CHALMERS
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Multi-user VR ergonomic assessment

Feasibility of using multi-user VR for ergonomics studies in manufacturing environments

Master's thesis in Production Engineering

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Cover: Two ergonomic experts performing an ergonomic assessment in a multi-user VR environment, generated with DALL·E from ChatGPT

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ABSTRACT

This thesis studies the limitations and solutions of VR for ergonomics assessment as well as assesses the advantages and disadvantages of using Multi-user VR for ergonomic assessments. As industries attempt to improve workplace ergonomics, utilizing cutting-edge technologies could increase the efficacy of these assessments. This research explores the capabilities of multi-user VR to enable collaborative ergonomic studies, permitting multiple evaluators to interact within a simulated environment in real-time. Such integration could significantly boost the precision and efficiency of ergonomic assessments.

This thesis assesses the potential and difficulties of integrating VR and multi-user VR in ergonomic assessments using an extensive methodology that includes a literature study, expert interviews, and a validation case study. Multi-user VR improves collaborative analysis, and by allowing remote evaluations and doing away with the requirement for physical prototypes, VR drastically cuts down on the time and expense involved in traditional ergonomic assessments.

The study does, however, also point out a number of difficulties such as the requirement for improved sensory feedback and more realistic interaction features in VR environments. For VR technology to be widely adopted and effective in ergonomic assessments, these issues must be resolved.

The ergonomic assessments can be more precise as well as done faster with help of advanced VR technologies, which will increase the productivity and safety of manufacturing plants. This thesis lays the groundwork for more research into improving how VR is used in ergonomic assessments and expanding its use across different industries.

Keywords: VR, Multi-user VR, Single-user VR, ergonomics, ergonomic assessment, simulation, DHM, manikin, IPS, IMMA, manufacturing environments

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In closing, we reflect on the journey that has been this thesis with immense gratitude for all the support and knowledge shared by everyone involved. It is our hope that this research contributes valuable insights into ergonomic assessments and fosters further innovation in the application of VR technologies.

Thank you,

Jose Maria van der Ploeg and Soureesh De
Gothenburg, May 2024

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List of Acronyms

	Description
MSDs	*Musculoskeletal Disorders*
WHO	*World Health Organisation*
VR	*Virtual Reality*
IPS	*Industrial Path Solutions*
DHM	*Digital Human Modelling*
IEA	*International Ergonomics Association*
EU	*European Union*
REBA	*Rapid Entire-Body Assessment*
HMD	*Head-mounted Display*
RULA	*Rapid Upper Body Assessment*
KPI	*Key Performance Indicators*
AI	*Artificial Intelligence*
AR	*Augmented Reality*
MR	*Mixed Reality*
XR	*Extended Reality*
SUS	*System Usability Scale*
CAD	*Computer Aided Design*
3D	*Three-dimensional*
2D	*Two-dimensional*
MTM	*Method-Time measurement*
EAWS	*European assembly worksheet*
UAS	*Universal Analysing system*
RNL	*Reach-bounded non-linear*
IVE	*Immersive virtual environment*
MoCap	*Motion Capture*
IK	*Inverse Kinematics*
FoV	*Field of view*

1. INTRODUCTION

In this introductory chapter of the present master's thesis, an explanation of the background behind this research is provided, followed by a presentation of the aims and purposes to be achieved. Building upon these, research questions have been formulated to steer the progression of the work towards addressing them. Ultimately, this chapter concludes by delineating the scope and limitations of this endeavour, alongside a brief outline of the main points covered in the present report.

1.1. Background

Today's manufacturing industry faces intense competition worldwide, necessitating the optimization of production costs and quality, alongside compliance with increasingly stringent environmental regulations. Moreover, companies confront the escalating pressure of evolving consumer demands, which are becoming more sophisticated. This dynamic compels the sector to embrace new and innovative technologies, generating significant interest not only among industrial stakeholders but also within academic circles [1]. Among the numerous aspects receiving heightened attention from companies striving to differentiate themselves in the market is the enhancement of workers' workspaces, or more specifically, the improvement of ergonomics within these spaces. This emphasis underscores the importance of creating work environments that are not only conducive to productivity but also prioritize comfort and user-friendliness, thereby fostering the well-being of employees [2].

The increasing significance of ergonomics in the manufacturing industry in recent years is primarily attributed to the substantial economic losses associated with issues stemming from poor ergonomics. One of the main concerns revolves around the work absences that workers need to take due to Musculoskeletal Disorders (MSDs). These disorders encompass injuries and/or conditions that affect the movement of the human body or its musculoskeletal system, thereby hindering their ability to perform their work effectively [3]. This issue results in millions of individuals worldwide having to leave their jobs for periods of time to recover from such injuries. According to the World Health Organization (WHO), approximately 1.71 billion people globally suffer from musculoskeletal conditions, making them the leading cause of disability [4]. Additionally, from the perspective of production and the quality of manufactured products, it has been demonstrated that poor ergonomics also have a negative impact [5], as they limit the capabilities and potential of workers in performing any task.

Identifying ergonomic issues in production lines once they are operational and the product is already on the market can escalate costs significantly. This is because rectifying the problem requires halting or relocating production during the replacement period, in addition to modifying or procuring new machinery to address the ergonomic issue. This is where new technologies come into play, as they can be immensely useful in proactively identifying problems. If during the design phase, work is conducted using a computer model enabling simulations, it becomes easier to make alterations if necessary. Identifying ergonomic issues in the early stages of the virtual manufacturing process reduces both the time and expenses needed to rectify them. It also minimizes the risk of worker injuries and enhances overall workplace well-being. Therefore, physical ergonomics plays a crucial role in the manufacturing process as it examines the relationship between human physical attributes and their work environments [6].

One of the technologies that proves to be immensely helpful in designing and simulating future workspaces or scenarios, thereby enabling the identification of potential ergonomic and design issues in a faster and more cost-effective manner, is Virtual Reality (VR). VR allows for the creation of a digital environment that provides an immersive experience accurately replicating physical presence in various settings. In the manufacturing industry, it opens doors to numerous possibilities for enhancing ergonomics and production efficiency. Additionally, VR offers the advantage of enabling designers and workers to experience the workspace from different perspectives, facilitating the identification of areas for improvement and design optimization. This capability of VR to create virtual work environments is also invaluable in employee training, allowing them to familiarize themselves with procedures and operations before encountering real-world situations.

The integration of VR in the realm of ergonomics within productive environments opens new perspectives towards collaboration and teamwork. The evolution towards multi-user VR environments not only promises to replicate human interaction in virtual settings but also enhances understanding of teamwork dynamics and collective ergonomics. The fact that multiple users interact within the same virtual environment offers the opportunity to study and optimize the ergonomics of interactions among individuals in productive environments, potentially resulting in significant improvements in efficiency and occupational safety. The ability of VR to simulate work environments before actual implementation and its potential to enhance ergonomics and worker well-being represent just a small fraction of the possibilities offered by this burgeoning technology.

1.2. Aim and purpose

In this master's thesis, the aim is to investigate the feasibility of utilizing multi-user VR to enhance collaboration and ergonomic assessments, both in the early stages of designing productive environments and throughout their lifecycle. To achieve this, the current state of using VR for ergonomic assessments will be examined through a literature review. Subsequently, a series of interviews will be conducted with experts from both academic and professional fields to establish an initial understanding of the concept of multi-user environments in VR.

Finally, we intend to validate our findings and demonstrate the potential of multi-user VR ergonomic assessments through a case study involving collaboration among different ergonomists interacting with current technologies used for ergonomic assessments and an approach to multi-user VR via the IPS IMMA software.

1.3. Research questions

The current implementation of VR in ergonomic assessments of manufacturing environments, where two individuals cannot be simultaneously present in the virtual environment, or traditional simulation applications through a screen, seem to be insufficient or less than ideal for unlocking the true potential of this approach to solve ergonomics-related issues. It is for this reason that the impact of multi-user functionality in VR for ergonomic evaluations is intended to be studied.

Given the context of this thesis, this report will address the following two research questions:

RQ1. Which are the current potential limitations of using VR for ergonomic assessments today and how can they be solved?

RQ2. In assessing ergonomic methodologies, can the incorporation of multi-user VR and simulation demonstrate overall improvement in ergonomics of production environments / workstations?

1.4. Scope and delimitations

The delimitations of this project are built around the extent of previous knowledge, the availability of technology, the timeframe, and the specific methods and focus areas chosen. This study addresses a novel application with limited prior research, as very little previous knowledge exists about the topic of using multi-user VR for ergonomic assessments.

The technology required for multi-user VR for ergonomic assessments is currently non-existent, which posed a significant limitation in this research. Additionally, the project is constrained by a 16-week timeframe, which impacts the depth and breadth of the study.

There was also a late incorporation of the multi-user IPS platform from Industrial Path Solutions software, which we expected to be able to use much earlier in the process and made us change to the Chalmers multi-user VR platform to perform the experimental part of this thesis. However, both platforms only offer a use of them with static scenes, where entire representations of the movements performed of a certain task cannot be visualised.

This thesis is confined to examining physical ergonomics only, without addressing cognitive or other aspects of ergonomics. The scope is further narrowed to manufacturing engineering, specifically within the context of the PLENUM project goals.

The study does not consider the entire throughput of a factory, focusing instead on specific ergonomic assessments within the manufacturing process. Furthermore, long-term consequences of using VR for ergonomic assessments are not evaluated in this research.

Lastly, there is a notable difference between the resolution capabilities of the Chalmers multi-user VR platform and the VR capabilities of IPS/IMMA, which may influence the findings and applicability of the results.

1.5. Thesis outline

The present report comprises seven sections arranged sequentially, and the following table provides an overview of each, refer to table 1-1. The first section is the introduction itself, followed by the theory and methodology, and concludes the report with the results, conclusions, and potential future work on this topic.

Table 1-1: Table of the thesis outline with a brief description of each chapter

CHAPTER	TITLE	DESCRIPTION
Chapter 1	Introduction	The study's problematic is introduced, accompanied by essential information to provide readers with context.
Chapter 2	Theory	All areas of influence in the thesis are elaborated upon in detail to enhance comprehension of the subject matter.
Chapter 3	Methodology	The execution of the work and its organization are explained thoroughly to provide insight into the methodology employed.
Chapter 4	Results	The most significant results from each of the studied parts are outlined to offer a comprehensive understanding.
Chapter 5	Discussion	Interesting aspects throughout the process are emphasized, spanning from methodology to results, considering the scope of the study.
Chapter 6	Conclusion	Conclusions drawn upon the study's completion are presented to summarize key findings and insights.
Chapter 7	Future Work	New avenues for research, which may be of interest, are proposed to encourage further exploration and development of the subject matter.

2. THEORY

In this second chapter of the report, we explore the theoretical background that supports the research field of this master's thesis. Our aim is to provide a thorough context and enhance the understanding of the key themes central to this study. These fundamental themes include ergonomics, VR, and digital human modelling (DHM), each explored in detail across various sub-sections.

2.1. Ergonomics

Ergonomics, also known as human factors, is defined by the International Ergonomics Association (IEA) as "the scientific discipline concerned with understanding the interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design to optimize human well-being and overall system performance." [7] Today, ergonomics has evolved into a very broad concept that not only encompasses physical activities but also includes any aspect of work associated with human activity such as cognitive aspects or psychological factors, which influence human behaviour. [8]

2.1.1. Production ergonomics

Ergonomics is experiencing significant development in productive environments that employ human workforce, as the performance of companies is directly dependent on the daily performance of their workers. For this reason, production ergonomics has become a key discipline in optimizing worker interactions with industrial tasks. This branch of ergonomics is focused on creating safe and sustainable work environments that not only improve worker productivity and well-being but also the throughput of the company. By integrating engineering concepts with an advanced understanding of the factors that affect industrial productivity, production ergonomics seeks to harmonize human needs and capabilities with work processes. Essentially, it strives to achieve an optimal balance between precise engineering and the dynamic needs and capabilities of the workers. [8]

Figure 2-1: People working in a production environment, from Bloomberg [54]

2.1.2. MSDs’

The capacity to perform any type of work is closely linked to one's physical health. When symptoms such as discomfort, pain, or numbness are experienced, these warnings from the body might be ignored, and tasks may continue. However, this leads to reduced efficiency; work becomes slower, less powerful, and less precise, with an increased likelihood of errors, and in extreme cases, can result in severe accidents. This issue is particularly prevalent in the manufacturing industry, where the human body's tolerance limits, when surpassed, can force an employee to take sick leave to recover from physical ailments. If this physical impairment affects the worker’s ability to move and handle loads, it is typically identified as a work-related musculo-skeletal disorder (abbreviated as WMSD or MSD). These disorders are diverse, caused by a variety of physical factors. Pain, discomfort, and fatigue are often experienced as initial symptoms, while more pronounced signs, such as a reduction in functional abilities, restricted range of motion, and decreased muscle strength, become noticeable and clearly observable [8].

Figure 2-2: Person feeling the low-back pain MSD, from Cornerstone physiotherapy [55]

MSDs represent the most significant work-related health issue affecting sickness absenteeism in Europe, leading to half of all work absences and costing the EU €240 billion annually in lost productivity, as reported by Fit for Work Europe in 2013 [9]. Additionally, these disorders are the leading cause of permanent disability related to work [8].

2.1.3. Ergonomic assessments

An ergonomics assessment, sometimes referred to as an ergonomic risk assessment or workplace assessment, is a procedure utilized to assess the potential risk of MSDs that arise from discrepancies between the design of the workplace and the abilities of the employees. After identifying physical risk factors, measures are implemented to enhance the work environment systematically for employees. The objective is to enhance the well-being, job performance, and job satisfaction of employees [10].

Ergonomists conduct these assessments by doing an observational analysis of the task being assessed, performing interviews of the workers, and the use of specialized tools and methods. They systematically evaluate workstations, tasks, and equipment to identify ergonomic hazards. Commonly, ergonomists employ ergonomic methods, which will be explained further in this chapter, to analyse specific risk factors and postures. These methods allow for a detailed examination of the physical demands placed on workers, helping to pinpoint areas for improvement. The resulting data is then used to recommend modifications that can range from simple adjustments to workstations to comprehensive redesigns of work processes to better align with ergonomic principles.

2.1.4. Ergonomic methods

Physical loads can influence and affect the human body in various ways, depending on factors such as anthropometric differences, posture, duration, and force. Therefore, it is crucial to systematically measure these factors to guarantee that the evaluation of the loads' impact on the human body is precise [11]. There are numerous ergonomic methods, which can be found in table 2-1 [11], and each one is designed to assess the ergonomics of certain parts or groups of parts of the human body while performing a particular task.

All these ergonomic methods can be classified into one or more than one category: Posture-based, Biomechanics-based or Environment-based [8]. Posture-based ergonomic methods are designed to study joints angles and positions, on the other hand, Biomechanics-based ergonomic methods consider forces and torques applied to the human body and its joints. Environment-based ergonomic methods consider other factors that also affect the ergonomics of the human body like vibrations, duration of the task, temperature and more [11]. However, this report will only focus on the Rapid Entire-Body Assessment (REBA) method, since it is the only method that will be used in this thesis.

Table 2-1: Table of the ergonomic methods, from "Simulations of ergonomic assemblies" Master Thesis [11]

METHODS	POSTURE-BASED	BIOMECHANICS-BASED	ENVIRONMENT-BASED
RULA	x		
REBA	x		
OWAS	x		x
EAWS	x	x	x
KIM	x	x	x
HARM	x		x
RAMP	x	x	x
JSI	x		x
NIOSH		x	

2.1.4.1. REBA ergonomic method

The REBA method was created by Sue Hignett and Lynn McAtamney at Nottingham Hospital in the United Kingdom and was introduced in 2000. This method emerged from collaborative efforts among ergonomists, physiotherapists, and nurses who studied approximately 600 work postures. REBA enables the comprehensive analysis of postures involving the upper limbs (arms, forearms, wrists), trunk, neck, and lower limbs. It also distinguishes between different types of grip and levels of muscle activity [12].

The ergonomic scores in the REBA method are calculated through a series of steps that involve evaluating the posture of different body parts, the type of movement, and the force exerted. Each body part is assigned a score based on its position and the type of activity performed. These scores are then combined into two groups: one for the upper limbs and one for the trunk, neck, and legs. The scores from these groups are further analysed in combination with the type of grip and coupling, and finally, an overall REBA score is generated. This score indicates the level of ergonomic risk, with higher scores representing greater risk and necessitating immediate intervention. The REBA worksheet, which provides a detailed guide for this scoring process, can be found in Appendix A. [12]

2.2. VR

In recent years, VR has become a popular topic in information technology. With the advent of affordable, consumer-grade VR headsets designed for gaming and entertainment, VR is experiencing a resurgence. VR creates a simulated environment that immerses users so deeply they feel as though they are truly present in that space [13]. In our thesis project, we are using the HTC Vive system. The main hardware components of the HTC Vive VR include a head-mounted display (HMD), two handheld controllers, one for each hand and two set of sensors that enable the tracking of the HMD and the controllers in the virtual environment.

