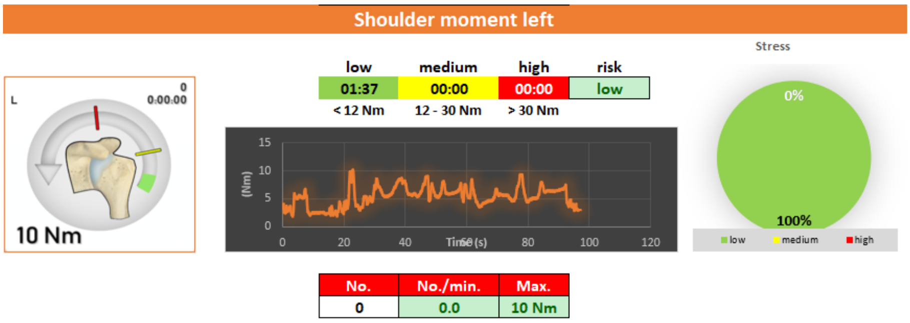


Figure 97. Left shoulder moment graph of Participant 5 (Non-exoskeleton record).

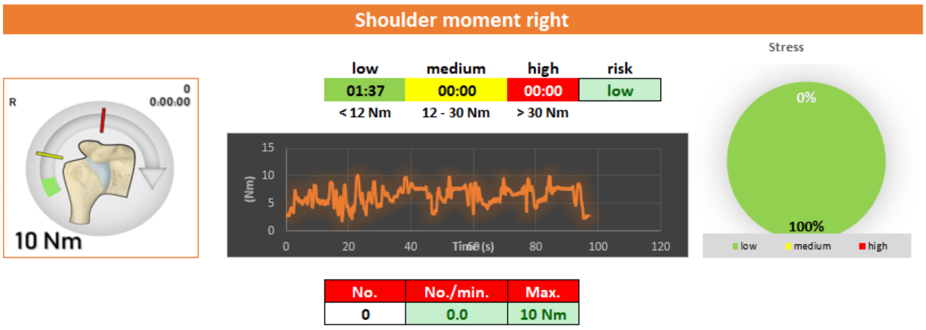
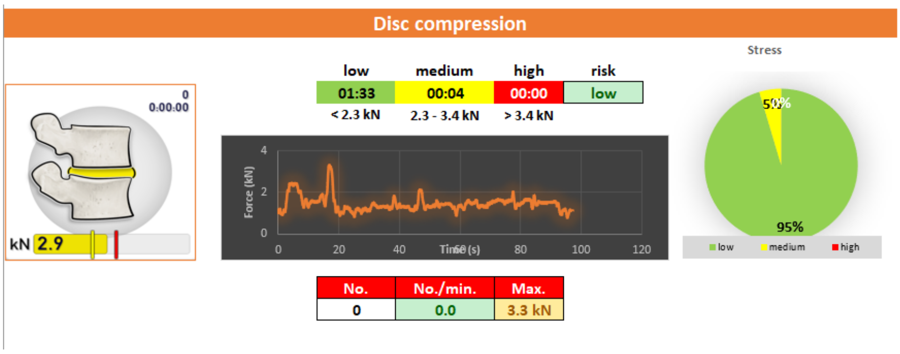


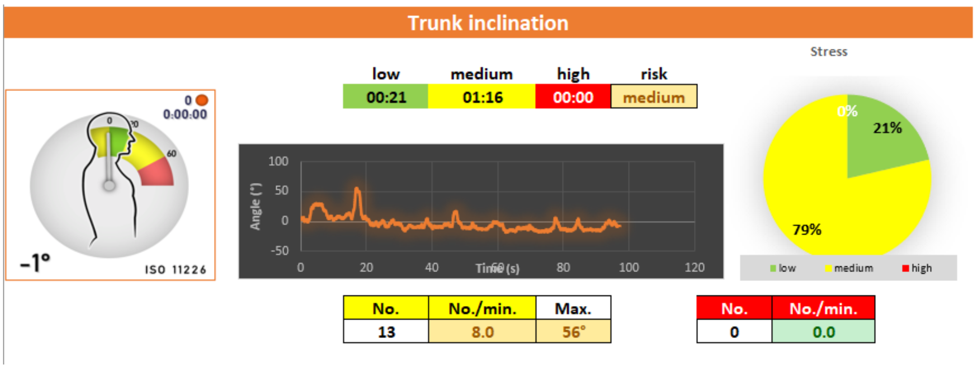
Figure 98. Right shoulder moment graph of Participant 5 (Non-exoskeleton record).



low	medium	high	risk
01:33	00:04	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.3 kN

Figure 99. Disc compression graph of Participant 5 (Non-exoskeleton record).



low	medium	high	risk
00:21	01:16	00:00	medium

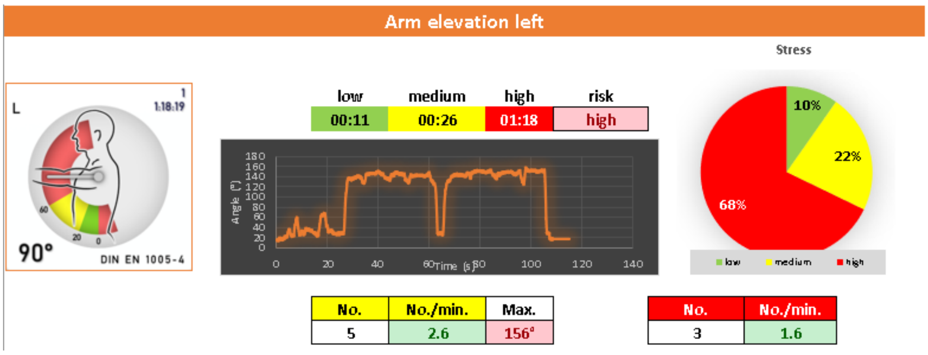
No.	No./min.	Max.
13	8.0	56°

No.	No./min.
0	0.0

Figure 100. Trunk inclination graph of Participant 5 (Non-exoskeleton record)

7.6 Participant 6

7.6.1 Exoskeleton

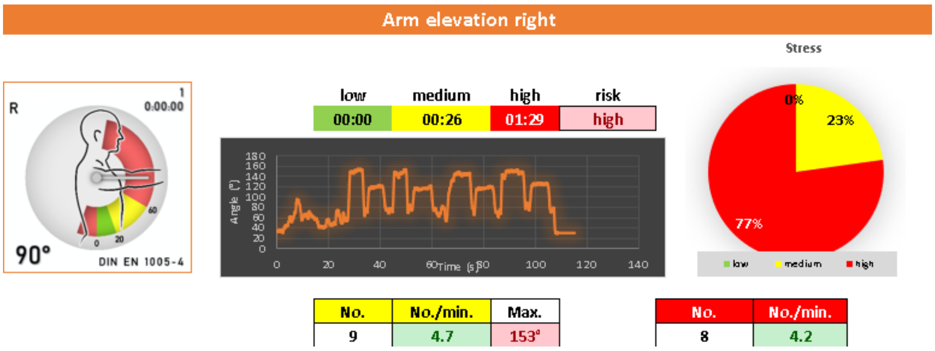


low	medium	high	risk
00:11	00:26	01:18	high

No.	No./min.	Max.
5	2.6	156°

No.	No./min.
3	1.6

Figure 101. Left arm elevation graph of Participant 6 (Exoskeleton record).

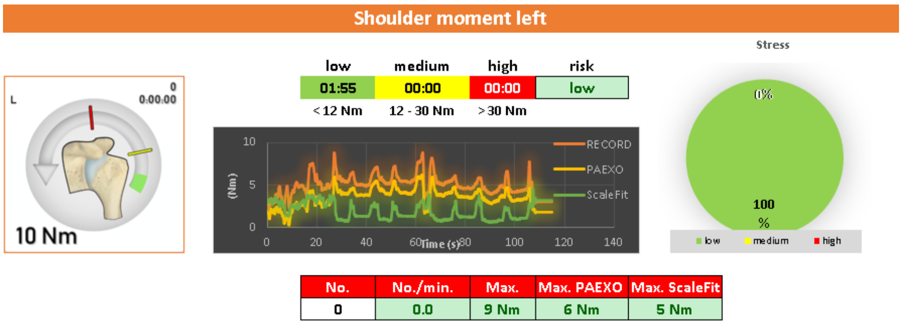


low	medium	high	risk
00:00	00:26	01:29	high

No.	No./min.	Max.
9	4.7	153°

No.	No./min.
8	4.2

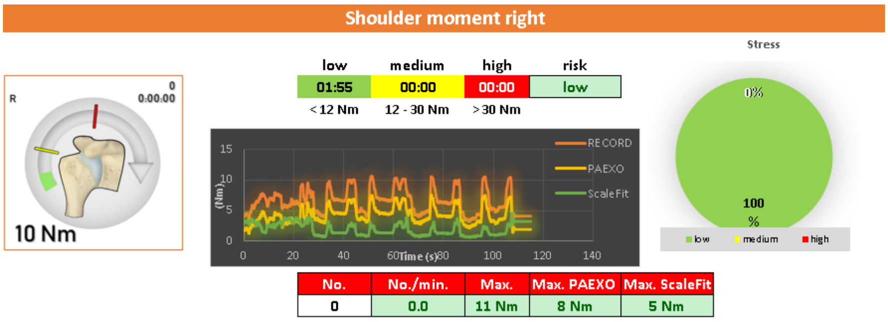
Figure 102. Right arm elevation of Participant 6 (Exoskeleton record).