Beyond gaming and entertainment, VR is also very utilized in production and manufacturing. Engineers use VR to design and simulate production lines, enabling virtual presentations and modifications before physical setup. This technology enhances training programs by providing immersive, risk-free environments for workers to learn and practice tasks. And in the context of this thesis, VR also facilitates ergonomic assessments, allowing for the optimization of workstations and identification of potential ergonomic problems. These applications of VR are proven and will prove to be extremely helpful as they improve efficiency, safety, and overall productivity in manufacturing processes [14].

Figure 2-3: VR being used in production environments, from iStock [56]

2.2.1. Controllers

VR controllers are a part of the VR hardware, which enables movement in the VR space. The controllers are engineered to deliver a natural and realistic experience within the VR environment. They feature buttons and thumb sticks to enhance functionality and control, offering users familiar elements like those found on traditional gamepads [15].

HTC Vive Controllers - The controllers are equipped with Steam VR Tracking sensors. For input, they feature a multifunction trackpad, grip buttons, a dual-stage trigger, a system button, and a menu button. The controllers can be used for approximately 6 hours on a single charge. They include a Micro-USB port for charging [16].

2.2.2. Head Mounted Display (HMD)

A head-mounted display (HMD) is the primary interface for VR technology, presenting computer-generated virtual scenes directly to the user via the eyes. An HMD serves not only as the output for virtual scenes in larger VR setups but also functions as a standalone, portable VR device. Immersion is a key concept in defining VR technology and is also its most critical metric. Wearing a high-performance HMD can create a strong sense of immersion for the user by displaying images from the system. This high-performance HMD primarily relies on advanced virtual display technology for its technical capabilities [17].

HTC Vive Headset - The dual AMOLED screens on the headset have a diagonal size of 3.6 inches each. The resolution is 1080 X 1200 pixels per eye (2160 X 1200 pixels combined). The refresh rate is 90 Hz, and the field of view (FoV) is 110 degrees [16].

2.2.3. Multi-user VR

Aiming for a more collaborative approach in the use of VR technology, the concept of “multi-user VR” has emerged. This approach allows multiple stakeholders to interact simultaneously within the same virtual space. By enhancing the technology to closely mimic real-world interactions, its applications have expanded to include VR meetings, collaborative training, and improved ergonomic assessments.

Figure 2-4: Multiple people working together in the same VR environment, from Ultraleap [57]

For instance, in our thesis, we enable multiple users to collaborate within a VR environment to conduct ergonomic assessments. Using multi-user VR, individuals can work together remotely, facilitating global connections among team members. This technology allows for real-time interaction within a shared virtual world, making it valuable for training, education, collaboration, and beyond. Businesses can leverage these multi-user VR spaces to enhance various aspects of their operations [18].

2.2.3.1. Chalmers multi-user VR platform

The Chalmers multi-user VR platform was developed by a team of researchers at Chalmers University of Technology, in collaboration with Volvo Car Corporation [19]. This platform was created to address the growing need for continuous training and development in the automotive industry, driven by increasing product complexity and the need for efficient operator training. Utilizing the Unity Game Engine, the platform incorporates detailed computer-aided design (CAD) data and realistic virtual environments to simulate various assembly tasks, enhancing training efficiency and safety.

The platform enables a robust multi-user experience by allowing up to 16 people to interact in real-time within the same virtual environment. Each participant is represented by an avatar that can communicate with the other avatars through proximity voice chat and visual interaction. However, the platform currently supports only static virtual bodies, meaning dynamic simulations are not visible in the virtual environment. Despite this limitation, the platform supports a variety of training scenarios, such as collaborative assembly tasks and safety drills, making it a versatile tool for training, education, and collaboration. This shared virtual space allows users to train on complex tasks without disrupting actual production, thus improving learning outcomes and operational efficiency [19].

Figure 2-5: Figure of a demonstration of the multi-user VR platform, from [19]

2.3. DHM

DHM is a field which aims to develop detailed models of the human body, in such a way that the various physical aspects can be simulated as accurately as possible. Anthropometrics and biomechanics are key areas in this field, and it is predominantly used to assess ergonomic factors. Ergonomists can assess the whole motions or postures of a person doing certain tasks in the industry and improvements can be made accordingly. Such assessments are very important in the domain of production engineering, where operators engage in tasks with significant risks. It can be very helpful for the comfort and safety of the operators in a factory or workstation [20].

The primary purpose of simulation and visualization software is to evaluate ergonomic factors as the industry moves towards industry 4.0. These assessments are crucial in situations where ergonomic design can significantly affect user comfort and safety, such as in industrial workstations. DHM is essential because it enables engineers and designers to assess new product designs and workplace ergonomics early on. This preliminary assessment aids in the early detection of possible ergonomic problems prior to the creation of physical prototypes, enabling a more effective design process that incorporates ergonomic concerns from the start. In addition to improving workplace safety and product usability, this method helps cut down on the time and expense involved in iterative physical prototyping. [20].

Combining DHM with VR further enhances these capabilities by providing an immersive environment where designers and engineers can visualize and interact with DHM models in real-time. This integration allows for more precise ergonomic assessments and adjustments, facilitating a better understanding of spatial relationships and ergonomic impacts. This combination is especially valuable in production environments, where detailed ergonomic analysis is crucial for ensuring the workforce safety and efficiency [21].

2.3.1. IPS IMMA

Industrial Path Solutions (IPS) is a comprehensive software suite designed to streamline manufacturing processes through advanced algorithms. Leading manufacturing companies worldwide rely on IPS for tasks such as evaluating assembly potential, designing flexible components, optimizing robotic operations, and simulating intricate flow and surface treatment processes [22].

Figure 2-6: Two digital human models and human-machine interaction, from IPS [22]

One of the multiple modules that IPS offers is IPS IMMA, which utilizes fast and efficient algorithms for easy evaluation of assembly ergonomics, considering human diversity through a realistic biomechanical model. It ensures collision-free assembly motions for both the human and the object being assembled. By simulating any work family of manikins, which will be explained further in this chapter, IPS IMMA accommodates human diversity effectively. The comfort function of the manikin is designed to minimize biomechanical load, sparing the user from manually positioning each joint. With its powerful, realistic biomechanical model, IPS IMMA enables automatic motion generation, eliminating the need for creating static postures. Its ease of use is further enhanced by a simple instruction language [23]. Additionally, IPS IMMA offers two crucial functions for the development of this thesis: automated ergonomic assessments using the RULA or REBA methods, and VR capabilities. These features are extremely beneficial for engineers and ergonomists working with the software.

2.3.1.1. Manikin families

An innovative feature of IPS IMMA is its manikin family, which enables the creation of a customized set of manikins with varying anthropometries. This allows users to run simulations for the entire family simultaneously, accommodating a diverse range of body types and sizes in the ergonomic evaluation process. The manikin family feature allows users to conduct ergonomics assessments for an entire group of manikins in a single run. This means that users can evaluate the biomechanical load on different members of the worker population by setting up just one simulation [24].

3. METHODOLOGY

To comprehensively address the proposed research questions, the study was organized into three distinct but interconnected phases: a literature review, an interview study, and a validation case involving experimental trials. Each phase was aimed at exploring different aspects of the use of VR in ergonomic assessments and at providing a comprehensive view of the potential benefits and the challenges of adding this new VR and multi-user VR capability in this field.

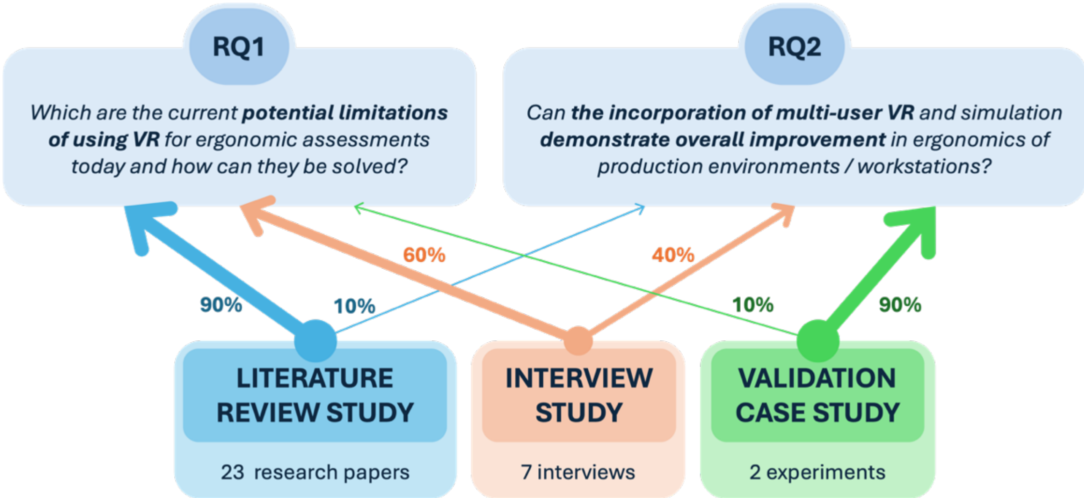

Figure 3-1: Diagram on how each part of the thesis contributed to the two RQ

3.1. Literature Review

The purpose of the literature review phase was to provide a thorough overview of the state of knowledge on the use of VR in ergonomic assessments by methodically gathering and analysing the existing research. This stage was essential for determining the main themes, identifying the common constraints, and revealing the viable solutions that have been investigated in earlier research. These results played a crucial role in setting the stage for our interview study and validation case. The literature review will primarily address RQ1 while also touching on RQ2, though in less detail.

For the literature review, extensive searches were carried out on Scopus and Google Scholar, as they are widely recognized academic database, known for its extensive collection of scholarly articles. The searches utilized key phrases such as 'Multi-user VR ergonomic assessment' and 'VR in ergonomics' to ensure a thorough exploration of the topic. From these searches, a total of 23 papers were deemed relevant and directly contributed to answering the research questions. This selection of papers included a variety of studies that provided insights into the difficulties and possibilities associated with using VR for ergonomic assessments and the advantages of multi-user VR over single user VR and desktop applications.

We followed a semi-systematic approach for our analysis. Initially, we searched for papers, read the titles and abstracts, and evaluated their relevance and potential value to our thesis. If a paper was considered valuable, we read through it in detail and noted the advantages and disadvantages from our thesis perspective. These notes were then classified into bullet points or themes, which helped us easily identify and compare findings across different papers. This process allowed us to compile a comprehensive list of limitations and solutions, forming a structured foundation for further research and analysis in our study.

3.2. Interview Study

The interview study was designed to complement the literature review with the aim of answering RQ1, while also setting the basis on how to approach RQ2 and the design phase of the validation case study. This phase aimed to deepen our understanding of the practical and theoretical challenges and opportunities associated with using VR in ergonomic assessments. A particular focus was placed on multi-user VR and their impact on the field.

In the interviews, we divided the work between us to ensure a smooth and productive conversation with the interviewees. One of us was responsible for asking the questions, while the other took detailed notes on the responses. This division allowed the interviews to feel more like discussions, promoting a relaxed and open exchange of ideas. After each interview, we reviewed all the questions and notes, compiling comprehensive answers for each question. Once the interviews were analysed and understood, we wrote down the conclusions and main ideas extracted from the discussions. This process enabled us to compare the findings with our literature review and other interviews, ensuring a robust and well-rounded analysis.

To capture a broad and informed perspective, we selected a mix of academic researchers and industry practitioners known for their work in ergonomics and VR. The participants included:

- **Francisco Gracia:** Ph.D. student specializing in VR and Product Design at Skövde University.
- **Dan Högberg:** Professor of Human-Centric Production and Ergonomics at Skövde University.
- **Cecilia Berlin:** Professor of Human Design and Factors at Chalmers University of Technology.
- **Roland Örtengren:** Senior Professor of Human Factors Engineering and Ergonomics at Chalmers University of Technology.
- **Dan Lämkull:** Professor of Ergonomic Assembly at Chalmers University of Technology and Ergonomist at Volvo Cars.
- **Puranjay Mugur:** Ergonomic Simulation Engineer at Volvo Cars.
- **Maciej Zdrodowski;** Ergonomist and Human Factor expert at Volvo Cars
- **Johan Cruse:** Tools and Methods Manager for Retails Competence Development at Volvo Trucks, working with multi-user VR for training purposes.
- **Peter Mårdberg:** Applied researcher in the Geometry and Motion Planning Department at FCC.

Using a semi-structured interview format allowed for flexibility and depth in our discussions, ensuring that all relevant topics were covered thoroughly [25]. Participants provided their perspectives on the current state of VR technology in ergonomic assessments, influenced by their respective backgrounds and expertise. They discussed the specific technologies they employ in ergonomics and identified any limitations they face in their current workflows. A significant focus was on how VR tools, particularly multi-user VR, fit into these processes.

The interview questions explored the potential advantages of using multi-user VR in ergonomic assessments, especially in designing and modifying production environments or workstations. Interviewees were also questioned about the advantages and drawbacks of single-user VR versus multi-user VR, particularly in terms of how collaborative tools could address and potentially overcome existing challenges. The discussion also covered the potential economic benefits and the time efficiency of incorporating multi-user VR tools in ergonomic assessments.

Using VR tools to include many stakeholders in ergonomic assessments was discussed. The interview questions were also related to the practical difficulties, such as the learning curve involved in using VR technologies, and the key performance indicators (KPIs) used in companies to gauge the effectiveness of ergonomic assessments. Another topic of discussion was safety regulations pertaining to the use of VR technology in ergonomic assessments in industrial situations. Along with the anticipated advancement of VR technology over the next five to ten years, the importance of cutting-edge technologies like AI and machine learning in augmenting VR-based ergonomic assessments was also taken into consideration.

Rich qualitative data from the interview study was expected to be taken so to improve our understanding of the present and possible applications of VR in ergonomic assessments. The insights from these interviews were invaluable in validating the findings from the literature review and helped us to design of our validation case study. Consent was obtained from all interviewees to use their names and affiliations in our thesis report and any associated documentation. For a detailed list of all the interview questions used in this study, please refer to the Appendix B.

3.3. Validation Case Study

The validation case study was designed to apply and test the insights gathered from both the literature review and the interviews, mainly aimed at answering RQ2 but also concluding the study behind RQ1 by gathering real-experience data. The primary aim was to explore how different technologies—desktop applications, single-user VR, and multi-user VR—influence the ergonomic assessment process in a practical setting. For this, ergonomic experts were supposed to use these platforms and ergonomically assess three representative manufacturing tasks, to identify and suggest improvements in the posture of the manikins.

The experiments were conducted in the Stena Innovation Laboratory (SII-Lab) at Chalmers University of Technology in the Lindholmen Campus, a cutting-edge facility designed for advancing digitalized production and Industry 4.0. Equipped with 5G, collaborative robots, and VR/AR technologies, the lab provides an ideal environment for testing new ideas and conducting practical research [26].

Each session required the collaboration of at least two ergonomic experts to study how this collaborative approach of the multi-user VR experience would fit inside the world of ergonomic assessments. Initially, they received a brief explanation on the project's objectives and the setup of the experiment, and then, they started on a sequence of assessments across the three manufacturing tasks. The experiment was structured so that each task was assessed using three different technological platforms: desktop applications, single-user VR, and multi-user VR. The platforms were set in a pre-determined order, that will be explained further, to systematically explore how each influenced the ergonomic assessment process.

After completing an assessment on one platform, they were asked to suggest an improved posture for the manikins, with the option to carry forward, modify, or enhance their previous recommendations as they progressed to the next platform of one task. They followed this procedure across the three representative tasks, making a total amount of nine assessments. To add a quantitative dimension to the qualitative insights, the duration spent on each platform for every task was carefully recorded. Their final decision on how to improve the posture of the manikin and any noteworthy observations during the assessments were also noted.

We involved four ergonomic specialists for our two experiments.

- **Puranjay Mugur:** Ergonomic Simulation Engineer at Volvo Cars.
- **Lars-Ola Bligård:** Researcher in design & Human Factors at the Department of Industrial and Materials Science, Chalmers University of Technology
- **Dan Lamkull:** Dan Lämkull: Professor of Ergonomic Assembly at Chalmers University of Technology and Ergonomist at Volvo Cars.
- **Maciej Zdrodowski:** Ergonomist and Human Factor expert at Volvo Cars

Puranjay and Lars performed the first experiment, and Dan and Maciej closed the experimental phase of this thesis. As for every task, the specialists followed a three-step process as they went through every platform, each step will be called phase, so the chronological order for every task will go from phase 1 to phase 3. In the initial phase, specialists required additional time to familiarize themselves with the tasks. As the experiment progressed to the other two phases, they spent less time on them, as they were assessing something that they had already seen before.

For the first experiment, the order of platform usage was determined randomly, detailed in table 3-1. This order served as a baseline from which unbiased insights could be taken regarding each platform's initial impact. This approach ensured that the first exposure to each platform was unaffected by prior usage of another.

Table 3-1: Order of the experiment 1 with Lars-Ola and Puranjay

EXPERIMENT 1	TASK 1	TASK 2	TASK 3
PHASE 1	Multi-user VR	Desktop Applications	Desktop Applications
PHASE 2	Single-User VR	Single-User VR	Single-User VR
PHASE 3	Desktop Applications	Multi-user VR	Multi-user VR

For the second experiment, the order was strategically adjusted based on the outcomes of the first experiment, detailed in table 3-2. This change was designed to facilitate more direct comparisons between platforms in each phase of the experiment. By contrasting the different platforms systematically, we aimed to identify specific strengths and limitations from each technology. Priority was given to contrasting the single-user VR and multi-user VR platforms directly against each other, as these platforms were the most interesting for the results of this master's thesis.

Table 3-2: Order of the experiment 2 with Dan and Maciej

EXPERIMENT 2	TASK 1	TASK 2	TASK 3
PHASE 1	Single-user VR	Multi-user VR	Single-user VR
PHASE 2	Desktop Applications	Desktop Applications	Multi-user VR
PHASE 3	Multi-user VR	Single-user VR	Desktop Applications

In the following table 3-3, it can be seen, considering the order from the first experiment, that the order of the second experiment maximized the comparison between platforms across all the phases of every task assessed. We could finally compare the single-user VR platform against the multi-user VR platform in all three phases, the desktop application platform against the single-user VR platform in two phases and the desktop application platform against the multi-user VR platform in two phases.

Table 3-3: Order from both experiments merged to one table to easily see the comparison between platforms

		PHASE 1	PHASE 2	PHASE 3
TASK 1 Handle	Exp1	Multi-user VR	Single-user VR	Desktop Application
	Exp2	Single-user VR	Desktop Application	Multi-user VR
TASK 2 Mudguard	Exp1	Desktop Application	Single-user VR	Multi-user VR
	Exp2	Multi-user VR	Desktop Application	Single-user VR
TASK 3 Cables	Exp1	Desktop Application	Single-user VR	Multi-user VR
	Exp2	Single-user VR	Multi-user VR	Desktop Application

Single-user VR **VS** Multi-user VR	**3 phases**
Desktop Application **VS** Single-user VR	**2 phases**
Desktop Application **VS** Multi-user VR	**2 phases**

Following the completion of the practical sessions as part of the validation case study, the ergonomic specialists participated in a semi-structured interview, which can be found in Appendix C.I. During this interview, they provided detailed feedback on their experiences using the three platforms. They discussed the ease or difficulty of assessing postures, their preferred platforms for ergonomic assessments, the advantages or challenges identified in each method, and their visions for the future of ergonomic assessments. They were also asked about the importance of 3D immersion for accurate assessments and how having multiple stakeholders in a multi-user VR setting could potentially improve ergonomics. These discussions offered valuable insights into whether immersive 3D environments and the presence of multiple stakeholders in VR could enhance the ergonomic assessment process, and how these technologies might be integrated in future assessments.

After the interview, the specialists were sent a usability survey via email, which they were asked to complete within the next 48 hours. This survey, found in Appendix C.II, was designed to evaluate the system usability of all three platforms based on the System Usability Scale (SUS) developed by John Brooke in 1996 [27]. Also, the survey provided crucial quantitative data that complemented the qualitative insights from the semi-structured interviews, enriching the overall research data set.

Once the experiments were completed and all feedback was gathered, the improvements suggested by the ergonomists in each task, across each experiment and phase, were implemented. Subsequently, the ergonomic scores could be compared with the scores obtained from the base scenes of each task to evaluate the impact of each approach.

This validation case study provided critical information into how different technologies can be used to enhance ergonomic assessments as well as the answers to our posed RQ2. By directly comparing desktop applications, single-user VR, and multi-user VR in a structured experiment, we gained a deeper understanding of the potential benefits and limitations of each approach. The feedback from ergonomic specialists highlighted the importance of immersive environments and collaborative tools in improving ergonomic practices.

3.3.1. Tasks

This study utilized three representative assembly tasks, chosen for their similarity to common processes in car assembly, to examine how ergonomists interact with these technologies. A virtual representation of the chassis of a Volvo XC40 was used, and the tasks were designed around it using the IPS IMMA 2023 R2 software, with the manikin set to a height of 1756 cm and a weight of 78 kilograms. The tasks were deliberately designed with poor ergonomics, indicated by a red REBA ergonomic score (8-10) from the IPS IMMA 2023 R2 software. The required CAD files were sourced from the SII Lab's existing collection or downloaded from the internet, except for the mudguard, which was designed using SHAPR3D software.

As we do not currently have the technology to simulate the entire sequences of all three tasks in multi-user VR, only the final posture was assessed for all three methods to eliminate biases. This approach ensured a consistent basis for comparing the effectiveness of the desktop applications, single-user VR, and multi-user VR.

3.3.1.1. TASK 1 - HANDLE TASK

The first task, wanted to simulate the assembly of the backseat's grab handle. It involved the manikin picking up a handle from a nearby table or shelf and fixing it to the roof above the back seat window on the driver's opposite side. It was assumed that the handle would automatically fix into place when correctly positioned.

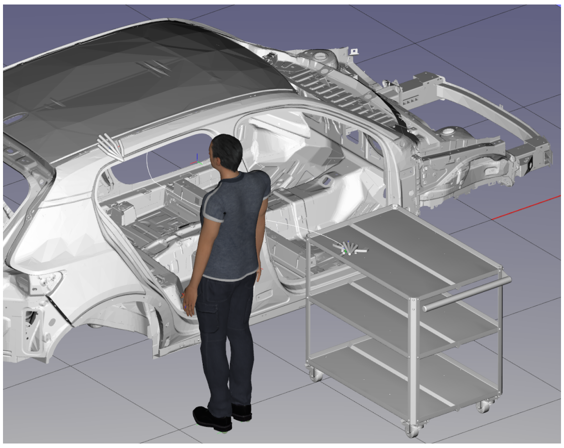

Figure 3-2: Initial position for Task 1

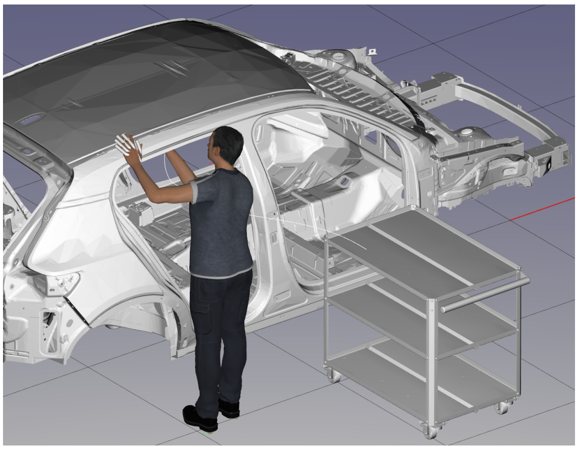

Figure 3-3: Final position for Task 1

3.3.1.2. TASK 2 - MUDGUARD TASK

The second representative task consisted in attaching a mudguard behind the front wheel of the car. This task involved the manikin picking up a mudguard from the table and attaching it to the rear of the wheel of the car. The mudguard's CAD model, designed using SHAPR3D, was assumed to automatically attach to the chassis, but only when it was positioned accurately in the correct place and orientation.

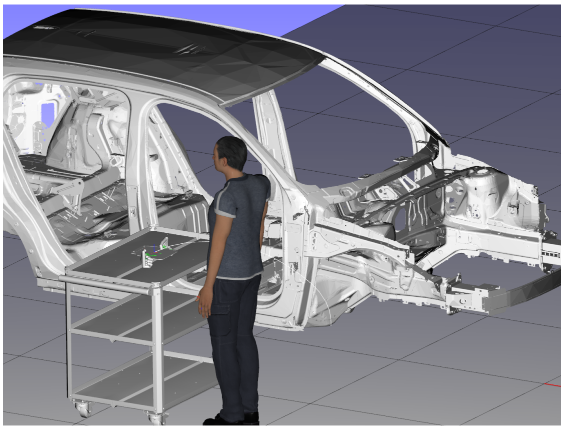

Figure 3-4: Initial position for Task 2

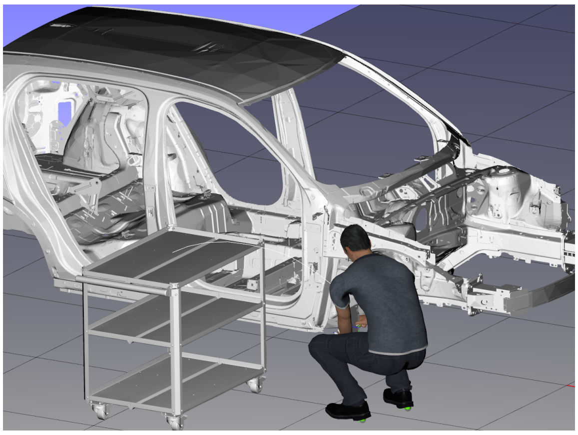

Figure 3-5: Final position for Task 2

3.3.1.3. TASK 3 - CABLES TASK

The last representative task consisted in connecting two different connectors with each other, where the manikin needed to attach a male connector to a corresponding female connector fixed to the chassis. For simplicity, the connecting wires were not displayed in the software or CAD diagrams.

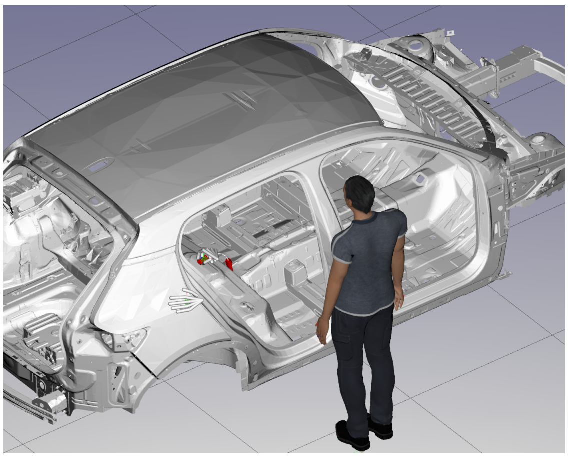

Figure 3-6: Initial position for Task 3

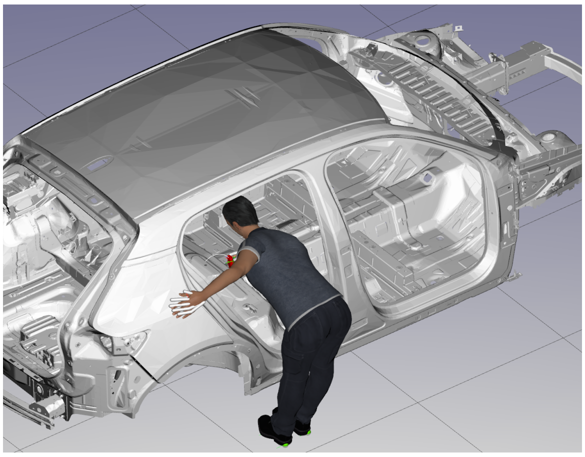

Figure 3-7: Final position for Task 3

3.3.2. Platforms

The platforms and technologies that have been used in this validation case study, which have been previously introduced, will be discussed in greater detail below. Additionally, it is important to note that prior to conducting the ergonomic assessments, each set of ergonomic experts received a brief demonstration on navigating each platform. This preparatory step was essential for ensuring the efficiency of the experimental process.

3.3.2.1. DESKTOP APPLICATION

Both experts were meant to work together discussing how to improve the posture of the manikins presented in the scene of the task using the IPS IMMA 2023 R2 software. They viewed the posture on a desktop screen, and they navigated the scene using the mouse and keyboard, manipulating the 3D view through the 2D screen of the computer. Additional resources and tools were also available for use, provided they were accessed via the computer screen. This setup facilitated a thorough ergonomic assessment from various angles, ensuring an effective evaluation and improvement process.

3.3.2.2. SINGLE-USER VR

Only one VR headset was shared between the participants during the assessment. While one participant wore the headset to interact with the virtual environment using the IPS IMMA 2023 R2 software, the other observed the same VR view on a desktop screen. This setup allowed both participants to view the final posture and the VR environment simultaneously, ensuring a comprehensive perspective on the ergonomic assessment. Participants were given the flexibility to switch roles; the one initially viewing through the headset could swap with the one watching on the desktop, allowing both to experience the immersive and desktop-based views. Instructions on how to teleport within the VR environment were provided to help participants navigate effectively. However, the initial setup for displaying the VR view on the desktop was managed by the researchers, not the participants, to streamline the process and avoid confusion.

3.3.2.3. MULTI-USER VR

Both participants wore VR headsets and assessed the posture together in the Chalmers multi-user VR platform. For the assessments in the multi-user VR environments, the platform was changed because the new IPS multi-user platform was released only a few weeks before the thesis completion, while the Chalmers multi-user VR platform was already available and ready to use. Both platforms had similar capabilities for our needs, providing only static body postures but additional training was provided on teleportation within this specific VR environment, as it differed from the IPS IMMA single-user VR setup. Throughout the assessments, experts cooperated by discussing both in the VR environment, on how the improved posture of the manikin should be.

4. RESULTS

The findings of this research are arranged into three discrete sections: the review of relevant literature, the study of interviews, and the validation case study. Every section offers a distinct perspective on the application of VR and multi-user VR in ergonomic evaluations, emphasising the benefits, difficulties, and real-world uses of these technologies. This methodical technique makes it possible to comprehend VR optimisation for ergonomic gains in manufacturing settings in detail and study the feasibility of the implementation of the multi-user VR capabilities for these purposes.

4.1. Literature Review

This section provides a basic overview of the state of VR technology in ergonomic assessments by synthesising the results of a comprehensive review of previous research. It highlights major issues, limitations, and solutions that have been looked at in the literature.

4.1.1. Overview from Literature

VR technologies are increasingly being implemented across various industrial sectors, such as automotive assembly, construction, and energy. This involves not just aiding product design through virtual prototypes and VR-based personnel training, but also the planning, evaluation, and optimization of assembly processes. VR technologies enable interactions with digital prototypes and virtual models of planned workstations right from the initial stages of planning. Industrial case studies demonstrate the effectiveness of using VR in designing manufacturing workstations, showing significant advantages over designs done using only traditional desktop computer setups. Therefore, VR can facilitate quick feedback from key groups early in the design process, enabling faster iterations and eliminating the need for expensive physical prototypes [28]. This approach is particularly useful for evaluating assembly tasks, offering a cost-effective and flexible alternative to physical mock-ups. Through VR, users can experience and evaluate ergonomic features in a simulated setting that replicates real-world tasks, using technologies like motion capture (MoCap) and sensors to assess muscle fatigue and discomfort. This advancement suggests a future where ergonomists could remotely fine-tune workstations in VR to prevent MSDs' [29].

At General Motors, the Global Ergonomics Lab within the Manufacturing Engineering department is actively engaging in VR sessions utilizing Process Simulate. The Ergonomics team employs VR to provide product and manufacturing engineers with a deep dive into their designs, offering them a 3D visualization of various complex assemblies and operations. These immersive studies are primarily aimed at assessing human factors such as reachability, line of sight, accessibility, and hand clearance. The use of immersive technology has improved human simulation studies throughout the vehicle development process, particularly in designing safer workstations. Additionally, it has fostered enhanced collaboration between product engineering and manufacturing engineering teams, helping to minimize late-stage design modifications in the product lifecycle [30].

Fiat Chrysler Automobiles has introduced a preventive ergonomic approach called ErgoUAS for designing new workplaces. This method is utilized during both the Product Design and Process Industrialization phases. ErgoUAS integrates the European Assembly Work Sheet (EAWS) and the Universal Analysing System (UAS). EAWS serves as an initial ergonomic assessment tool to evaluate the risk of biomechanical overload. On the other hand, UAS is an example of the Method-Time-Measurement (MTM) system, which is employed to determine the times and methods for work by describing the sequence of operations for a specific task and assigning a pre-determined standard time based on the observation of the worker and the nature of the movements during the task [31].

4.1.2. Benefits From Literature

Virtual prototypes of workplaces enable comprehensive analysis and optimization of solutions, especially regarding work safety, without the need for physical prototypes. This method allows for the testing and simulation of various "human-machine" configurations in a virtual environment, reducing study costs and enhancing safety. Dangerous scenarios that could threaten an operator’s health can be tested virtually without involving real machinery. This significantly minimizes the risk of accidents during simulations, ensuring safer and more efficient evaluations [2].

Using VR is not only safe but also cost-effective. It can optimize factory layouts before they are built, potentially reducing operating costs by up to 50% [6]. Additionally, VR can significantly enhance the optimization of manufacturing processes and activities, offering considerable advantages [6]. Factors like posture evaluation, handling of weights, repetitive tasks, and the structure of job roles are crucial considerations. Consequently, every element within the work environment, including tools, devices, and materials to be manipulated, should be engineered to ensure that employees can perform tasks in a manner that optimizes movement efficiency, conserves energy, and minimizes the potential for harm. The use of VR technology can enhance the examination of manufacturing processes [6].