low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9 Nm	6 Nm	5 Nm

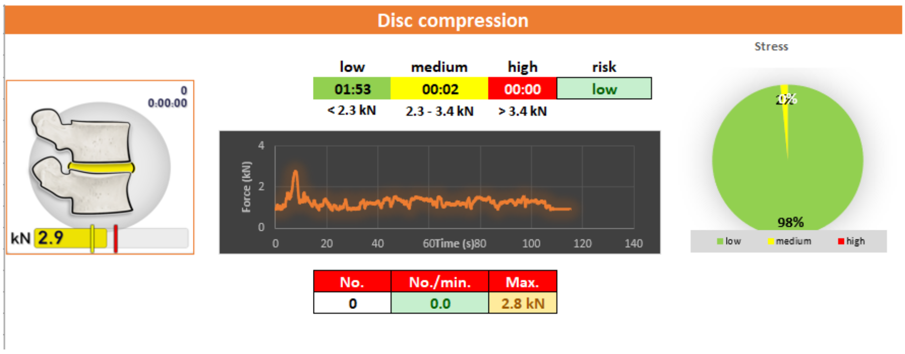
Figure 103. Left shoulder moment graph of Participant 6 (Exoskeleton record).



low	medium	high	risk
01:55	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	11 Nm	8 Nm	5 Nm

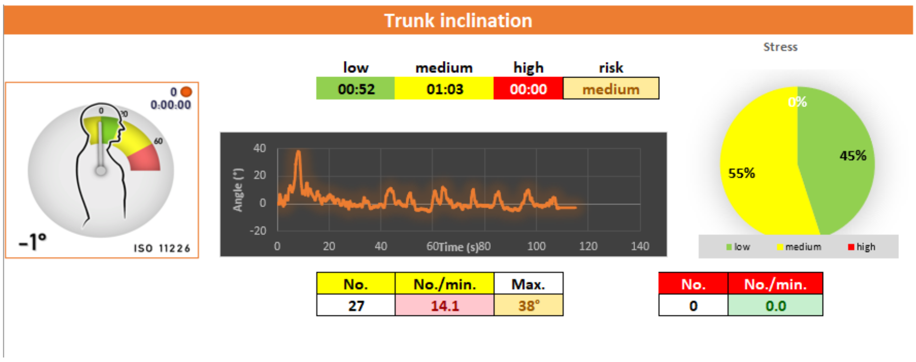
Figure 104. Right shoulder moment graph of Participant 6 (Exoskeleton record).



low	medium	high	risk
01:53	00:02	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.8 kN

Figure 105. Disc compression graph of Participant 6 (Exoskeleton record).



low	medium	high	risk
00:52	01:03	00:00	medium

No.	No./min.	Max.
27	14.1	38°

No.	No./min.
0	0.0

Figure 106. Trunk inclination graph of Participant 6 (Exoskeleton record).

7.6.2 Non-exoskeleton

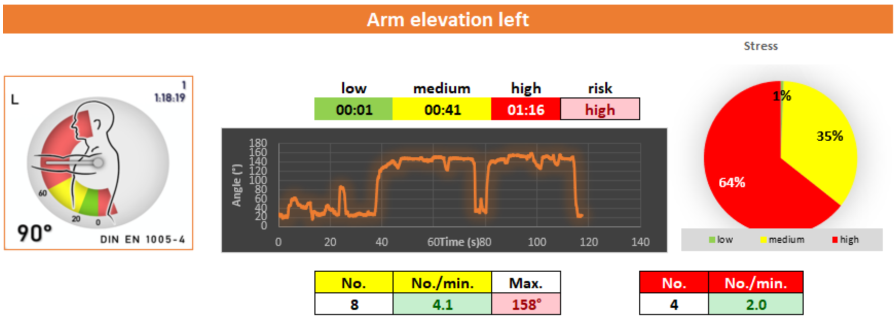


Figure 107. Left arm elevation graph of Participant 6 (Non-exoskeleton record).

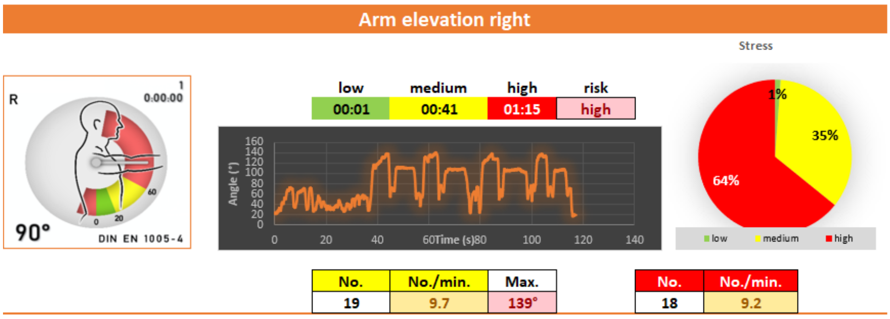


Figure 108. Right arm elevation graph of Participant 6 (Non-exoskeleton record).

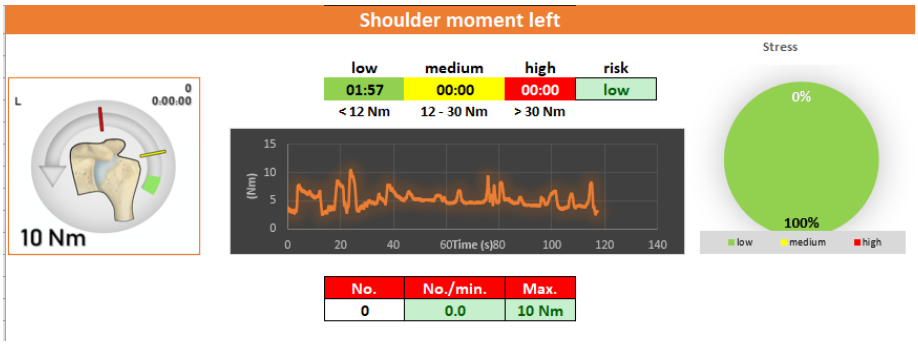


Figure 109. Left shoulder moment graph of Participant 6 (Non-exoskeleton record).

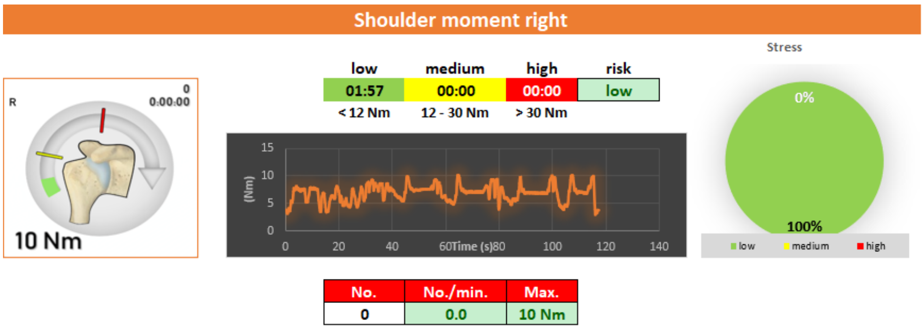
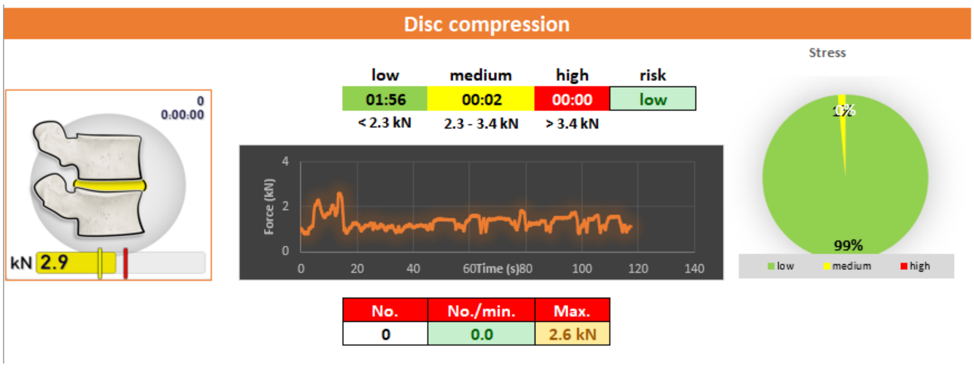


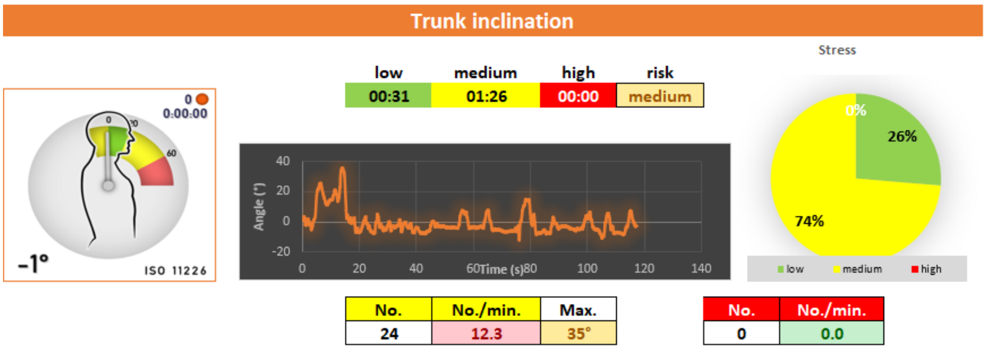
Figure 110. Right shoulder moment graph of Participant 6 (Non-exoskeleton record).



low	medium	high	risk
01:56	00:02	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.6 kN

Figure 111. Disc compression graph of Participant 6 (Non-exoskeleton record).



low	medium	high	risk
00:31	01:26	00:00	medium

No.	No./min.	Max.
24	12.3	35°

No.	No./min.
0	0.0

Figure 112. Trunk inclination graph of Participant 6 (Non-exoskeleton record)

7.7 Participant 7

7.7.1 Exoskeleton

low	medium	high	risk
00:13	00:32	01:07	high

No.	No./min.	Max.
9	4.8	130°

No.	No./min.
3	1.6

Figure 113. Left arm elevation graph of Participant 7 (Exoskeleton record).