In many large organizations, stakeholders frequently collaborate with teams that are spread across the globe during the product design process. Furthermore, events like the Covid-19 pandemic and increased awareness of climate change have intensified the interest in minimizing air travel for face-to-face meetings. Consequently, there is a growing need for tools that can facilitate effective remote collaboration throughout all phases of the design process [32]. Multi-user VR can be extremely beneficial in addressing this need.

The advantages of Multi-user VR can range from enabling collaboration among people from various global locations to facilitating a cooperative approach to assessing ergonomic tasks to supporting training programs where multiple workers are needed to complete a factory task. Yangming et al. (2019) carried out a study in the construction field using VR technology [33]. While this paper focuses on training workers in the construction sector, the approach is also applicable in manufacturing environments. For instance, Volvo Trucks has successfully implemented this strategy in their production facilities [34]. René et al. (2020) also explored the use of VR in training [28]. Training operators in a virtual environment offers numerous advantages, including the potential to establish safer training settings that reduce the risks of personal injury, quality problems, or adverse impacts on lead times and production efficiency. It also allows for the training of operators on tasks in potentially hazardous situations that cannot be duplicated in the actual production system [19].

By using multi-user VR, more stakeholders can be added in the three-dimensional environment such as designers and ergonomists. While the operator will perform the task in the virtual world and their motions can be tracked using various software like IPS IMMA. IPS IMMA can also evaluate the ergonomic scores and give it to the user. An ergonomist and a designer can join the same virtual world with the help of multi-user VR and assess and change the design of the workstation accordingly [35].

4.1.3. Limitations From Literature

The application of VR in ergonomic assessments offers promising advances in design and safety evaluations, yet a review of the literature reveals significant limitations that may hinder its broader utility. These challenges, documented across various studies, range from direct user interaction issues to broader technological and systemic barriers that affect the integration of VR into practical ergonomic contexts. This section will go into these limitations, categorizing them into two main groups: VR limitations and, Ergonomic and simulation limitations. Understanding these limitations is crucial for developing more effective and user-friendly VR solutions in ergonomic assessments.

4.1.3.1. VR limitations

Immersive VR technologies, while advancing rapidly, still face several significant limitations that impact user experience and broader adoption. Primary among these is the lack of haptic feedback, which inhibits the full sensory experience of VR [2]. Additionally, current VR systems may struggle to accurately capture certain body movements, further detracting from the realism of virtual environments [36]. In controlled VR settings, users benefit from the ability to manipulate variables such as lighting and noise. However, these environments often fail to replicate the tactile sensations and physical resistance encountered in real-world tasks, such as assembly processes. This absence can lead to diminished user immersion and can induce motion sickness [28].

Moreover, VR often demands large physical movements, which can be impractical or even hazardous in confined spaces. These expansive gestures may result in user fatigue, risk of injury, and damage to equipment. For users with mobility limitations, such demands can render VR experiences inaccessible and uncomfortable. The requirement for extensive physical interaction over long periods can also cause health issues like eye strain [29]. Another practical challenge is the physical constraint imposed by the VR equipment, such as cables, which can restrict movement and impact the overall experience [37].

While VR controllers offer precise control, allowing users to perform intricate tasks within virtual environments, they fall short in supporting natural interactions that involve the entire hand and all fingers. A more advanced approach would be to employ technology that can precisely and instantly track hand movements, enabling a more natural interaction within the virtual space as one would experience in the real world [38].

Further compounding these issues are the ergonomics of the VR headsets themselves. Problems such as excessive weight, high localized pressure on the head, thermal discomfort, visual fatigue, and motion sickness can discourage prolonged use and negatively affect the user's health. These ergonomic challenges hinder the widespread acceptance of VR technologies and underscore the necessity of prioritizing ergonomics in the design of VR systems [39]. This is particularly vital as competition within the VR industry intensifies, demanding improvements that enhance user comfort and safety [40].

One crucial ergonomic factor in VR is the interpupillary distance (IPD)—the measurement between the centres of the pupils—which plays a key role in how three-dimensional images are perceived. Incorrect IPD settings can cause visual convergence issues, leading to discomfort and symptoms akin to being "cross-eyed". Accurate IPD adjustment is essential in VR headsets to prevent pain or simulator sickness, yet many headsets either lack this feature or offer only a limited adjustment range. As IPD varies from person to person and can change with age, the ability to customize this setting is critical for ensuring a comfortable and immersive VR experience [41].

4.1.3.2. Ergonomic and simulation limitations

VR has proven its potential in early-stage ergonomic design, effectively identifying issues before they become embedded within processes. This is extensively discussed in the 'Benefits from Literature' subsection, highlighting VR’s contributions to ergonomics. Despite the substantial evidence supporting VR's benefits, its practical application in ergonomic analyses is limited. Typically, VR is utilized to analyse pre-established production processes that already include all necessary devices, buildings, and equipment [6]. While VR offers significant value in these initial phases, complex issues that arise later often require traditional methods like real-life prototype testing and ergonomic assessments to provide deeper insights [28].

Moreover, challenges in utilizing VR and digital human models (DHMs) extend to designing for diverse human anthropometrics, as discussed by Lin et al. (2020). The research points out the limitations of DHMs in predicting human behaviour accurately and customizing products for specific individuals. Ergonomic evaluations using DHMs predominantly rely on data representing the general population. This approach can be less effective for individuals whose body types do not conform to these generalized datasets, including minority groups who may not be adequately represented [42]. This highlights a significant gap in the current use of VR and DHMs, underscoring the need for more inclusive and accurately predictive ergonomic design tools.

4.1.4. Solutions From Literature

After going through the benefits and limitations from this section, literature also reveals a variety of technological solutions that significantly enhance the future application and effectiveness of VR and ergonomic assessments. These innovations not only address existing limitations but also open new avenues for more precise and user-friendly ergonomic evaluations. The following sections will delve into how these solutions, particularly those involving advanced VR and motion tracking technologies, are being integrated into current workflows to optimize design processes and improve user interactions within virtual environments.

4.1.4.1. VR solutions

The integration of new digital tools into existing workflows, particularly in design, has seen a notable increase with the incorporation of Virtual and Augmented Reality (XR) technologies. These tools enhance visualization capabilities in virtual spaces and are particularly useful with digital human models (DHM). Presently, XR tools are primarily tailored for individual use, yet there is burgeoning interest in their application for collaborative efforts. Francisco et al. (2022) have explored this by developing methods for design reviews that simultaneously employ XR and traditional screen-based tools. This hybrid approach leverages the immersive depth of XR for exploring 3D designs while utilizing screen-based tools for tasks like note-taking and other non-3D software applications. Such integration facilitates effective teamwork by providing each member with technology that best suits their role and needs [32].

In parallel, the enhancement of user experience in VR focuses heavily on both hardware and software improvements. To address issues related to VR, improving the hardware design of VR headsets is crucial. Additionally, there is a pressing need to refine design guidelines for VR software content. Illnesses related to VR often discourage prolonged engagement with VR content. To improve the user experience, VR content developers need to focus on more than just the aesthetics of content; they must ensure that the content does not cause discomfort due to factors like rapid scene transitions or overly dynamic interface effects. Future research should aim to develop more detailed guidelines for VR software design, which would involve comprehensive studies into the effects of these design elements on user comfort. Finally, it is essential to establish a design model that integrates human factors with a comprehensive evaluation system for head-up displays. Future considerations could include personalizing HMD to fit individual physical conditions such as head circumference, which would help in reducing many issues. A combination of expert subjective evaluations and statistical data analysis could be used to develop a thorough index system for evaluating human factors associated with VR headsets, leading to a holistic set of subjective and objective evaluation methods [39].

Another significant advancement in VR interaction is the development of technologies like the Leap Motion device, which tracks hand movements in real time. This technology allows users to interact within VR environments naturally, using their hands without the need for physical controllers. This interaction style is not only intuitive but also makes the VR experience more immersive and accessible [38].

Addressing the ergonomic challenges in VR, particularly those associated with the necessity for large physical movements, has led to innovative solutions such as the reach-bounded, non-linear (RNL) input amplification approach. This method allows smaller, more controlled physical movements to be amplified into the larger motions expected within the virtual environment. It maintains a psychological sense of body ownership and reduces the risk of fatigue and accidental collisions, making VR more accessible and minimizing ergonomic strain [29].

Additionally, Haneen et al. (2022) have demonstrated how Immersive Virtual Environments (IVEs) can be instrumental in studying human behaviour under varied environmental conditions. By simulating changes in temperature, lighting, and comfort levels, these virtual settings allow for the testing and enhancement of indoor environments [43], such as manufacturing plants, without the need for physical prototypes. This method is not only cost-effective but also enables the exploration of different heating, cooling, and ventilation systems, as well as emergency scenarios, to ensure that the final design maximizes energy efficiency, safety, and worker productivity. This comprehensive approach to virtual testing before actual construction represents a significant shift in how environments are designed and optimized.

4.1.4.2. Ergonomic and simulation solutions

Addressing the limitation in current VR systems where they struggle to accurately capture certain body movements, it is essential to explore solutions that enhance the motion tracking capabilities within virtual environments. VR and MoCap technologies are being increasingly recognized for their potential to enhance ergonomic assessments in the workplace. Ilona et al. (2022) explored this application through an experiment in Pilsen, Czech Republic, involving 20 participants. The study demonstrated how VR combined with MoCap could significantly aid in identifying and rectifying ergonomic issues, thus enhancing workplace safety and comfort. However, the researchers noted the prohibitive cost of such technologies, especially for smaller enterprises [44]. Similarly, F. Caputo et al. (2018) reported positive outcomes in ergonomics by utilizing VR and MoCap to simulate and analyse two existing workstations at different companies [31].

While MoCap systems excel at tracking detailed movements, their complexity and cost generally confine their use to specialized research settings. Conversely, VR provides a more accessible option for everyday settings through the use of Inverse Kinematics (IK). In VR setups, HMDs, controllers, and Vive Trackers help create digital models, or "manikins," that mimic user movements. IK processes the data from these devices to replicate the virtual model's joint movements according to the user's actual motions. Although adding more trackers can improve accuracy, it also complicates the setup, making it less comfortable and more expensive [45].

Further research by Jan et al. (2021) evaluated the effectiveness of commercial VR technology, specifically the HTC Vive tracker combined with the Final IK system, for modelling work environments and assessing ergonomic risks. The study highlighted discrepancies in the precision of the HTC Vive system compared to a marker-based optical MoCap system, Qualisys, which is considered a benchmark for motion analysis due to its high accuracy. The findings emphasized the need for careful consideration of potential inaccuracies in ergonomic evaluations when using VR technologies, despite acknowledging the cost-effectiveness of VR tracking systems for recording joint angles [46].

In response to these challenges, Lin et al. (2020) proposed advancing ergonomic evaluations through the use of real-time sensor tracking devices and wire-free sensors within VR environments. These technologies could provide more personalized ergonomic guidelines and potentially revolutionize product design, evaluation, and manufacturing. Despite the advancements in VR technology for design and simulation, the diversity of human bodies presents a significant challenge in creating human-centred VR systems. The paper suggests that Mixed Reality (MR) could be a viable alternative, adding real-time information to the user's environment and supporting a more inclusive and reliable design process. MR facilitates collaborative prototyping by integrating designers, users, and ergonomists, aiming to address the limitations of VR and digital human models by offering a more adaptable and user-centred design methodology [42].

4.2. Interview Study

In this section, we share the qualitative information that was gathered by speaking with experts in the field. This section explores the viewpoints and real-world experiences of experts who include VR and other technology into their ergonomic practices, providing an informed understanding of the benefits and drawbacks of these tools.

4.2.1. Overview and key aspects from interviews

In exploring the integration of VR technologies within ergonomic assessments, Francisco Garcia emphasized the importance of discerning the real value of VR in specific scenarios to maximize its benefits, suggesting that not all tasks may benefit from a general application of VR technology. He also pointed out the need to choose carefully between VR and AR based on task requirements, as each offers distinct advantages in different contexts [47].

The evolution of these technologies is closely tied to advancements provided by software developers, as improvements in VR and AR functionalities directly impact their utility in ergonomic assessments. This dependency highlights the importance of continual development and the role of software providers in shaping the future of ergonomic technologies [47].

When addressing the capabilities of multi-user VR, Dan Högberg and representatives from Volvo discussed the critical nature of interactions within these environments. For VR to be truly beneficial in ergonomic assessments, the simulation of interactions between manikins or avatars must accurately reflect real human behaviours. This fidelity is crucial for assessing potential ergonomic issues effectively and developing realistic solutions [48][50].

Moreover, integrating throughput with ergonomic considerations, as noted by Roland Örtengren, ensures that efficiency and worker safety are balanced, enhancing overall workplace design. This approach not only optimizes operational workflows but also promotes a safer working environment [49].

Trust in the technological assessments is evident in Volvo's approach, where ergonomic interventions are triggered based on the scores from VR simulations. This reliance underscores the perceived accuracy and reliability of VR-derived data in making informed decisions about workplace safety [50].

Finally, the potential of ergonomic assessments to serve as a marketing tool was highlighted, with Volvo predicting that demonstrating a commitment to ergonomic safety could become a significant factor in attracting and retaining talent. This aspect points to the broader implications of ergonomic assessments beyond immediate worker safety, extending to corporate reputation and workforce satisfaction [50].

4.2.2. Benefits from interviews

The conducted interviews provided some of the benefits of using VR and related technologies in ergonomic assessments and design processes. One of the primary advantages identified is the significant reduction in costs, as outlined by Dan Högberg. By streamlining processes and minimizing the need for physical prototypes, companies can save on material and operational expenses [48].

In addition to cost savings, there is a substantial gain in time efficiency. Dan Högberg, Cecilia Berlin, representatives from Volvo, and Peter Mårdberg all noted that the use of VR technologies allows for the rapid simulation and iteration of design scenarios. This time efficiency enables teams to explore more options and scenarios within the same developmental timeframe, enhancing the depth and thoroughness of the design and assessment processes [48][50][51].

Another crucial benefit discussed by Dan Högberg is the reduction in environmental impact. By decreasing the reliance on physical materials and the need for travel, VR contributes to a lower carbon footprint associated with the design and evaluation phases [48].

Furthermore, Cecilia highlighted the advantage of direct feedback facilitated by VR environments, particularly in collaborative settings. The immediacy of feedback in VR not only accelerates the iteration process but also enhances the collaborative efforts among team members, allowing for real-time adjustments and shared insights, which are vital for optimizing design and ergonomics in workplace environments [36].

4.2.3. Limitations from interviews

4.2.3.1. VR limitations

Cecilia highlights a significant limitation in VR's inability to support effective collaboration among users, which is crucial for team-based ergonomic assessments. Both Francisco and Cecilia note that body and hand tracking in VR often lacks accuracy and responsiveness, which can detract from the realism and effectiveness of the simulations. Additionally, Cecilia points out the limited FoV provided by many VR systems, which can restrict users' perceptions and interactions within the virtual environment [47][36]. For instance, if the hand is positioned behind the body, the VR system might fail to detect it [36].

Comfort remains a critical concern with VR tools, particularly headsets, which Cecilia finds can be uncomfortable for extended use. Both Dan Högberg and Cecilia discuss the ease of use of VR tools, emphasizing that despite advances, significant usability barriers still exist that can delay the general adoption and effectiveness in ergonomic studies [48][36].

Francisco identifies usability friction specifically related to the multi-user VR experience, where the complexities increase due to the need for multiple functionalities that often are not compatible with each other. This lack of compatibility can significantly complicate the user experience as different systems struggle to integrate seamlessly within a shared virtual environment. Representatives from Volvo further elaborate on software friction, particularly emphasizing issues related to cybersecurity. This includes concerns that to utilize some of the available VR systems effectively, companies would need to share sensitive private data. The unwillingness to compromise on data privacy leads to reluctance in adopting these systems, posing additional challenges for companies looking to integrate VR into their regular workflows. These frictions highlight significant hurdles in not only adopting VR technology but also in scaling its use across collaborative platforms that require stringent data security measures [47][50].

Francisco, Dan Högberg, Cecilia, Roland, and representatives from Volvo all discuss the difficulty of simulating accurate weight sensation and the physical feeling of objects within VR, which is crucial for true-to-life ergonomic assessments. Issues such as proper simulation of lighting, heat, and other environmental factors also present challenges that affect the authenticity and utility of VR environments [47][48][36][49][50].

Cecilia addresses additional limitations related to regulations or safety considerations when using VR tools. She highlights the current absence of specific regulations governing the use of VR technologies in work environments, which complicates the establishment of standardized safety practices. Furthermore, Cecilia notes potential issues with collisions within virtual environments, a problem exacerbated by the loss of a sense of reality that current VR technology often induces. This issue becomes particularly pronounced in multi-user VR environments, where the interaction between participants without accurate spatial awareness can lead to misunderstandings and accidents. These collision problems, if not properly managed or anticipated during the design of VR experiences, can pose significant risks to users and hinder the practical utility of VR for collaborative work settings [36].

4.2.3.2. Ergonomic and simulation limitations

The interviews with experts also noted some limitations within ergonomics and the simulation technologies used to do ergonomic assessments. One of the primary concerns discussed by Cecilia and Roland revolves around the fidelity of software-generated ergonomic scores. There is often uncertainty about which ergonomic assessment method should be applied in different scenarios, leading to potential inconsistencies in outcomes [36][49].

Further complicating ergonomic evaluations, Dan Högberg and Roland pointed out the issues with robotic and non-natural body movements within VR simulations. These unnatural movements can impact the accuracy of ergonomic assessments, as they may not accurately represent the physical dynamics of human motions in various work-related tasks [48][49].

Moreover, the consistency of ergonomic assessments is also a challenge, as highlighted by Francisco and Cecilia. Different ergonomists may produce varying scores for the same assessment scenario due to differing interpretations and applications of the observational ergonomic methods. Cecilia additionally noted the issue of non-standardized ergonomic certification, which can lead to disparities in assessment results and methods employed [47][36].

Another related limitation seen both literature review and the interview study are the variation in ergonomic methods used across different companies. This lack of standardization in ergonomic assessments means that results can vary significantly depending on the company or the ergonomic expert conducting the evaluation. This diversity in approaches can make it difficult to compare results across different settings or to establish a unified standard for ergonomic safety in VR environments.

These challenges underscore the need for more standardized procedures and better simulation technologies in VR to enhance the reliability and accuracy of ergonomic assessments, ensuring they are effective in improving workplace safety and design.

4.2.4. Solutions and future from the interviews

To end the interview study results, they revealed several innovative solutions addressing current limitations in VR ergonomic assessments and also, some insights of the future direction of the VR technologies in ergonomic assessments. Francisco discussed the development of multi-user VR systems specifically designed to overcome the inherent inability to collaborate effectively in traditional VR setups [47]. To address the challenge of accurately simulating weight sensations, both Dan Högberg and Cecilia have explored biomechanical solutions that enhance the physical realism of virtual environments [48][36]. Additionally, Peter introduced the concept of Smart Gloves designed to improve the simulation of hand and finger movements, offering a more intuitive and responsive way to interact with virtual objects, thereby increasing the accuracy of ergonomic assessments [51].

Looking towards the future, Francisco anticipates the rise of asymmetric collaboration models in VR, which would allow different users to have varying levels of control and interaction based on their specific roles and tasks [47]. Dan Högberg and Peter see significant potential in AI-driven motion prediction, although they note that this technology will require extensive training to achieve high levels of accuracy [48][51]. Dan also emphasizes ongoing efforts to enhance the accuracy and responsiveness of VR technologies, which are critical for effective ergonomic evaluations [48]. Furthermore, both experts in Volvo and Peter highlight the development of dynamic ergonomic scoring systems within software platforms, enabling real-time, adaptive assessments that can respond to the changing conditions of the work environment [50][51].

4.3. Validation case Study

The last section of the findings describes the results of using several technologies in a controlled experiment. Based on evaluations by ergonomic specialists, it analyses how well desktop application, single-user VR, and multi-user VR help in identifying and analysing ergonomic problems.

Figure 4-1: Image of Dan Lämkull and Maciej Zdrodowski performing one assessment of the validation case in the multi-user VR platform

4.3.1. Qualitative data

This section consolidates findings from semi-structured interviews conducted after a series of experiments using three different platforms for ergonomic assessments: a multi-user VR platform, single-user VR, and desktop applications. Interviewees included both frequent and novice users of these technologies, providing a diverse range of insights into their applicability and effectiveness in ergonomic studies.

4.3.1.1. Semi-structured interview after the experiment

Experience using Platforms – According to Dan Lämkull and Maciej Zdrodowski, the multi-user VR platform offers significant collaborative advantages and is technically similar to other VR systems. In contrast, desktop applications often display robotic behaviours and are time-consuming, primarily due to issues like misinterpreting the scale of CAD models [52]. The difference in familiarity with these platforms was clearly evident between Lars-Ola, who was new to all three platforms, and Puranjay, who used them regularly. This discrepancy highlighted how prior experience with these platforms can significantly affect user engagement and effectiveness [53]. All individuals agreed that the multi-user VR platform was especially user-friendly, facilitating easier navigation. The ability of VR to allow users to physically move around enhances the ergonomic assessment process, leading to more informed decision-making in a virtual environment [52][53].

Preferred Platform for Ergonomic assessment - The preference for ergonomic assessments distinctly favours the multi-user VR platform in case of Dan Lämkull and Maciej Zdrodowski, primarily because of its flexibility to support both single-user and multi-user operations. This adaptability is crucial as it enables users to mimic and physically experience the tasks performed by the manikins. Engaging directly with these simulations provides a more accurate ergonomic assessment, allowing for a thorough understanding of the physical demands and potential strain involved in specific tasks [52]. However, according to Lars-Ola Bligård and Puranjay Mugur the choice of platform can vary depending on the scenario. If the assessment involves multiple stakeholders or needs collaborative input, then either single-user or multi-user VR platforms would be more suitable due to their interactive capabilities. On the other hand, if the assessment is to be conducted independently without the need for collaborative input, a desktop application might be enough. This option is generally adequate for solo work and can be effective in environments where simpler assessments are required [53].

Obstacles in Multi-user VR platform – Despite the advantages of the multi-user VR platform for ergonomic assessments, several challenges remain. Key obstacles include the need for a transparency mode to avoid collisions, the ability to display real avatars or manikins accurately, and the integration of haptic feedback or vibrational and colour indicators during interactions with virtual objects. Additionally, simulating physical contact more realistically poses a challenge; for instance, having a tangible surface to mimic real-world interactions could greatly enhance the user experience [52]. Moreover, effective use of the multi-user VR platform requires specific background knowledge, which can be a barrier for new users. Currently, the technology also requires a designated area for setup, which can limit its applicability in various environments. However, advancements are being made with new VR headsets that do not require camera setups, potentially allowing for use in more locations [53]. Another notable issue is the potential for sensory confusion when users in the virtual environment hear real-world sounds or conversations. This overlap can disrupt the immersive experience and cause confusion, detracting from the effectiveness of the VR simulation [53].

3D Immersion vs Desktop Application – According to Dan Lämkull and Maciej Zdrodowski, both VR environments and desktop applications hold their merits in the realm of ergonomic assessments. VR technology is particularly crucial for confirming and fully understanding scenarios that desktop applications can only outline. The immersive nature of VR allows for a deeper, more intuitive understanding of ergonomic postures and work environments, which is less feasible with desktop applications. Knowing when to use each tool—taking advantage of VR's immersive capabilities for complex assessments and employing desktop applications for more straightforward tasks—is key to effective ergonomic evaluation [52]. However, Lars-Ola Bligård and Puranjay Mugur note that while seeing things in 3D and experiencing a more immersive environment can significantly enhance the accuracy and confidence in ergonomic assessments, these elements are not strictly necessary. Desktop applications, although less immersive, still provide a valuable platform for assessing ergonomics [53] They can be particularly useful for initial evaluations or in situations where VR accessibility is limited. Thus, the choice between VR and desktop applications should be guided by the specific requirements and constraints of the assessment at hand.

Impact of Multiple Stakeholders in VR Setting – Dan Lämkull and Maciej Zdrodowski emphasize that incorporating multiple stakeholders in a multi-user VR setting significantly enhances the ergonomics assessment and improvement processes for operators. While companies like Volvo Cars typically do not employ multiple ergonomists in day-to-day operations, the participation of additional experts is crucial for complex tasks. In environments such as automotive assembly, where tasks often require the simultaneous activity of two operators, the inclusion of diverse stakeholders—ergonomists, engineers, operators, and managers—becomes essential. Each brings a unique perspective that contributes to a more comprehensive evaluation of ergonomic needs. This multi-disciplinary approach, facilitated by VR, allows for more effective communication and collaboration, leading to better-informed decisions and more precise ergonomic enhancements [52]. Lars-Ola Bligård and Puranjay Mugur note that while a single ergonomist can assess specific tasks effectively, the collaborative nature of a multi-user VR environment fosters a deeper, more nuanced understanding of ergonomic challenges. This collective examination not only broadens the perspective but also enhances the decision-making process, ensuring that the ergonomic improvements implemented are both accurate and beneficial for all operators involved [53].

Future of Ergonomic assessments – The future of ergonomic assessments should leverage technological advancements to improve accuracy, efficiency, and accessibility. Integrating built-in ergonomic feedback mechanisms and advanced tools such as smart gloves will significantly enhance the precision of assessments. Moreover, simplifying the calibration process required for using VR equipment and addressing ongoing calibration issues will make VR technologies more user-friendly and effective for ergonomic evaluations [52]. It is also crucial to support the recording and assessment of full-body motions and to offer features like haptic feedback in VR environments. These capabilities will allow for a more comprehensive analysis of ergonomic risks and the physical demands placed on workers [52]. Incorporating cycle times into simulations will further enhance their utility, providing a more dynamic understanding of tasks and their ergonomic implications [52]. Real-time adjustments, allowing users to embody the manikin and adopt suggested positions themselves, will expedite the assessment process. The integration of a display within the VR environment that shows ergonomic scores in real-time would be invaluable. This feature would enable a continuous visualization of ergonomic zones throughout the motion of a task, leading to more effective assessments [53]. Finally, facilitating remote ergonomic assessments by allowing individuals who are not in the same physical location to collaborate would be a transformative step forward. This capability would not only increase the flexibility and scope of ergonomic assessments but also foster broader collaboration and innovation in the field [52][53].

After seeing the results from the semi-structured interviews, in this section the focus will be put into the quantitative data taken from the validation case

4.3.2. Quantitative data

After examining the qualitative data from the semi-structured interviews, we shift our focus to the quantitative data analysis. This segment of our study explores three critical aspects: platform time-efficiency analysis, usability survey results, and ergonomic improvements derived from the pre-designed scenes. Each topic will provide a detailed numerical understanding that complements the insights gained from the qualitative interviews, offering a comprehensive view of the effectiveness and efficiency of the platforms tested.

4.3.2.1. Platforms time-efficiency study

In our experiments, we closely monitored how long it took ergonomic specialists to assess and suggest improvements for tasks using three different platforms: Desktop applications, Single-user VR and Multi-user VR. Our goal was to determine which platform allows for the most efficient assessment process. We recorded the time taken in each of the three phases (Please see section 3.3 for more information about the experiment phases), facilitating a comprehensive comparison of the platforms. To better visualize and understand these efficiency trends, we created graphical representations of the data. The average total time taken across all three platforms was calculated and depicted in a graph (Figure 4-2).

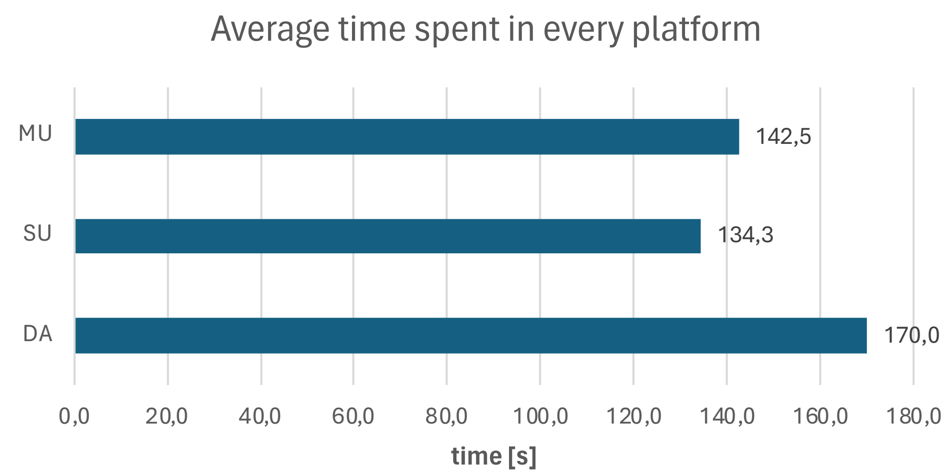

Figure 4-2:Clustered bar graph of the average time spent in every platform

Figure 4-2 illustrates that single-user VR logged the shortest average time, closely trailed by multi-user VR, with desktop applications taking considerably longer. This confirms single-user VR as the most efficient platform, although the difference between single-user and multi-user VR is minor compared to desktop applications. Contrary to our initial expectations, which projected multi-user VR as the most efficient due to its collaborative features and dual immersion capability, the ergonomic specialists opted for a different approach in single-user VR than we anticipated. Instead of alternating the VR headset between themselves, they preferred one user to wear the headset while the other utilized the VR view, a mode where a person can see what the headset wearer is viewing on a computer screen. This setup contributed to the minimal time disparity observed between the single and multi-user VR configurations. Desktop applications required more time primarily because they lacked the immersive VR experience and the navigation complexities of a 3D environment on a 2D interface. These factors contribute to the inefficiency seen in desktop applications, making them less suitable for rapid ergonomic assessment compared to the VR setups.

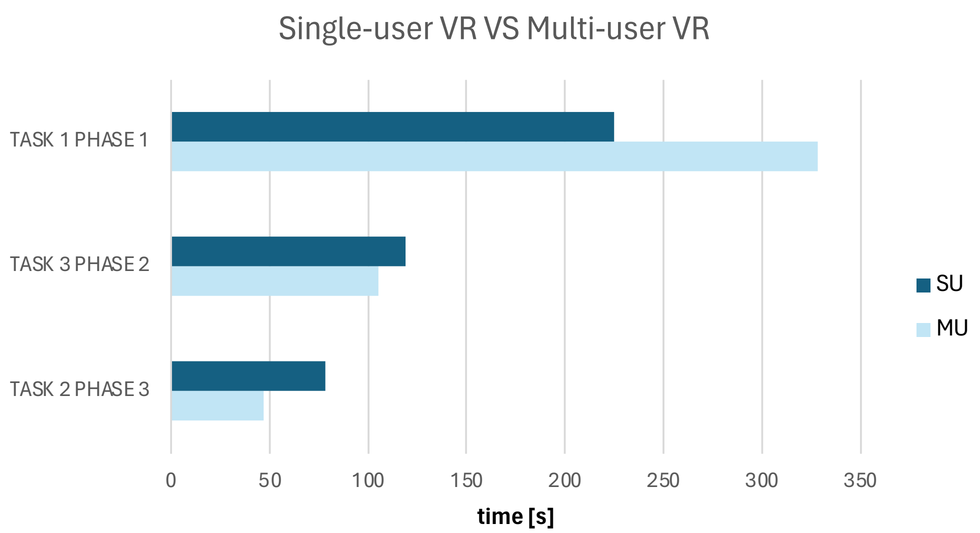

Figure 4-3: Clustered bar graph of the platform's comparison between single-user VR and multi-user VR

Figure 4-3 compares the time taken by ergonomic specialists to assess tasks across three phases using single-user and multi-user VR. The data reveals a progressive reduction in assessment time: Phase 2 is faster than Phase 1, and Phase 3 is faster than both preceding phases. This decrease is attributed to the specialists' growing familiarity with the tasks, having assessed them in different platforms during earlier phases.

Phase 1 is particularly significant, because it involves the initial assessment of static postures, marking the specialists' first interaction with the tasks in a VR environment. In this phase, single-user VR proves to be more time-efficient than multi-user VR. This initial efficiency strengthens the findings presented in Figure 4-2, demonstrating single-user VR's effectiveness for first-time task assessments.

However, the dynamics change in Phases 2 and 3, where multi-user VR becomes faster than single-user VR. This shift suggests that while multi-user VR initially adds complexity to task navigation and teleportation—owing to different software used—it ultimately becomes more efficient as users adapt to its functionalities.

An additional insight from the data is the similar overall time efficiency between the two VR modalities by the end of the three phases. Initially, multi-user VR's added complexity and the learning curve required for effective navigation may slow down task assessments. However, once the ergonomic specialists become accustomed to the multi-user environment, its collaborative features likely contribute to faster and more efficient assessments.