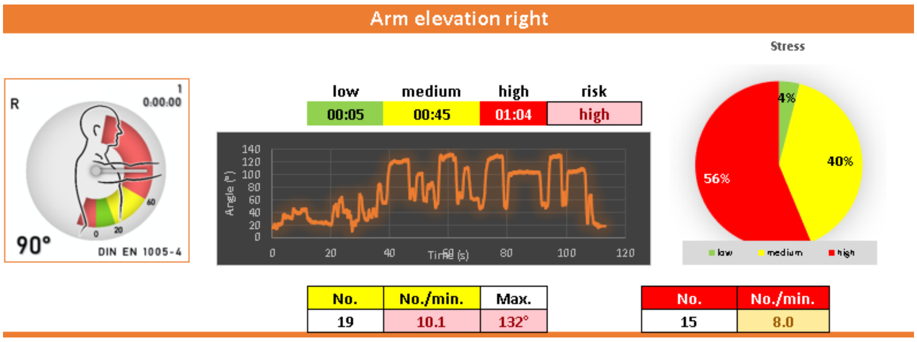


Figure 114. Right arm elevation of Participant 7 (Exoskeleton record).

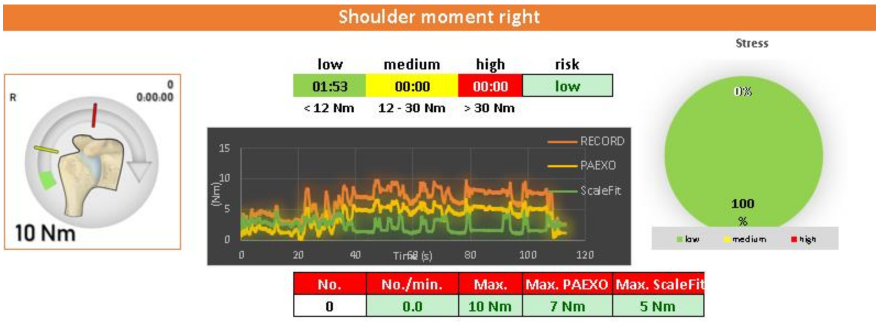


Figure 115. Left shoulder moment graph of Participant 7 (Exoskeleton record).

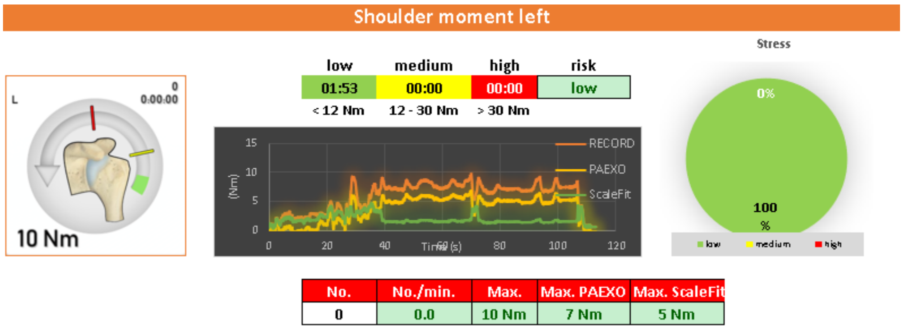


Figure 116. Right shoulder moment graph of Participant 7 (Exoskeleton record).

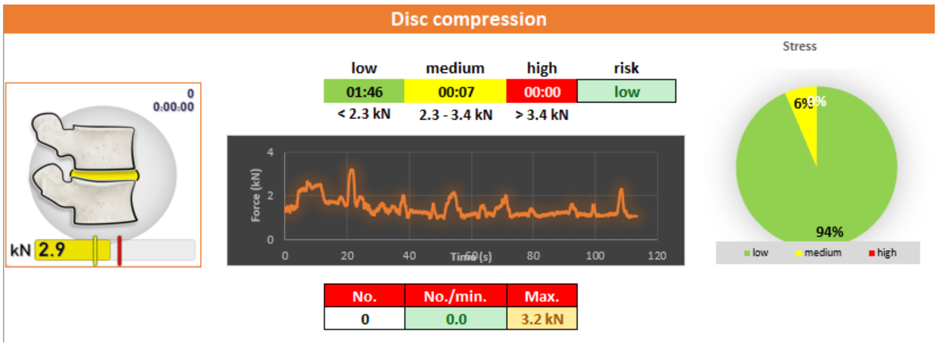
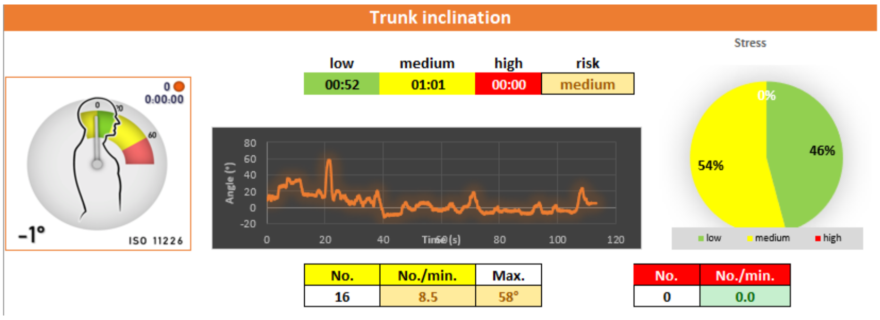


Figure 117. Disc compression graph of Participant 7 (Exoskeleton record).



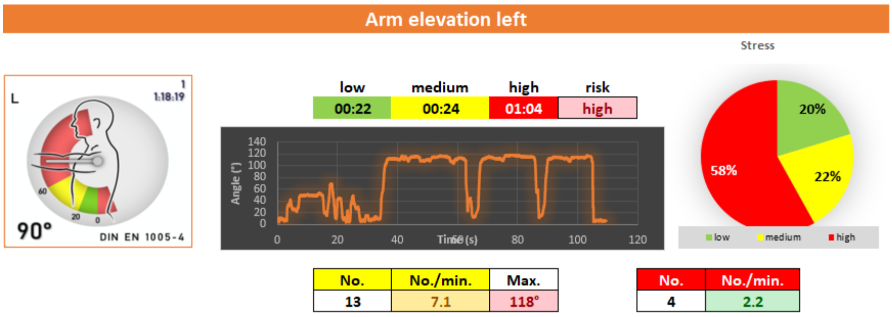
low	medium	high	risk
00:52	01:01	00:00	medium

No.	No./min.	Max.
16	8.5	58°

No.	No./min.
0	0.0

Figure 118. Trunk inclination graph of Participant 7 (Exoskeleton record).

7.7.2 Non-exoskeleton

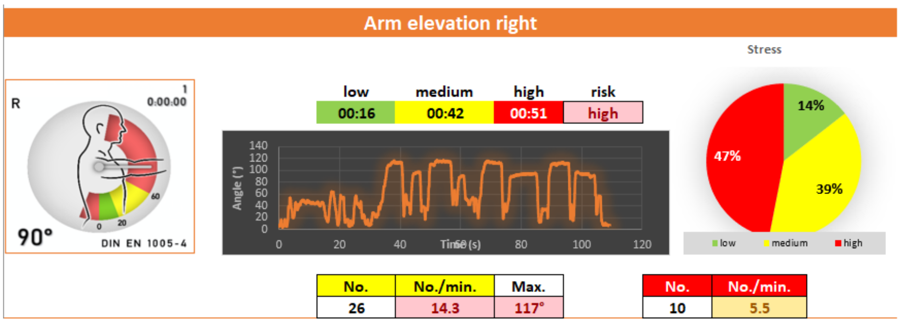


low	medium	high	risk
00:22	00:24	01:04	high

No.	No./min.	Max.
13	7.1	118°

No.	No./min.
4	2.2

Figure 119. Left arm elevation graph of Participant 7 (Non-exoskeleton record).

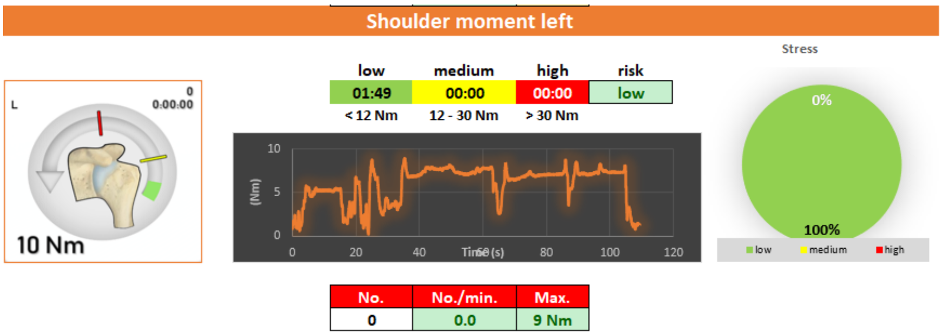


low	medium	high	risk
00:16	00:42	00:51	high

No.	No./min.	Max.
26	14.3	117°

No.	No./min.
10	5.5

Figure 120. Right arm elevation graph of Participant 7 (Non-exoskeleton record).



low	medium	high	risk
01:49	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	9 Nm

Figure 121. Left shoulder moment graph of Participant 7 (Non-exoskeleton record).