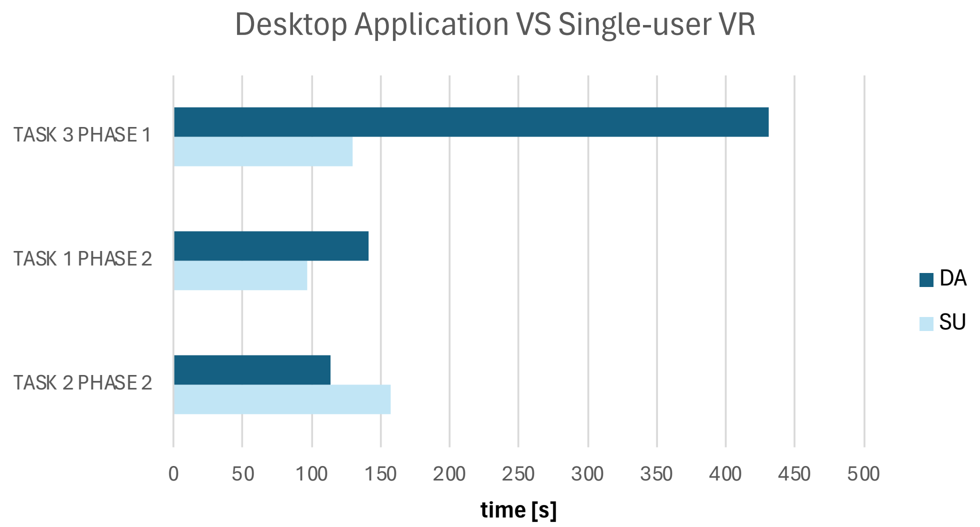

Figure 4-4: Clustered bar graph of the platform's comparison between desktop applications and single-user VR

Figure 4-4 illustrates that desktop applications consistently require more time than single-user VR for task completion, except for Task 2 Phase 2. This pattern reinforces the findings from Figure 4-2 regarding the greater efficiency of VR platforms. The deviation observed in Task 2 Phase 2 may be an outlier.

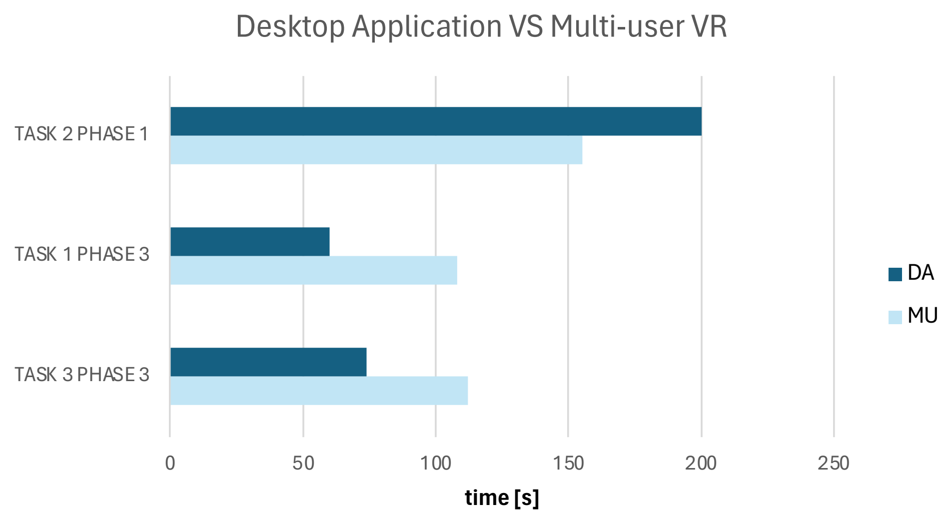

Figure 4-5: Clustered bar graph of the platform's comparison between desktop application and multi-user VR

In Figure 4-5, we observe that task assessments in multi-user VR take less time in Phase 1 but increasingly more time in Phase 3. This trend is unexpected and suggests that further analysis is needed to understand the factors influencing these varying performance levels across different phases.

4.3.2.2. Usability survey

This section presents the findings from the SUS [27] conducted to evaluate the user-friendliness and effectiveness of three different platforms for ergonomic assessments. The survey overall results are shown in table 4-1 and the answers given by all the ergonomic experts to each question can be found in the Appendix C.III.

Table 4-1: SUS scoring results from the usability survey

PERSON	Desktop Application	Single-user VR	Multi-user VR
P1	82,5	85	80
P2	32,5	45	45
P3	80	52,5	52,5
P4	72,5	65	60
Average	**66,9**	**61,9**	**59,4**
St. Dev.	23,31	17,49	15,05

The Desktop Application received the highest average usability score of 66.9, suggesting it is generally viewed as the most user-friendly of the three platforms assessed. This preference likely stems from participants' greater familiarity with desktop interfaces, as traditional computing environments have been in widespread use much longer than the comparatively newer VR technologies. However, the data also showed a high standard deviation of 23.31, indicating significant variability in user satisfaction and experiences. This variability is exemplified by the differing ratings from Participant 3 and Participant 2: Participant 3 rated the Desktop Application much higher than both VR platforms, indicating a strong preference for the conventional interface. In contrast, Participant 2 found both Single-user and Multi-user VR more effective than the Desktop Application, possibly reflecting a preference for more interactive and immersive environments. The broad range of experiences among users suggests that personal preferences and the non-immersive nature of the Desktop Application significantly influence usability ratings. Users who are accustomed to the interactive experiences offered by VR might find the Desktop Application less engaging, especially if their tasks benefit from the dynamic features that VR provides. Conversely, those more familiar with traditional computing might favour the well-known layout and controls of a Desktop Application, particularly if they have limited exposure to VR.

Single-user VR scored slightly lower than desktop application on average with 61.9 but exhibited more consistency among users, as indicated by a standard deviation of 17.49. Participant 1 found Single-user VR most beneficial for ergonomic assessments, potentially due to the combined benefits of having one participant in VR and one on the computer, effectively covering all bases without the risks associated with full immersion. Such risks might include collisions or other safety concerns, as VR users cannot see their physical surroundings. This setup might also explain why Multi-user VR did not emerge as their top choice, reflecting a preference for safety and effectiveness in an immersive environment where at least one person remains aware of the physical space.

Participant 2's equal score of both VR platforms above the Desktop Application provides a particularly insightful perspective. It suggests a strong preference for immersive experiences, which are crucial for effective ergonomic assessments. His perspective supports the notion that VR technologies, despite some usability challenges, provide significant advantages in settings that benefit from a high degree of interaction.

Receiving the lowest average score of 59.4, Multi-user VR was nonetheless noted for the most consistent user experiences, shown by the smallest standard deviation of 15.05. This consistency suggests that despite a lower overall satisfaction, participants generally agreed on its performance level. The stable and predictable user experience, combined with the immersive nature of VR, makes Multi-user VR potentially more suitable for tasks requiring detailed environmental interaction and user engagement. This platform's ability to facilitate immersive assessments, where multiple users can interact within the same virtual environment, could be particularly advantageous for complex ergonomic evaluations.

4.3.2.3. Ergonomic improvement

In this section of the Validation Case Study results, we explore the effectiveness of the proposed ergonomic improvements suggested by the two groups of ergonomists who participated in the experimental phase of the thesis. By utilizing the IPS IMMA 2023 R2 simulation software, we analysed the impact of these suggestions across three pre-designed tasks. This analysis aims to determine whether the modifications have indeed enhanced the ergonomic conditions for the manikins involved in these tasks. All the ergonomic scores given by the IPS IMMA 2023 R2 software from the base scenes and the improved scenes of the three tasks can be found in Appendix C.IV.

TASK 1 – HANDLE

In task 1 of our validation case study, focused on attaching a grab handle into a car, different proposals were noted for ergonomic improvement from our groups of ergonomists during both experiments. Lars-Ola Bligård and Puranjay Mugur recommended utilizing the industry-standard 'happy seat', an established assembly tool that facilitates seated operations within the vehicle, enhancing both reach and visibility for tasks requiring interior access. They suggested that allowing the operator to sit would greatly enhance visibility and alignment during the handle attachment process to the car. This seating arrangement was deemed beneficial as it enables the operator to align the attachment points between the handle and the car more efficiently, without compromising on ergonomic safety.

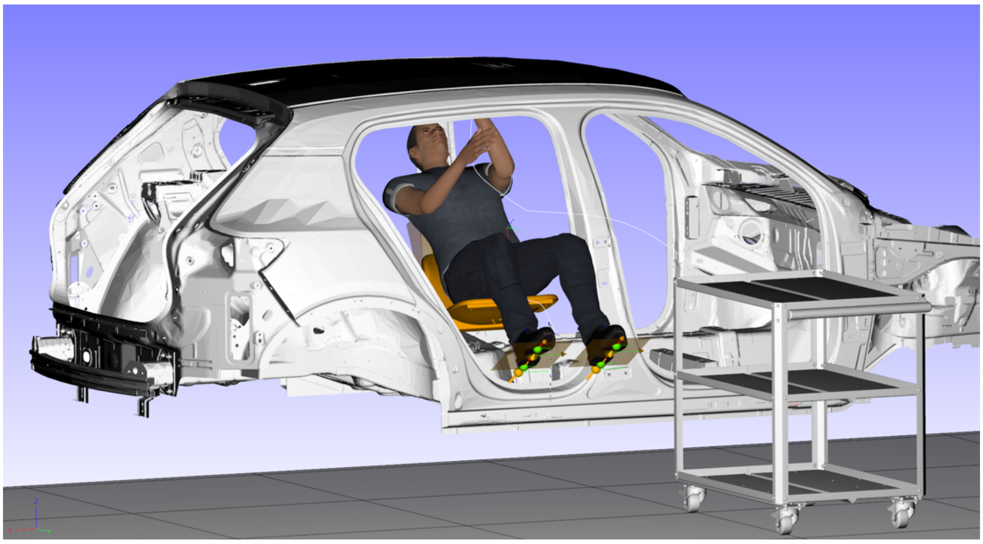

Figure 4-6: Improved posture of the manikin from task 1 proposed by Lars-Ola Bligård and Puranjay Mugur

Figure 4-6 illustrates the enhanced posture of the manikin in Task 1, as proposed by Lars-Ola Bligård and Puranjay Mugur. Initially, the ergonomic score was 8; following the improvements, it has been reduced to 7.

Conversely, Dan Lämkull and Maciej Zdrodowski advocated for maintaining the standing position. Their key suggestions included modifying the grip of the handle to a pinch grip and employing both hands for the task. Additionally, they recommended lowering the car slightly to alleviate the need for the manikin to maintain elevated shoulders—a position that increases the REBA ergonomic score and potentially leads to strain.

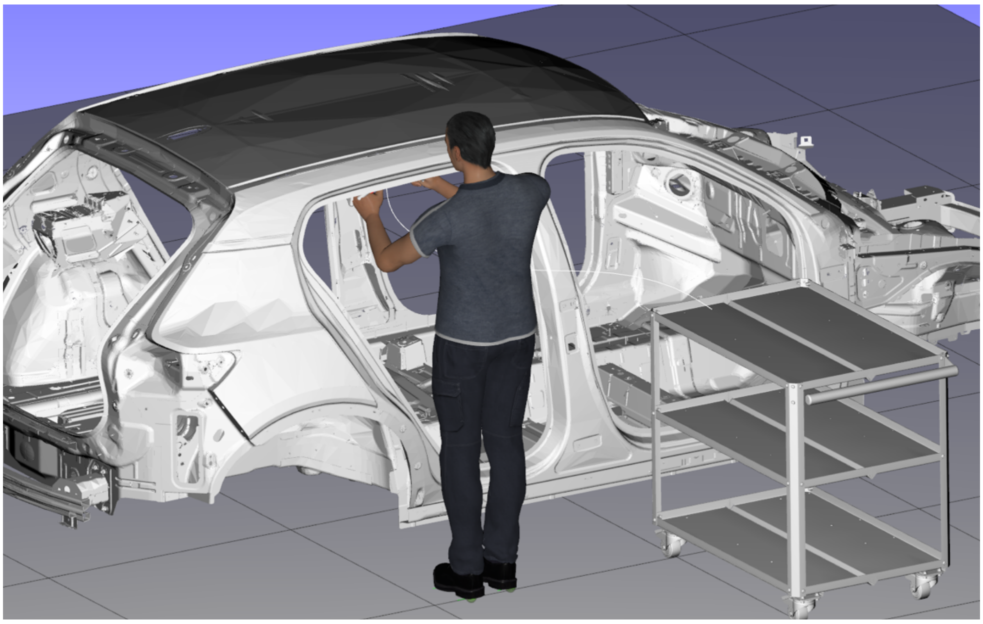

Figure 4-7: Improved posture of the manikin from task 1 proposed by Dan Lämkull and Maciej Zdrodowski

Figure 4-7 displays the improved posture for Task 1 as proposed in Experiment 2 by Dan Lämkull and Maciej Zdrodowski. The ergonomic score was initially 8, which has been significantly reduced to 4 following the improvements.

In both sets of suggestions, the primary ergonomic improvements were proposed during the first phase of the task assessment. Subsequent phases two and three were utilized to confirm initial discussions or to introduce minor modifications while retaining the core improvement strategies suggested earlier.

TASK 2 – MUDGUARD

In both Experiment 1 and Experiment 2, despite no communication between the groups, both sets of ergonomists independently arrived at the same suggestion for improving the task: elevating the car to a height of 900mm from the floor. This adjustment would prevent the manikin from having to bend its back or flex its legs excessively, and it would also provide greater control over avoiding accidental contact with the car chassis during the assembly process.

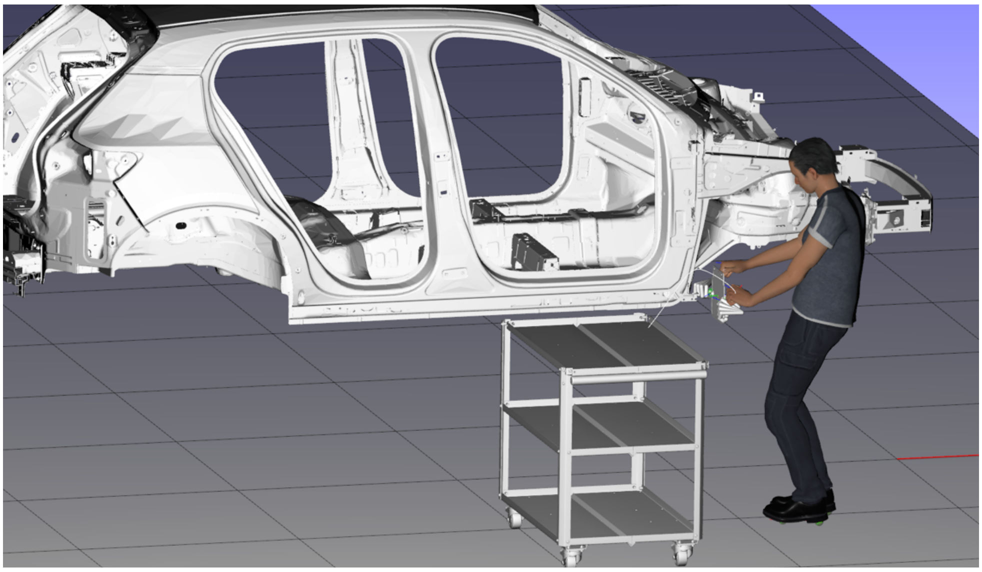

Figure 4-8: Improved posture of the manikin from task 2 proposed by all ergonomic experts

Figure 4-8 presents the improved posture for Task 2 as recommended by all the ergonomic experts across both experiments. Originally, the ergonomic score was 9, but it has been effectively reduced to 4 after the improvements.

TASK 3 – CABLE

Similar to Task 2, both groups from Experiment 1 and Experiment 2 concluded that the best ergonomic improvement for Task 3 involved elevating the car. However, there was a slight variation in their proposals regarding the optimal height: Lars-Ola Bligård and Puranjay Mugur suggested raising the car to 900mm from the floor, aligning with their previous recommendation, while Dan Lämkull and Maciej Zdrodowski recommended a slightly lower elevation of 700mm.

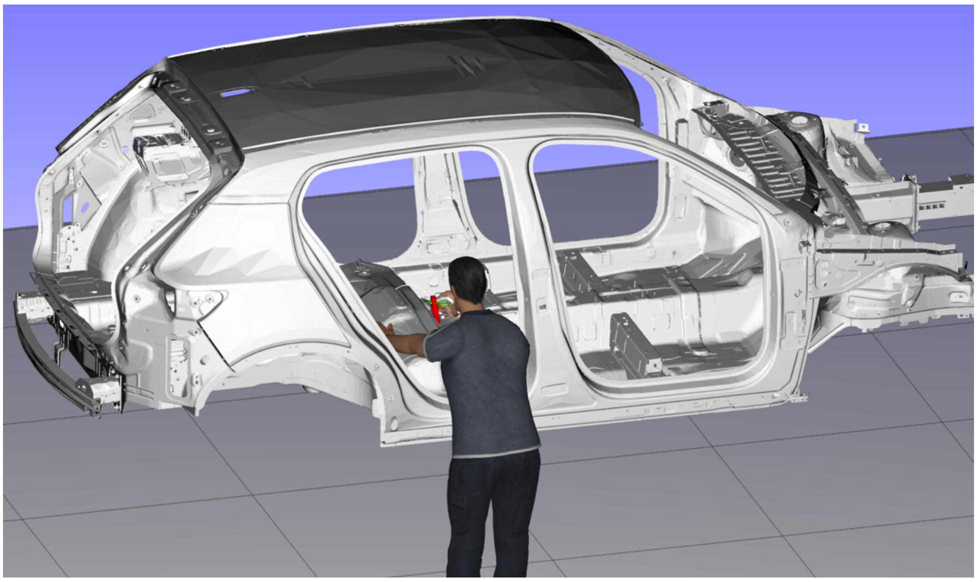

Figure 4-9: Improvement of the posture of the manikin from task 3 proposed by Lars-Ola Bligård and Puranjay Mugur

Figure 4-9 depicts the improved posture of the manikin in Task 3, as proposed by Lars-Ola Bligård and Puranjay Mugur. The initial ergonomic score was 11, which was reduced to 8 after the proposed improvements.

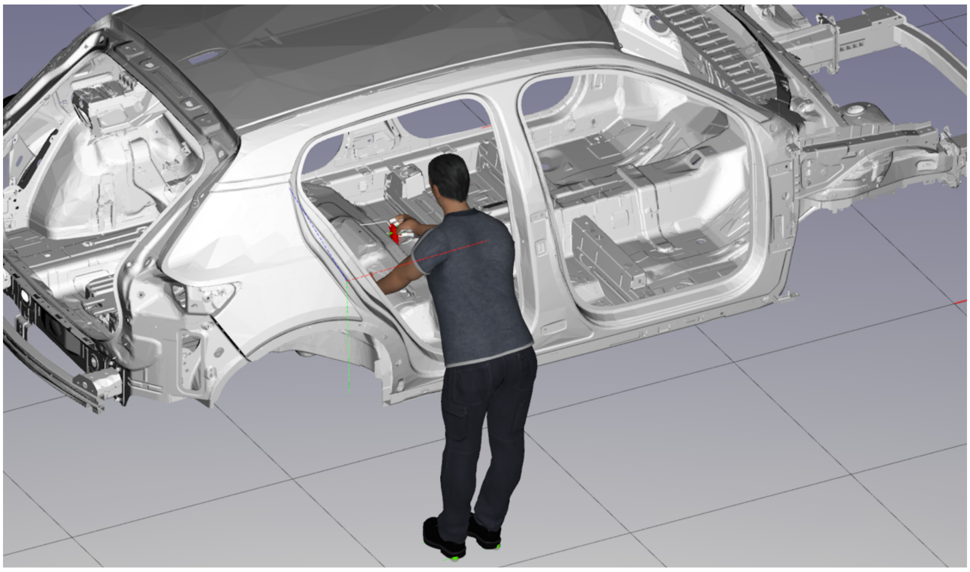

Figure 4-10: Improved posture of the manikin from task 3 proposed by Dan Lämkull and Maciej Zdrodowski

Figure 4-10 showcases the improved posture for Task 3 as proposed in Experiment 2 by Dan Lämkull and Maciej Zdrodowski. The initial ergonomic score of 11 has been significantly reduced to 6 following the improvements. The following table 4-2 displays the ergonomic scores for all tasks, before and after improvements.

Table 4-2: Ergonomic scores obtained in the improvement process of all tasks

REBA ERGONOMIC SCORE	TASK 1 - HANDLE		TASK 2 - MUDGUARD		TASK 3 - CABLE	
	EXP 1	EXP 2	EXP 1	EXP 2	EXP 1	EXP 2
BASE SCENE	8	8	9	9	11	11
IMPROVED SCENE	7	4	4	4	8	6

The ergonomic specialists provided an initial improvement during Phase 1, and subsequent exposure to the same task across different platforms did not lead to changes in their decisions. Instead, it reinforced their confidence in their chosen improvement. This effect likely stems from the differences in how environments are experienced in 2D versus 3D. In a 2D environment, such as CAD models, scales can be misinterpreted, but viewing these models in 3D within VR settings provided the participants with a clearer understanding and greater assurance. Additionally, the ability to mimic the postures and the proposed improvements directly within the VR environment allowed the participants to experience, to a certain extent, how operators would feel while performing the tasks. This hands-on interaction further solidified their confidence in the efficacy of their proposed improvements.

5. DISCUSSION

The findings of this thesis provide a comprehensive view of the impact and effectiveness of multi-user VR in ergonomic assessments within manufacturing environments. By integrating literature reviews, expert interviews, and practical validation case studies, this work offers insights into how VR technology can be leveraged to improve ergonomics and collaboration in industrial settings. This discussion section explores the implications of these findings and suggests areas for further research.

5.1. Methodology

This section explores the methodologies utilized in our study, including the literature review, the expert interviews, and a validation case study. Each method was designed to assess the impact of the VR technology on ergonomic assessments effectively, highlighting how these approaches collectively reinforce our findings and address our research questions.

5.1.1. Literature Review

The literature review aimed to establish a foundational understanding of the current state of VR technology in ergonomic assessments, identifying prevalent issues, technological advancements, and gaps in existing research. 23 papers were reviewed using databases like Scopus and Google Scholar. The review covered a wide range of topics within VR applications in ergonomics, providing a thorough background for the study. The findings from the literature review directly informed the design of the interview questions and helped in the structure of the validation case study.

The literature review, while essential to the foundation of this thesis, encountered several limitations that may have impacted its breadth and accuracy. First, the rapid pace of technological advancement in VR means that some of the research reviewed might already be outdated. This fast evolution requires continual updates to the literature to ensure that the most recent technologies and theories are considered.

Second, the scope of the literature review was constrained by the limited number of relevant research papers available. Despite efforts to comprehensively cover our thesis topic and respond to the research questions, only 23 papers were reviewed. This limitation could be due to the relatively new application of VR in ergonomic assessments, suggesting that the body of research is still expanding. Additionally, the strict timeline of the master's program, which required the thesis to be completed within 16 weeks, significantly limited the time available for a more extensive literature search. This restriction might have prevented a deeper exploration of existing research or the discovery of a broader range of sources.

Furthermore, the literature review was conducted using a semi-systematic or thematic approach rather than a fully systematic one. While this method allowed for a focused exploration of themes directly relevant to our research questions, a more systematic review could potentially reveal additional insights and provide a more structured compilation of data, possibly highlighting trends or contradictions in the research that were not captured in this review. Also, the thematic analysis relies heavily on the researcher's interpretation, which can vary significantly between individuals. This subjective element might influence the conclusions drawn from this thesis.

5.1.2. Interview Study

The Interview study helped us in getting Qualitative data or insights from specialists in this field. A group of academicians and industry professionals who are highly knowledgeable in the field of either ergonomics or VR technologies or both participated in semi-structured interviews. Both, academicians and industry professionals were interviewed to get different viewpoints. This study helped us more insights with respect to our thesis topic which not only helped us in getting answers to our research questions but also helped us in planning the experiments for the validation case study

There are also a few limitations to our study. Qualitative interviews inherently involve interactions that can introduce subjective biases. While semi-structured interview method facilitated in-depth exploration of the participants' perspectives on VR in ergonomic assessments, it's important to consider that a structured interview approach might have led to different conclusions. Moreover, the study's limited number of interviewees may not fully capture the diverse perspectives within the broader community of ergonomics and VR experts. This restricted sample size diminishes the ability to generalize findings across the field, as the views and experiences of a few individuals may not encompass the diverse opinions and practices present in the wider professional community.

Another significant limitation stems from the geographical and institutional homogeneity of the interviewees. All academic experts were from Chalmers University of Technology and the University of Skövde, while all industry experts were employed by Volvo Cars, Volvo Trucks, and IPS—all based in Sweden. This lack of geographical diversity means that the findings may predominantly reflect the industrial and academic contexts of Sweden. Such geographic concentration can introduce biases related to national policies, corporate cultures, and educational systems, which might not be applicable or replicable in other countries or regions. Furthermore, the concentration of experts from specific institutions and companies may lead to an over-representation of institutional practices or philosophies. For example, these institutions may have specific approaches to VR and ergonomics that do not necessarily align with global practices or emerging trends outside of Sweden.

5.1.3. Validation Case

The purpose of this study was to empirically evaluate the effectiveness of VR technologies in ergonomic assessments through controlled experiments. In the experiments, ergonomic experts evaluated the static posture for three tasks across various platforms—Desktop Applications, Single-User VR, and Multi-User VR—and provided recommendations for improvements. This study aimed to explore the advantages and limitations of Multi-user VR compared to Single-user VR and Desktop Applications, enabling us to determine the most suitable platform for specific scenarios.

This experiment presents several limitations. Firstly, the experiments were conducted in a controlled environment focused on specific tasks, potentially overlooking the complexities of real-world manufacturing settings. Additionally, the limited number of experiments, constrained by the availability of only four ergonomic experts, might lead to data that could be a bit biased or skewed.

5.2. Results

This section explores the results gathered from detailed studies including the literature review, the expert interviews, and the validation case study. The combination of these insights offers a clear framework for understanding the impacts of VR technology on ergonomic assessments, particularly in multi-user environments.

5.2.1. Literature Review

The literature review primarily focused on the benefits, limitations, and potential improvements of current VR technologies, with some attention given to Multi-user VR. It included examples of VR's application in ergonomics, such as General Motors' use of VR for complex assemblies and operations [30]. Virtual workplace prototypes facilitate safe and cost-efficient testing of human-machine interactions by simulating potential hazards in a virtual environment, thereby negating the need for physical models and significantly lowering risks and costs [2].

However, the review also identified significant challenges within VR technology. Solutions were found for some issues, such as tracking body movements using MoCap or IK [44][45], while others remain unresolved. Notably, the review pointed out the lack of satisfactory haptic feedback [2] and ergonomic issues with VR headsets [39][40][41]. Y. Chen et al. (2023) suggested several strategies for future enhancements in the ergonomics of VR headsets [39]. Moreover, the integration of AR and MR technologies could complement VR systems by providing additional layers of information and interaction that are currently unattainable in purely virtual environments [32][42].

The main findings that we got from Multi-user VR was that it allows designers and ergonomists to collaborate in a three-dimensional environment, where they can join operators performing tasks. Using software like IPS IMMA, motions are tracked, and ergonomic scores are evaluated in real-time. This enables both ergonomists and designers to assess and modify workstation designs directly within the virtual world [35].

The review firmly establishes that while VR and Multi-user VR hold significant promise for advancing ergonomic assessments, realizing this potential fully requires overcoming existing technological challenges. Future research should focus on developing more sophisticated VR systems that offer enhanced realism and user interaction, support wider inclusivity, and integrate seamlessly with other digital tools to provide a comprehensive ergonomic assessment toolkit. This advancement will not only optimize ergonomic designs but also significantly enhance the quality of workplace health and safety across various industries.

5.2.2. Interview Studies

The interview study, which draws on the experiences and knowledge of subject matter experts, clarifies several important aspects of incorporating AR and VR into ergonomic assessments. The use of these technologies, however inventive and advantageous in diverse circumstances, offers a complex range of advantages and obstacles that influence their acceptance and effectiveness in professional environments.

Experts such as Francisco Garcia emphasize the careful use of VR in ergonomic assessments, pointing out the necessity of choosing the appropriate technology based on the specific needs of the task at hand. This approach is crucial for determining whether to use VR or AR. The decision to adopt a particular technology should be strategic, tailored to the unique demands of the assessment rather than adopting a universal solution. This consideration is especially important in ergonomic assessments, where the characteristics of the task heavily influence which technology is most suitable [47].

The economic and operational benefits of using VR are evident. Dan Högberg and other experts have noted that the decrease in costs associated with physical prototypes and the faster design processes contribute to significant advantages in adopting VR technologies. These benefits go beyond simple cost savings, influencing environmental sustainability and enhancing the flexibility of operations, which are vital for companies aiming to stay competitive [48].

Despite these advantages, the technology also introduces significant challenges, particularly in terms of collaboration and usability. As Cecilia Berlin points out, the current VR systems often lack the capability for effective multi-user collaboration due to limitations in body and hand tracking accuracy, FoV, and the physical comfort of using VR headsets. These factors not only affect the user experience but also the fidelity and outcomes of the ergonomic assessments conducted within these virtual environments [36].

The fidelity of simulations in VR environments is another critical concern. The inability to simulate accurate weight sensations and physical interactions with objects can severely limit the utility of VR for ergonomic assessments, as noted by multiple experts. This highlights the need for continual technological enhancements to bridge the gap between virtual simulations and real-world dynamics [48].

Moreover, as Volvo Cars representatives pointed out, concerns about cybersecurity and data privacy offer serious obstacles to the widespread use of VR technologies. Companies are hesitant to implement systems that demand exchanging confidential data, which emphasizes the necessity for secure, legal VR solutions made to meet business requirements [50].

Looking forward, the potential for innovations such as multi-user VR systems, biomechanical solutions for simulating physical interactions, and AI-driven motion prediction is promising. These advancements could address many of the current limitations, enhancing both the realism and collaborative potential of VR in ergonomic assessments. The development of dynamic ergonomic scoring systems and asymmetric collaboration models, as anticipated by Francisco Garcia, Dan Högberg and Volvo Cars representatives, could revolutionize how ergonomic assessments are conducted, making them more adaptive and tailored to specific workplace conditions [47][48][50].

This interview study offers a detailed perspective on the role of VR and AR in ergonomic assessments, highlighting the transformative potential of these technologies alongside their existing challenges. As companies and technology providers work through these issues, the future of VR in ergonomics is set for significant developments, driven by both technological progress and a deeper understanding of their real-world applications. The continuous dialogue between ergonomic experts and technology developers will be essential in shaping the next generation of ergonomic assessment tools, ensuring they are not only technologically sophisticated but also comply with the practical, operational, and ethical standards of the workplace.

5.2.3. Validation Case

The validation case study provides insightful data on the effectiveness and efficiency of various platforms—desktop applications, single-user VR, and multi-user VR—in conducting ergonomic assessments. The qualitative and quantitative data gathered through semi-structured interviews and empirical analysis offer a comprehensive understanding of how each platform serves the specific needs of ergonomic evaluations.

The findings show that VR technologies are clearly preferred for ergonomic evaluations. VR technologies are preferred because of their improved collaborative features and immersive experiences, which can lead to more intuitive and informed decision-making processes. Regarding the collaborative features of multi-user VR, opinions among ergonomic specialists vary. Some believe that while not essential, these features are beneficial, whereas others suggest that while multi-user VR may not be necessary for simpler tasks, it proves advantageous for more complex assessments.

Despite these benefits, several drawbacks were noted with multi-user VR, such as the requirement for transparency modes to avoid user collisions and the incorporation of more haptic feedback. These technological developments are required to get over VR platforms' present drawbacks and provide a completely immersive and engaging experience. It is important for these issues to be resolved so that VR technology can progress to the point where it can smoothly combine real-world and virtual interactions.

Despite having the least immersive experience of all the applications, the desktop version is nevertheless useful, especially for simple or preliminary ergonomic studies. This platform's familiarity and ease of use make it an excellent choice for those who are less accustomed with VR technology or for scenarios where more complex interactive capabilities are not required.

The case study's conclusions emphasize the significance of continuous technological development and user-centered ergonomic tool design. There is a bright future for more thorough and useful ergonomic evaluations as VR technologies advance. The precision and efficacy of ergonomic examinations can be significantly increased by the development of VR platforms with real-time ergonomic feedback, sophisticated haptic systems, and better integration of physical aspects.

Moreover, the preference for multi-user VR suggests the possibility of remote collaborative ergonomic assessments, indicating a future in which geographical barriers are reduced and specialists from different locations can work together productively on ergonomic evaluations. This potential could significantly broaden the scope and significance of ergonomic evaluations, enabling high-quality ergonomic evaluation to be accessed anywhere in the world.

5.3. Future Work

To enhance future literature reviews, adopting a fully systematic review methodology, expanding the search to include more databases and journals, and potentially allocating more time to this phase of the research are recommended to ensure comprehensive and current coverage of the literature. Additionally, increasing the transparency of the selection criteria and interpretation methods could help address some of the subjective biases inherent in thematic analysis. These steps would aid in developing a more robust and wide-ranging understanding of the role of VR in ergonomic assessments.

To address the limitations in future research, expanding the pool of interviewees to include experts from diverse geographical locations and different industries would be beneficial. Including a broader range of academic institutions could help capture a wider array of research focuses and educational influences. These strategies would help overcome the potential biases and limitations inherent in the current study, providing a more robust and broadly applicable understanding of VR applications in ergonomics.

Other than that, in validation case, more amount of data will be very helpful. It would be more effective to have multiple ergonomists, each working with just one platform—desktop, single-user VR, or multi-user VR—instead of having one ergonomist handle all three. This method allows for clearer comparisons of how much time each platform takes and how much it improves ergonomic scores. Engaging a larger group of ergonomists to perform assessments would provide a broader range of data, contributing to a more detailed and potentially more generalizable conclusion regarding the optimal tools and techniques for ergonomic evaluations.