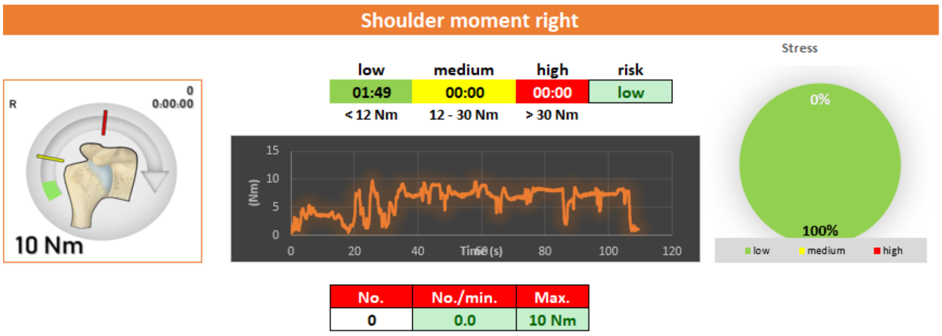


Figure 122. Right shoulder moment graph of Participant 7 (Non-exoskeleton record).

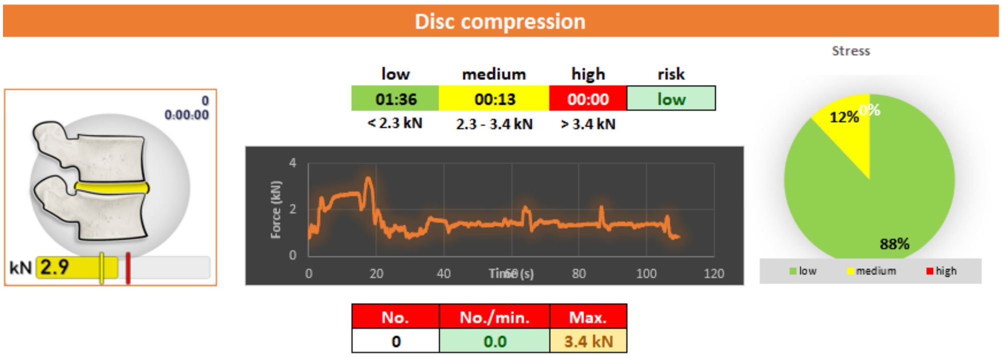


Figure 123. Disc compression graph of Participant 7 (Non-exoskeleton record).

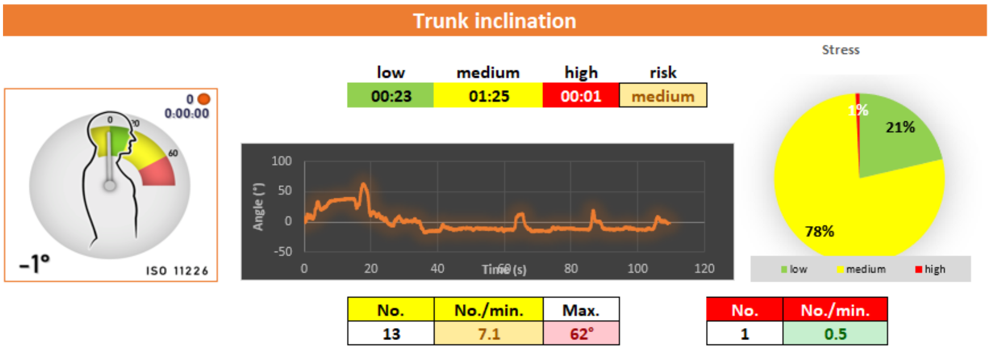


Figure 124. Trunk inclination graph of Participant 7 (Non-exoskeleton record)

7.8 Participant 8

7.8.1 Exoskeleton

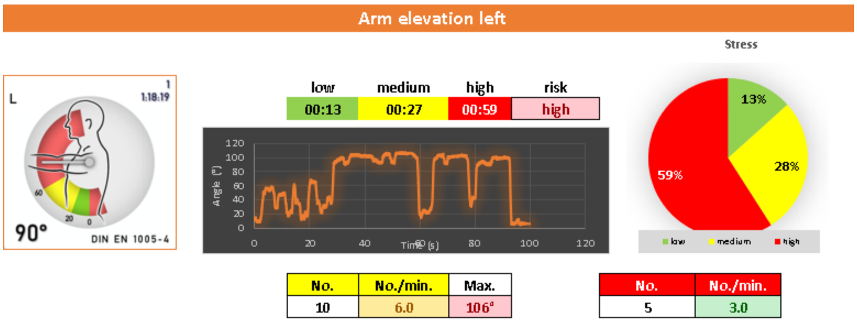
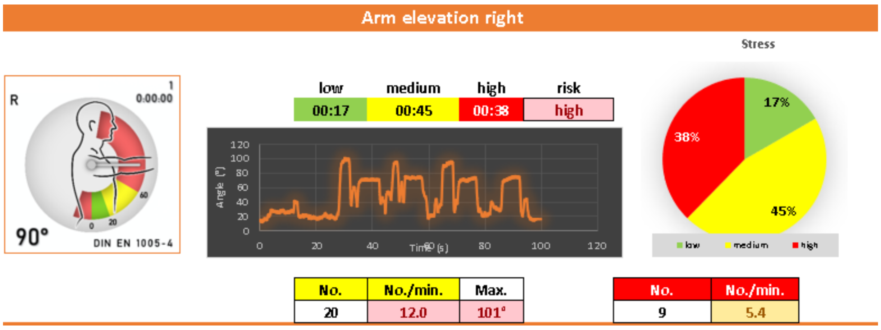


Figure 125. Left arm elevation graph of Participant 8 (Exoskeleton record).

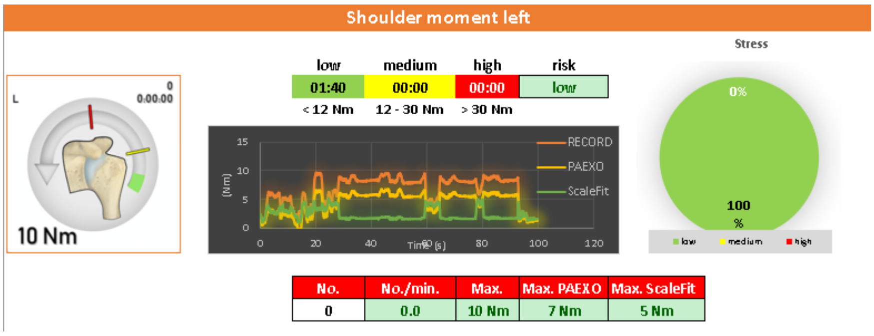


low	medium	high	risk
00:17	00:45	00:38	high

No.	No./min.	Max.
20	12.0	101°

No.	No./min.
9	5.4

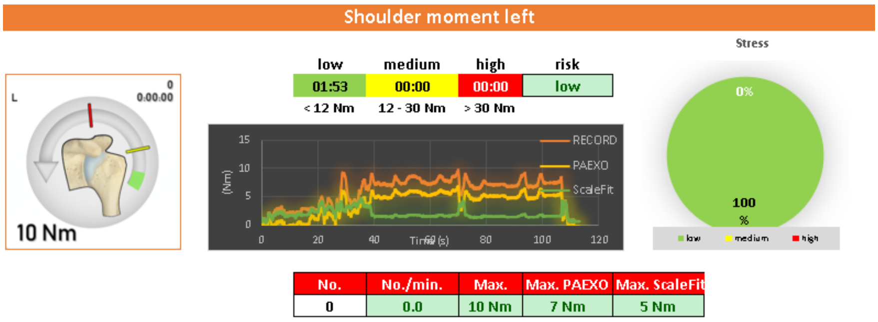
Figure 126. Right arm elevation of Participant 8 (Exoskeleton record).



low	medium	high	risk
01:40	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	5 Nm

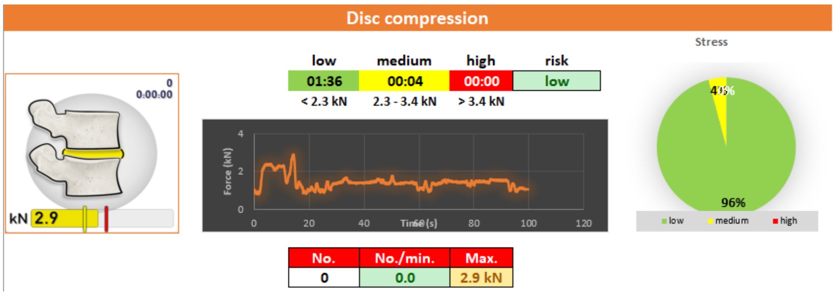
Figure 127. Left shoulder moment graph of Participant 8 (Exoskeleton record).



low	medium	high	risk
01:53	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	5 Nm

Figure 128. Right shoulder moment graph of Participant 8 (Exoskeleton record).



low	medium	high	risk
01:36	00:04	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	2.9 kN

Figure 129. Disc compression graph of Participant 8 (Exoskeleton record).

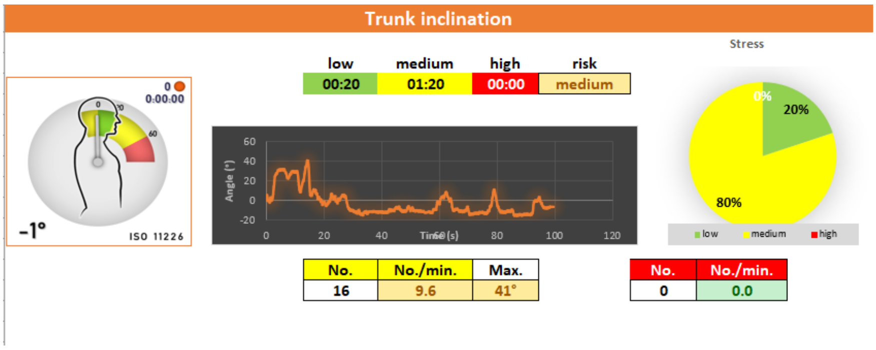


Figure 130. Trunk inclination graph of Participant 8 (Exoskeleton record).

7.8.2 Non-exoskeleton

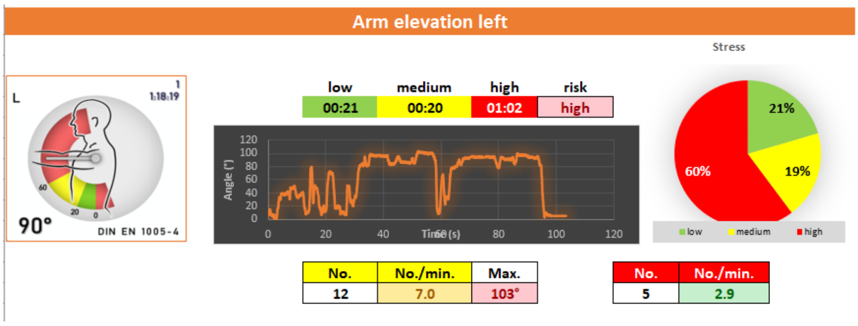


Figure 131. Left arm elevation graph of Participant 8 (Non-exoskeleton record).

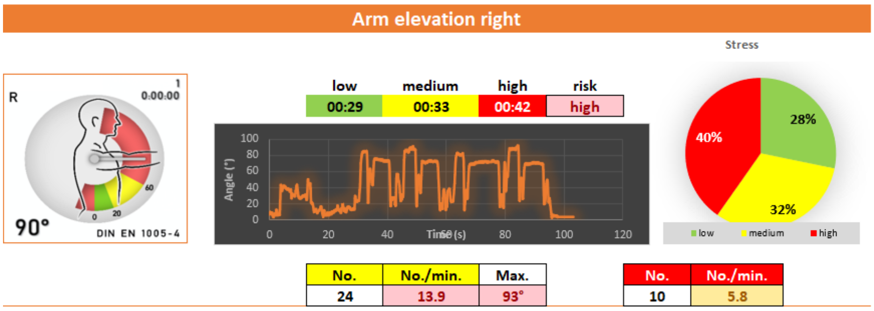


Figure 132. Right arm elevation graph of Participant 8 (Non-exoskeleton record).

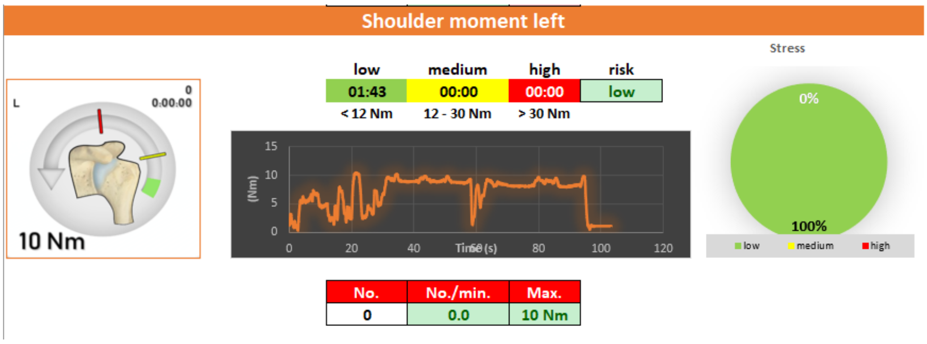


Figure 133. Left shoulder moment graph of Participant 8 (Non-exoskeleton record).

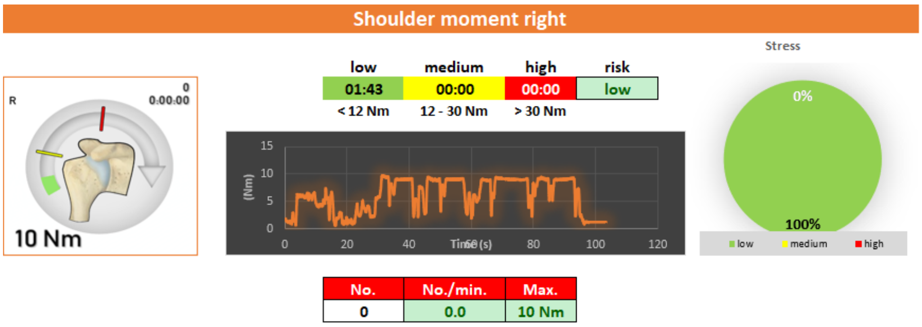


Figure 134. Right shoulder moment graph of Participant 8 (Non-exoskeleton record).

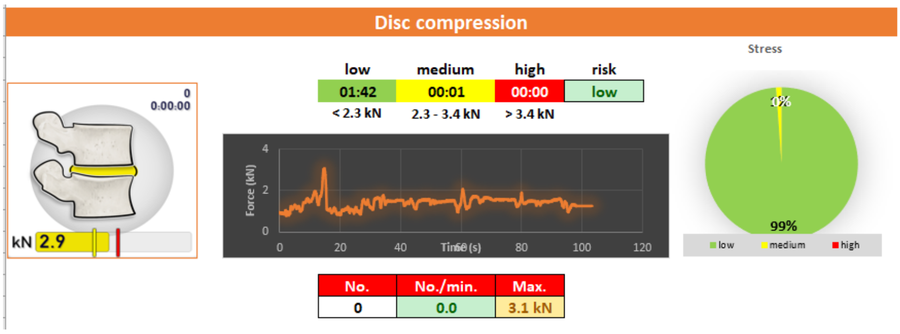


Figure 135. Disc compression graph of Participant 8 (Non-exoskeleton record).

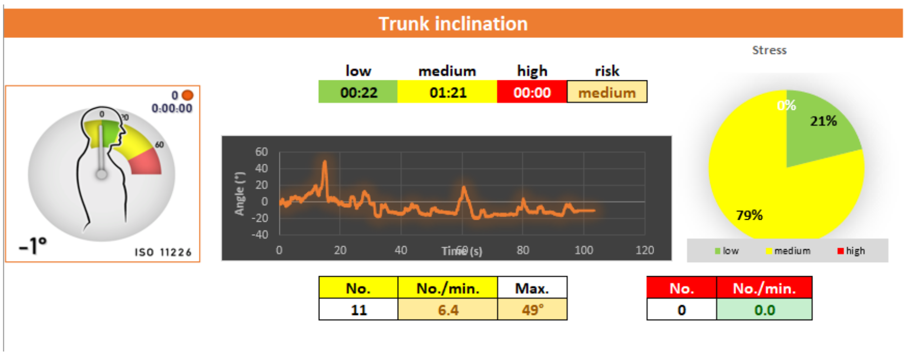


Figure 136. Trunk inclination graph of Participant 8 (Non-exoskeleton record)

7.9 Participant 9

7.9.1 Exoskeleton

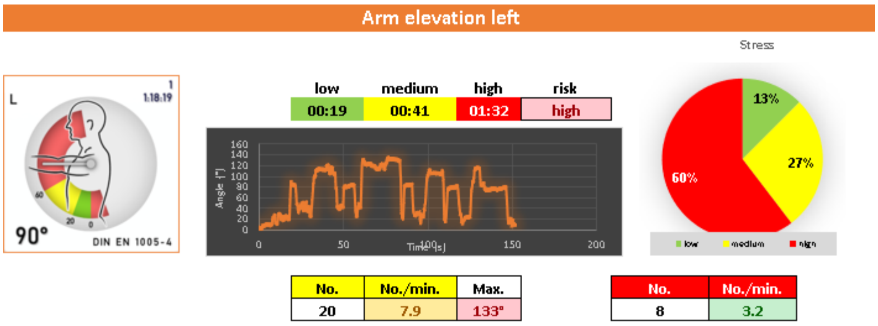
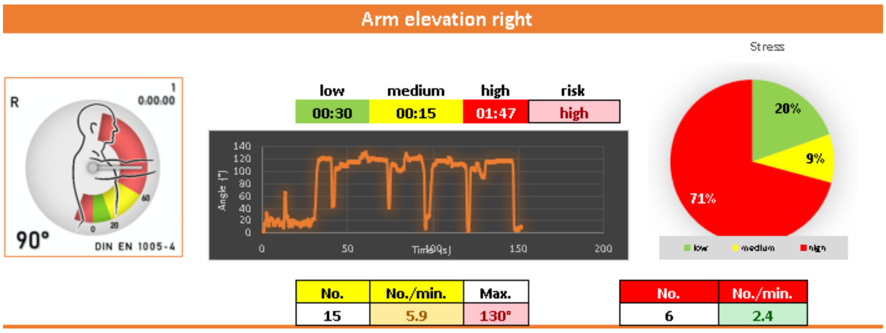


Figure 137. Left arm elevation graph of Participant 9 (Exoskeleton record).

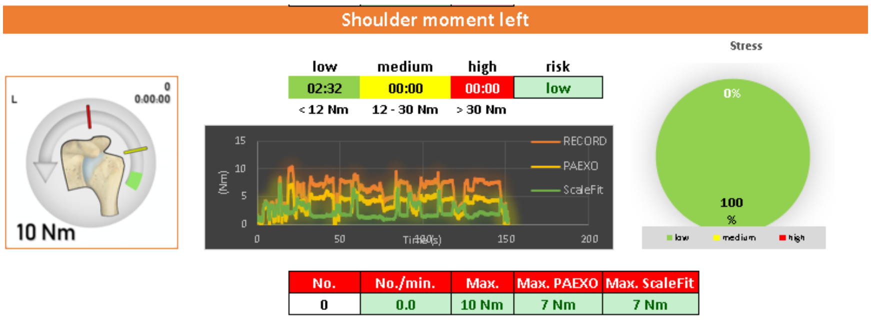


low	medium	high	risk
00:30	00:15	01:47	high

No.	No./min.	Max.
15	5.9	130°

No.	No./min.
6	2.4

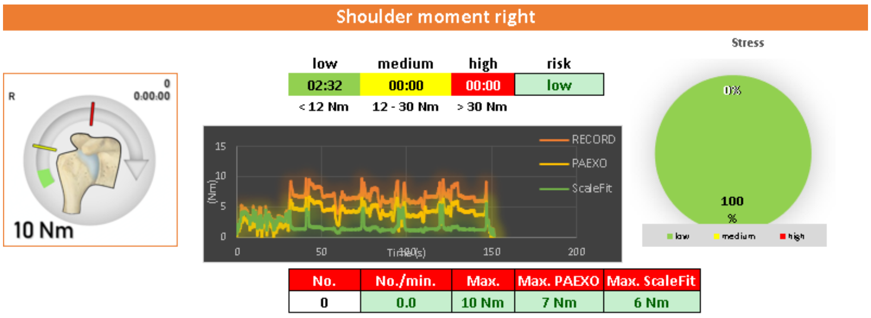
Figure 138. Right arm elevation of Participant 9 (Exoskeleton record).



low	medium	high	risk
02:32	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	7 Nm

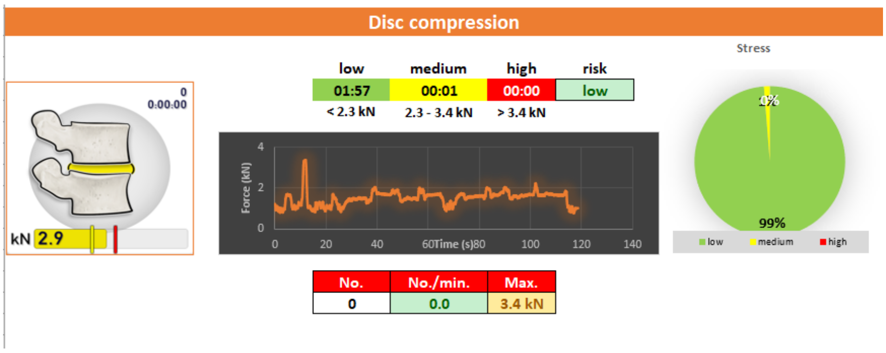
Figure 139. Left shoulder moment graph of Participant 9 (Exoskeleton record).



low	medium	high	risk
02:32	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	10 Nm	7 Nm	6 Nm

Figure 140. Right shoulder moment graph of Participant 9 (Exoskeleton record).



low	medium	high	risk
01:57	00:01	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.4 kN

Figure 141. Disc compression graph of Participant 9 (Exoskeleton record).

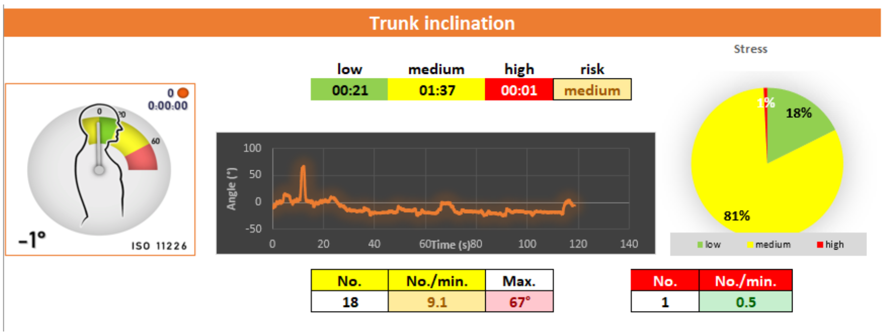


Figure 142. Trunk inclination graph of Participant 9 (Exoskeleton record).

7.9.2 Non-exoskeleton

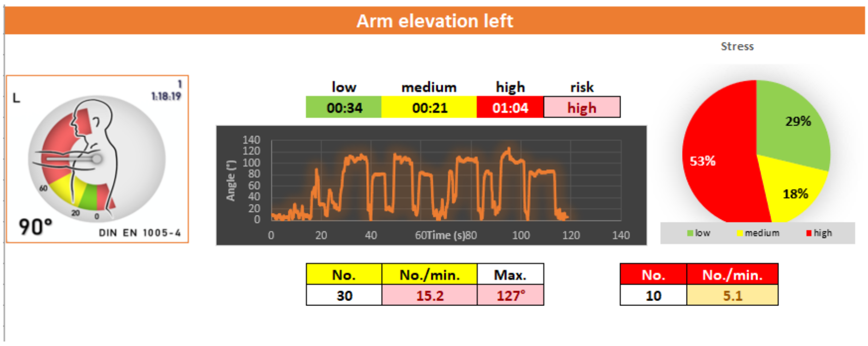


Figure 143. Left arm elevation graph of Participant 9 (Non-exoskeleton record).

Figure 144. Right arm elevation graph of Participant 9 (Non-exoskeleton record).

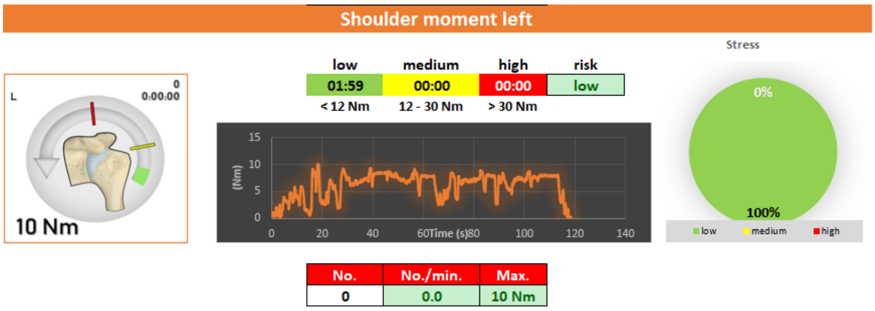


Figure 145. Left shoulder moment graph of Participant 9 (Non-exoskeleton record).

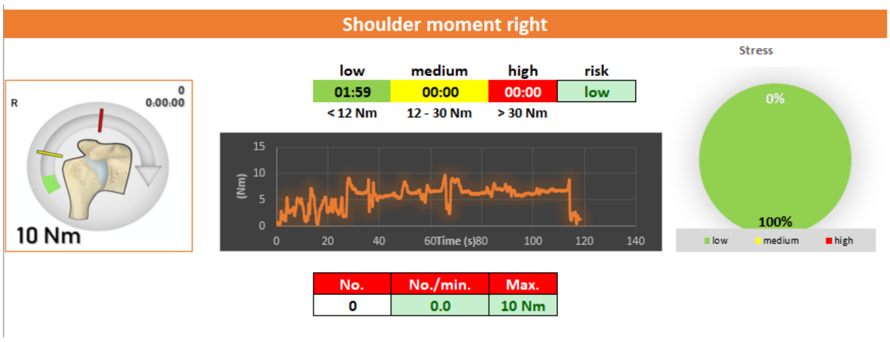


Figure 146. Right shoulder moment graph of Participant 9 (Non-exoskeleton record).

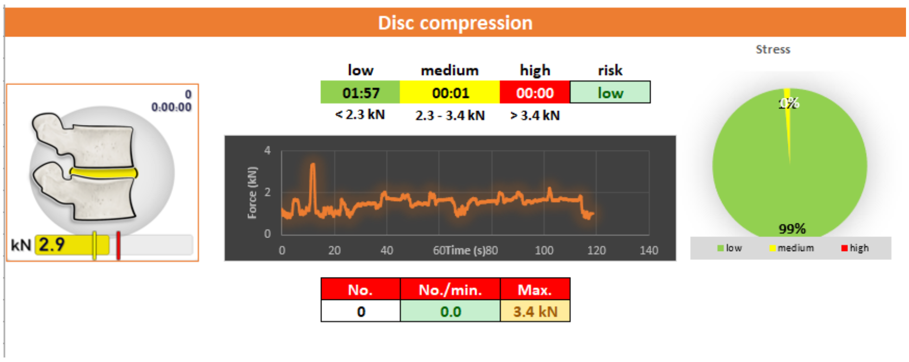


Figure 147. Disc compression graph of Participant 9 (Non-exoskeleton record).

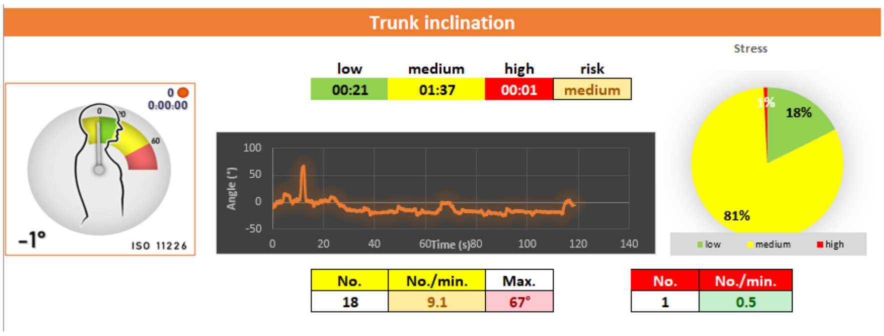


Figure 148. Trunk inclination graph of Participant 9 (Non-exoskeleton record)

7.10 Participant 10

7.10.1 Exoskeleton

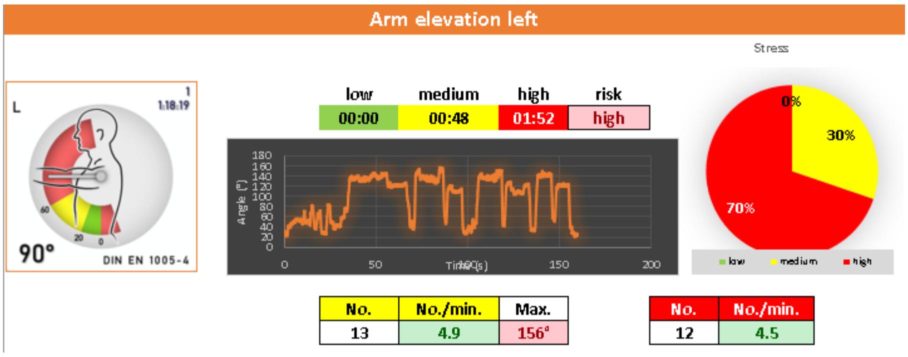
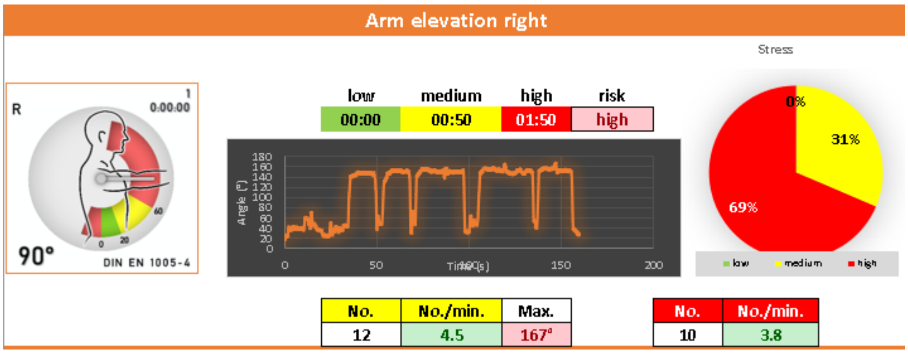


Figure 149. Left arm elevation graph of Participant 10 (Exoskeleton record).

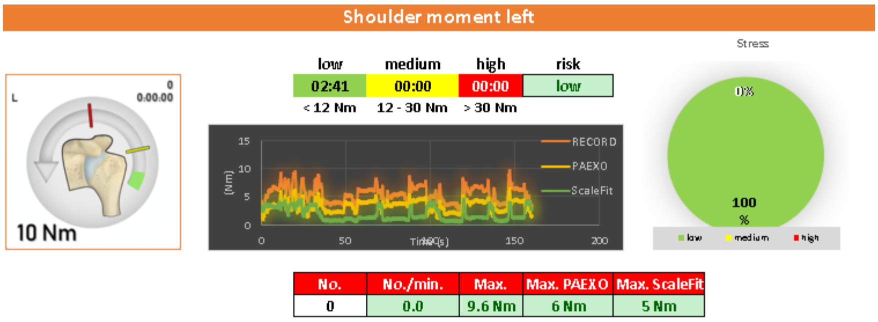


low	medium	high	risk
00:00	00:50	01:50	high

No.	No./min.	Max.
12	4.5	167°

No.	No./min.
10	3.8

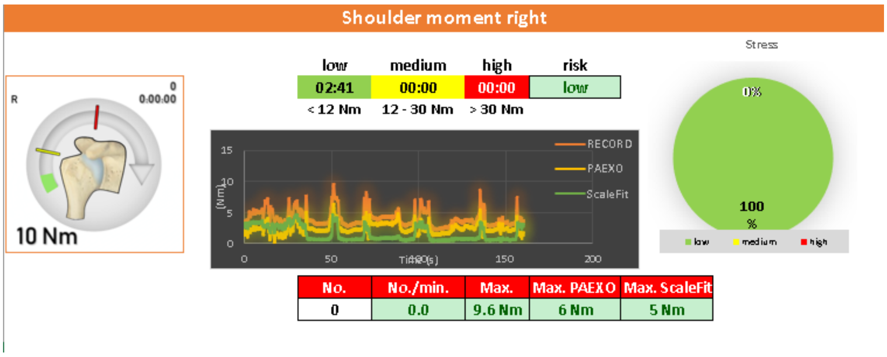
Figure 150. Right arm elevation of Participant 10 (Exoskeleton record).



low	medium	high	risk
02:41	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9.6 Nm	6 Nm	5 Nm

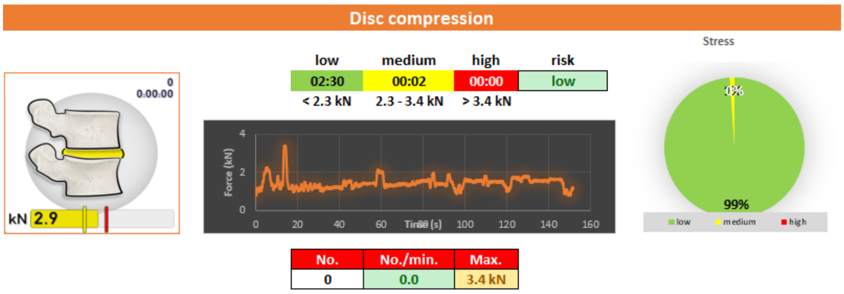
Figure 151. Left shoulder moment graph of Participant 10 (Exoskeleton record).



low	medium	high	risk
02:41	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	Max. PAEXO	Max. ScaleFit
0	0.0	9.6 Nm	6 Nm	5 Nm

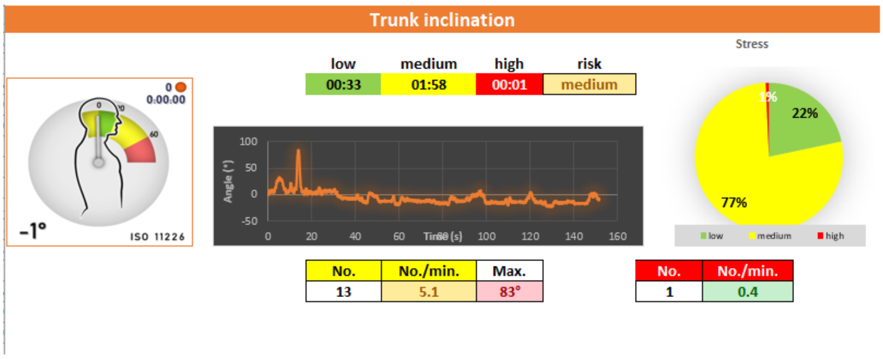
Figure 152. Right shoulder moment graph of Participant 10 (Exoskeleton record).



low	medium	high	risk
02:30	00:02	00:00	low
< 2.3 kN	2.3 - 3.4 kN	> 3.4 kN	

No.	No./min.	Max.
0	0.0	3.4 kN

Figure 153. Disc compression graph of Participant 10 (Exoskeleton record).



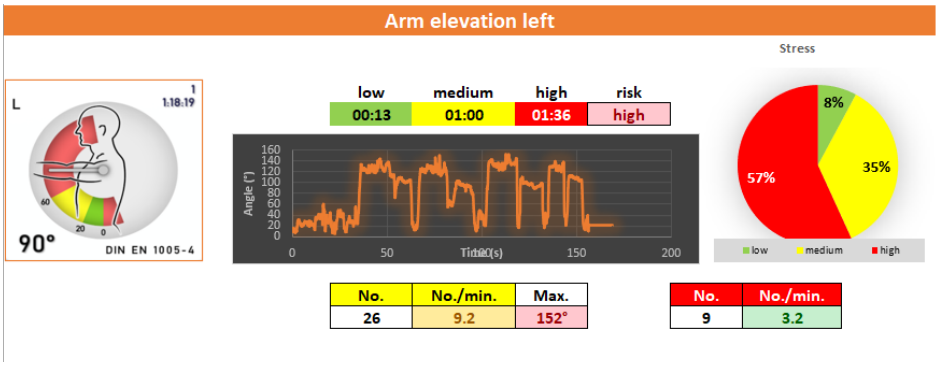
low	medium	high	risk
00:33	01:58	00:01	medium

No.	No./min.	Max.
13	5.1	83°

No.	No./min.
1	0.4

Figure 154. Trunk inclination graph of Participant 10 (Exoskeleton record).

7.10.2 Non-exoskeleton

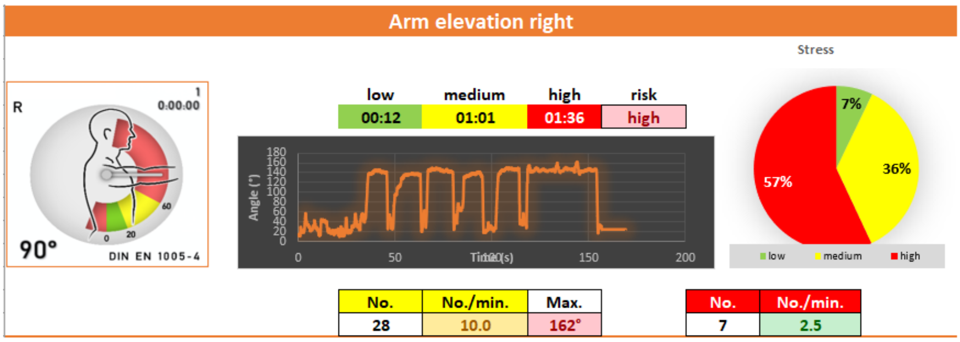


low	medium	high	risk
00:13	01:00	01:36	high

No.	No./min.	Max.
26	9.2	152°

No.	No./min.
9	3.2

Figure 155. Left arm elevation graph of Participant 10 (Non-exoskeleton record).

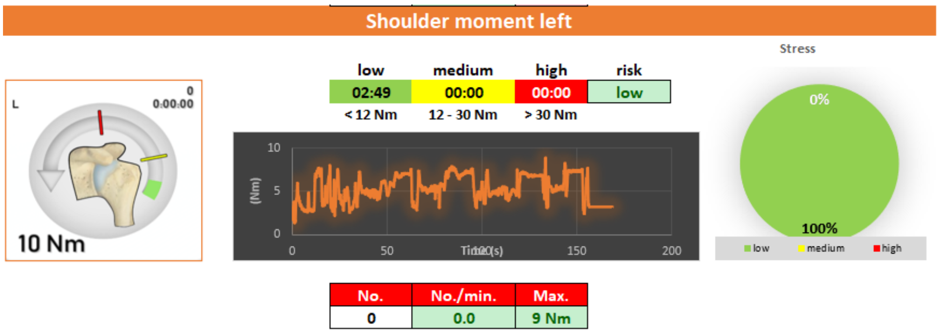


low	medium	high	risk
00:12	01:01	01:36	high

No.	No./min.	Max.
28	10.0	162°

No.	No./min.
7	2.5

Figure 156. Right arm elevation graph of Participant 10 (Non-exoskeleton record).



low	medium	high	risk
02:49	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.
0	0.0	9 Nm

Figure 157. Left shoulder moment graph of Participant 10 (Non-exoskeleton record).

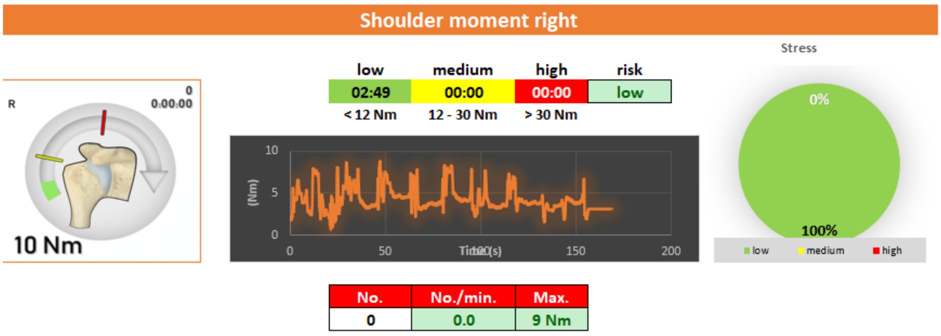


Figure 158. Right shoulder moment graph of Participant 10 (Non-exoskeleton record).

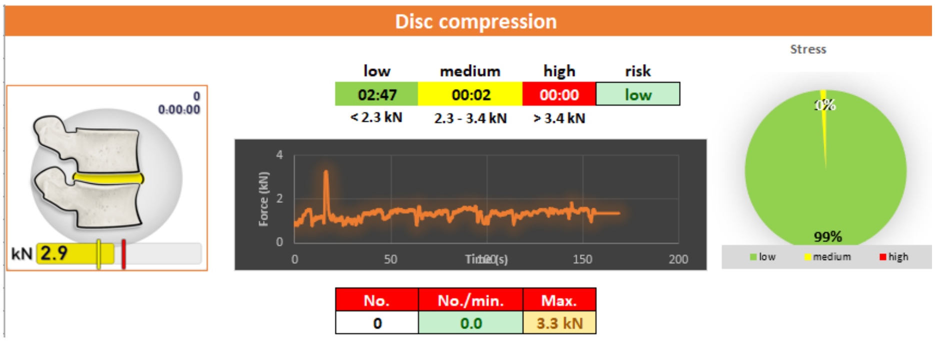


Figure 159. Disc compression graph of Participant 10 (Non-exoskeleton record).

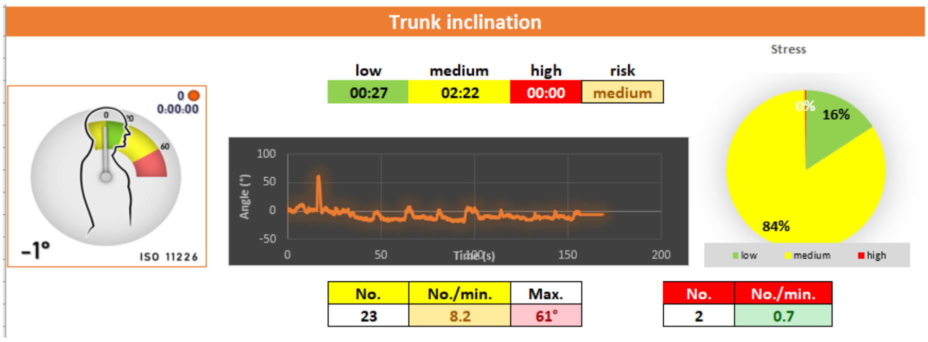


Figure 160. Trunk inclination graph of Participant 10 (Non-exoskeleton record)

7.10.3 Weight evaluation

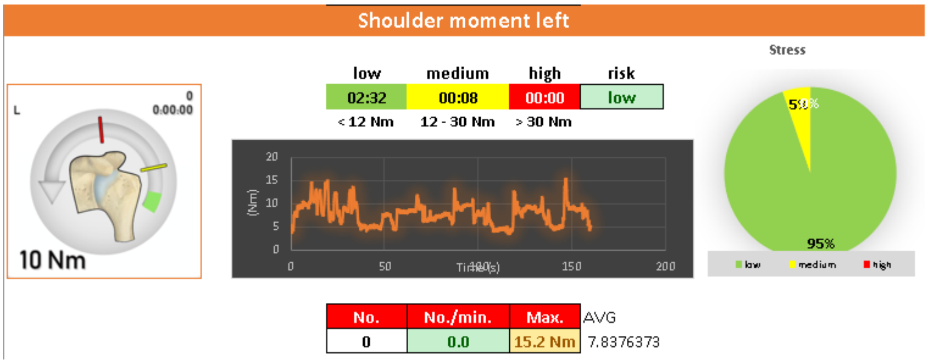
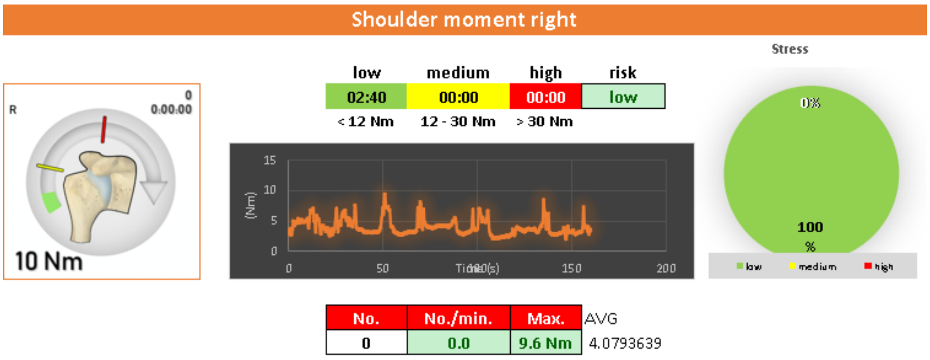


Figure 161. Left shoulder moment graph of Participant 10 (Weight record).

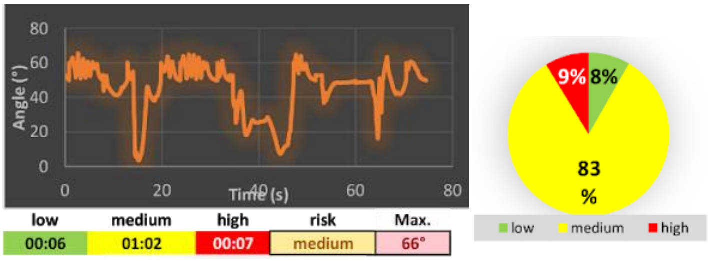


low	medium	high	risk
02:40	00:00	00:00	low
< 12 Nm	12 - 30 Nm	> 30 Nm	

No.	No./min.	Max.	AVG
0	0.0	9.6 Nm	4.0793639

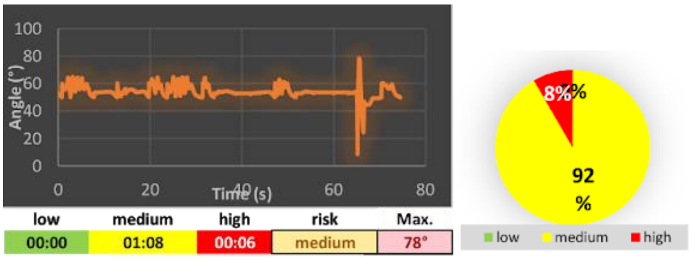
Figure 162. Right shoulder moment graph of Participant 10 (Weight record).

7.10.4 IPS-IMMA evaluation



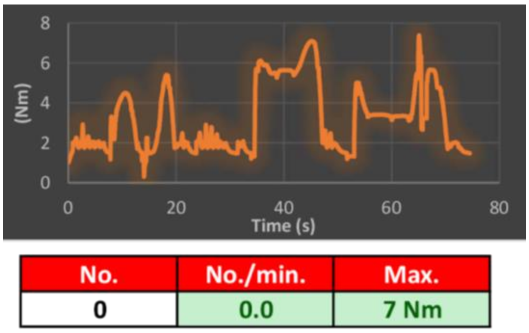
low	medium	high	risk	Max.
00:06	01:02	00:07	medium	66°

Figure 163. Left arm elevation graph of Participant 10 (IPS-IMMA simulation).



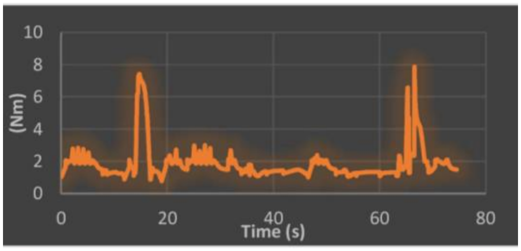
low	medium	high	risk	Max.
00:00	01:08	00:06	medium	78°

Figure164. Right arm elevation graph of Participant 10 (IPS-IMMA simulation).



No.	No./min.	Max.
0	0.0	7 Nm

Figure 165. Left shoulder moment graph of Participant 10 (IPS-IMMA simulation).



No.	No./min.	Max.
0	0.0	8 Nm

Figure 166. Right shoulder moment graph of Participant 10 (IPS-IMMA simulation).