Due to current technological constraints, ergonomists have been limited to reviewing static postures. However, when advancements allow, it would be highly advantageous for ergonomists to evaluate entire simulations across all three platforms—Desktop

Applications, Single-user VR, and Multi-user VR—before proposing improvements. Additionally, it would be extremely beneficial if VR technology allowed us to fully utilize the software's functionalities. This would enable designers and ergonomists to collaboratively and efficiently optimize workplace designs for maximum ergonomic effectiveness.

Looking ahead, when these technologies evolve, it will be beneficial to simulate entire factory operations rather than just individual workstations. This expanded scope would allow ergonomists to enhance the ergonomic conditions across a whole factory setting while also monitoring the throughput. Such comprehensive simulations would provide clear insights into the direct relationship between workplace ergonomics

6. CONCLUSION

This master's thesis has critically evaluated the application of VR in ergonomic assessments, highlighting its potential to transform traditional ergonomic studies through digitalization. By integrating a comprehensive literature review, expert interviews, and empirical validation studies, this research underscores VR's dual role in enhancing ergonomic assessments and facilitating collaborative problem-solving in complex manufacturing settings.

Our findings illustrate VR's significant benefits in terms of cost-efficiency and time savings, particularly through the use of multi-user VR, which supports a more intuitive and collaborative approach to ergonomic evaluations. This contrasts with the persistent preference for desktop applications among users less familiar with VR technology. Despite its advantages, the research identified persistent challenges, including the need for more refined haptic feedback and a deeper integration of realistic interactions within VR environments.

Through systematic analysis, the thesis demonstrates that while multi-user VR fosters a better understanding of ergonomic issues, it also necessitates further technological advancements to fully leverage its capabilities. The ongoing requirement for improvements in VR technology, particularly in enhancing user experience and realism, points to a significant area for future research.

This thesis aimed to investigate the potential limitations and solutions associated with current VR technologies for ergonomic assessments, as encapsulated in RQ1. While we identified several limitations, not all challenges were resolved; however, we have outlined future directions to address some of these challenges effectively. In RQ2, we examined whether the integration of multi-user VR and simulation could improve the ergonomics of production environments or workstations. Our findings indicate that while multi-user VR may not be necessary for straightforward scenarios, it becomes invaluable in complex situations where collaboration is crucial.

In conclusion, this study not only contributes to our understanding of VR's application in ergonomic assessments but also sets the stage for future advancements. It calls for continuous innovation in VR technology to better meet the complex demands of modern manufacturing environments, thereby paving the way for more dynamic and effective ergonomic practices.

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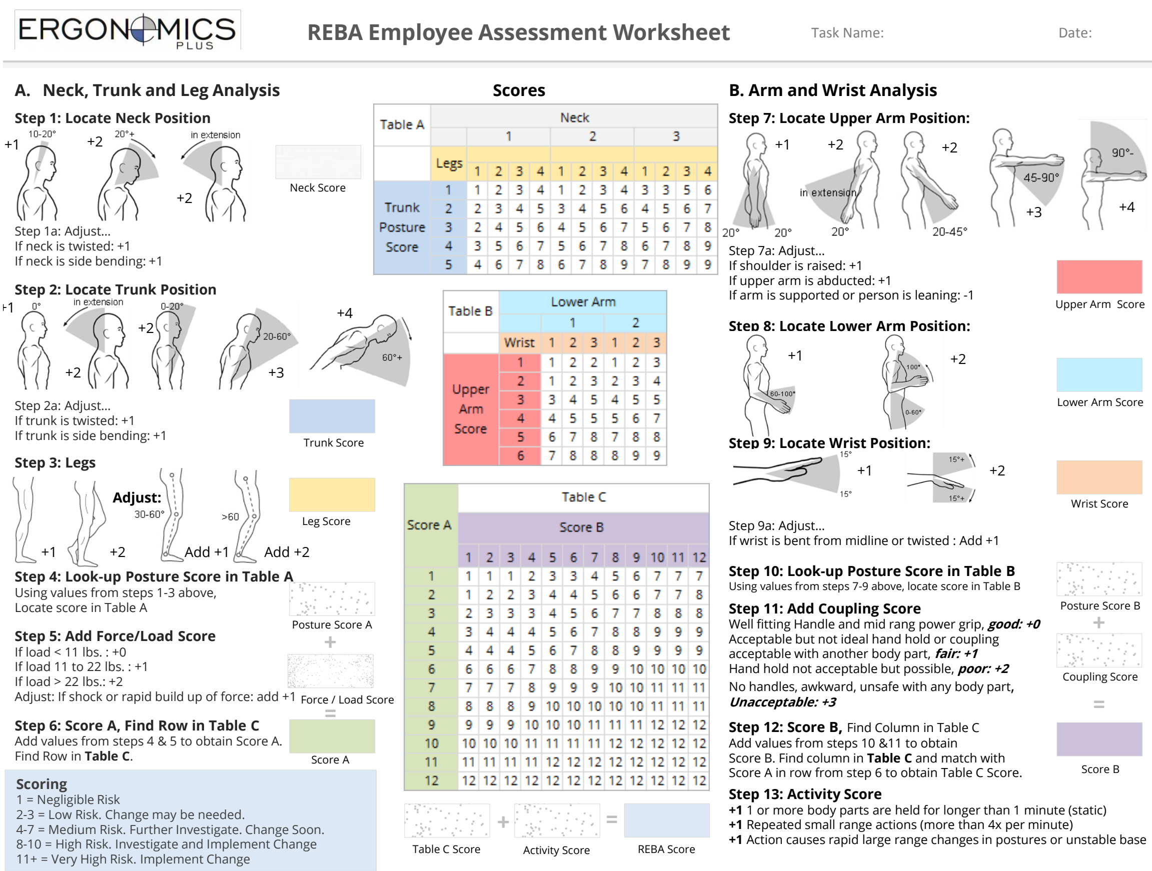
APPENDICES

A. Appendix – REBA



ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: Date:

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 (10-20°) +2 (20°+) +2 (in extension)

Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 (0°) +2 (in extension) +2 (0-20°) +3 (20-60°) +4 (60°+)

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 3: Legs

+1 +2 Adjust: Add +1 (30-60°) Add +2 (>60)

Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck 1				Neck 2				Neck 3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B		Lower Arm 1			Lower Arm 2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C

Score A	Score B 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score + Activity Score = REBA Score

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 (20° / 20°) +2 (in extension, 20°) +2 (20-45°) +3 (45-90°) +4 (90°-)

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 8: Locate Lower Arm Position:

+1 (60-100°) +2 (100°, 0-60°)

Lower Arm Score

Step 9: Locate Wrist Position:

+1 (15°) +2 (15°+)

Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B

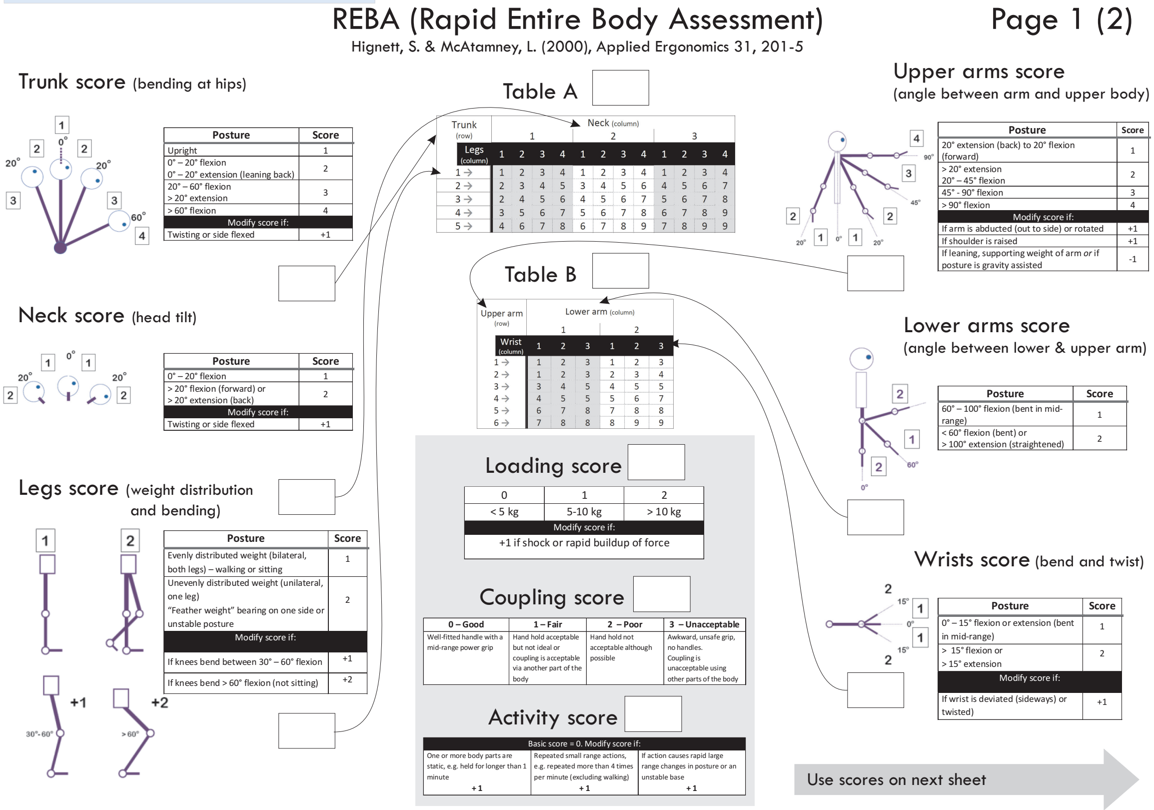
Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base



REBA (Rapid Entire Body Assessment) Page 1 (2)

Hignett, S. & McAtamney, L. (2000), Applied Ergonomics 31, 201-5

Trunk score (bending at hips)

Posture	Score
Upright	1
0° – 20° flexion 0° – 20° extension (leaning back)	2
20° – 60° flexion > 20° extension	3
> 60° flexion	4
Modify score if:	
Twisting or side flexed	+1

Neck score (head tilt)

Posture	Score
0° – 20° flexion	1
> 20° flexion (forward) or > 20° extension (back)	2
Modify score if:	
Twisting or side flexed	+1

Legs score (weight distribution and bending)

Posture	Score
Evenly distributed weight (bilateral, both legs) – walking or sitting	1
Unevenly distributed weight (unilateral, one leg) "Feather weight" bearing on one side or unstable posture	2
Modify score if:	
If knees bend between 30° – 60° flexion	+1
If knees bend > 60° flexion (not sitting)	+2

Table A

Trunk (row)	Neck (column) 1				2				3			
Legs (column)	1	2	3	4	1	2	3	4	1	2	3	4
1 →	1	2	3	4	1	2	3	4	1	2	3	4
2 →	2	3	4	5	3	4	5	6	4	5	6	7
3 →	2	4	5	6	4	5	6	7	5	6	7	8
4 →	3	5	6	7	5	6	7	8	6	7	8	9
5 →	4	6	7	8	6	7	8	9	7	8	9	9

Table B

Upper arm (row)	Lower arm (column) 1			2		
Wrist (column)	1	2	3	1	2	3
1 →	1	2	3	1	2	3
2 →	1	2	3	2	3	4
3 →	3	4	5	4	5	5
4 →	4	5	5	5	6	7
5 →	6	7	8	7	8	8
6 →	7	8	8	8	9	9

Loading score

0	1	2
< 5 kg	5-10 kg	> 10 kg
Modify score if:		
+1 if shock or rapid buildup of force		

Coupling score

0 – Good	1 – Fair	2 – Poor	3 – Unacceptable
Well-fitted handle with a mid-range power grip	Hand hold acceptable but not ideal or coupling is acceptable via another part of the body	Hand hold not acceptable although possible	Awkward, unsafe grip, no handles. Coupling is unacceptable using other parts of the body

Activity score

Basic score = 0. Modify score if:		
One or more body parts are static, e.g. held for longer than 1 minute **+1**	Repeated small range actions, e.g. repeated more than 4 times per minute (excluding walking) **+1**	If action causes rapid large range changes in posture or an unstable base **+1**

Upper arms score (angle between arm and upper body)

Posture	Score
20° extension (back) to 20° flexion (forward)	1
> 20° extension 20° – 45° flexion	2
45° - 90° flexion	3
> 90° flexion	4
Modify score if:	
If arm is abducted (out to side) or rotated	+1
If shoulder is raised	+1
If leaning, supporting weight of arm or if posture is gravity assisted	-1

Lower arms score (angle between lower & upper arm)

Posture	Score
60° – 100° flexion (bent in mid-range)	1
< 60° flexion (bent) or > 100° extension (straightened)	2

Wrists score (bend and twist)

Posture	Score
0° – 15° flexion or extension (bent in mid-range)	1
> 15° flexion or > 15° extension	2
Modify score if:	
If wrist is deviated (sideways) or twisted)	+1

Use scores on next sheet

B. Appendix – interview study semi-structured interviews

Interview to Francisco Garcia

<table>
<tr><td rowspan="2">FRANSISCO GARCIA RIVERA
francisco.garcia.rivera@his.se
XR specialist, researcher</td><td>Date: 23/2/2024 from 13:00 till 14:30</td></tr>
<tr><td>• PhD Student VR and Product design and ergonomics (Skövde University)</td></tr>
<tr><td colspan="2">• BACHELOR’S DEGREE: Mechanical engineering
• MSC: Intelligent Automation, Logistics, Materials and Supply Chain Management
• PhD candidate</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://www.his.se/mot-hogskolan/medarbetare/francisco.garcia.rivera/
- https://www.linkedin.com/in/francisco-garc%C3%ADa-rivera-86a90a173/?originalSubdomain=se

INTERESTNG PAPERS
- Improving the efficiency of virtual-reality-based ergonomics assessments with digital human models in multi-agent collaborative virtual environments à https://his.diva-portal.org/smash/record.jsf?pid=diva2%3A1697457&dswid=6065
- The Schematization of XR Technologies in the Context of Collaborative Design à https://his.diva-portal.org/smash/record.jsf?pid=diva2%3A1655442&dswid=8678</td></tr>
<tr><td colspan="2">QUESTIONS TO ASK
1. What are the potential benefits of collaboration in designing a factory using multi-user VR comparing it to the non-collaborative single user VR?
The potential benefits include a better sense of scale, role-based interactions, and involving different stakeholders in the design process. However, challenges such as friction due to multiple apps and perceived user reluctance may arise.

2. What are some limitations found on actual single-user VR (any kind of assessment ergonomic)? Can multi-user VRs solve these limitations?
Single-user VR limitations vary depending on the task and situation, especially in ergonomic assessments. Multi-user VR may address some of these limitations through a more collaborative approach.

3. What are the limitations of multi-user VR environments for ergonomic assessments?
Limitations include the need for a robust tracking system, particularly for capturing postures accurately.

4. Does multi-user VR lead to faster VR assessment work, and is it advantageous for designing a factory?
While multi-user VR may involve more stakeholders in the design process, it may not necessarily result in faster assessment work or be advantageous for factory design, as the primary goal is collaboration rather than simultaneous task execution.</td></tr>
</table>

5. **How do you replicate or simulate the experience of weight and other physical properties within your VR systems to enhance realism and efficacy in multi-user assessments?**

Technologies like motion capture and improved tracking systems can enhance realism and efficacy in multi-user assessments, without inherent limitations in simulating weight sensation.

6. **Do inaccurate ergonomic scores from software cause issues later, and how reliable are these scores?**

Ergonomic scores from software are approximations based on observational methods, which may not always be accurate. Although precise motion capture can help standardize evaluations, they still rely on observation.

7. **What problems related to ergonomics can still occur after designing a factory in VR, especially concerning postures?**

Challenges may arise regarding task knowledge transfer and difficulties in covering certain postures accurately using VR.

8. **What are the ergonomic benefits of multi-user VR assuming similar software graphics to single-user VR?**

Benefits include improved collaboration and involvement of various stakeholders in the design process.

9. **Are there specific scenarios or tasks where multi-user VR is particularly advantageous or disadvantageous?**

Advantages include collaborative design tasks, while disadvantages may arise in scenarios requiring simultaneous task execution.

10. **What are the cost implications of integrating VR into ergonomics assessments, and how can those be mitigated?**

Cost implications vary, but advancements in technology and wider adoption may lead to cost reductions over time.

11. **Can you provide examples of companies using multi-user VR and the improvements observed in ergonomics and quality?**

Companies like BMW, Volvo Trucks, CEVT, Volkswagen, and Kia have utilized multi-user VR for training, design, and aesthetic improvements.

12. **What quantitative data is used to assess the efficiency of current ergonomic methods?**

Quantitative data varies between companies and may include key performance indicators (KPIs) specific to each organization.

13. **In what cases can AR be used instead of VR for ergonomic assessment, and is multi-user AR better than multi-user VR?**

AR may be preferable for tasks involving modifications or analysis of existing environments, with camera-based AR like HoloLens 2 considered better for such purposes.

14. **Is it economically feasible to test with VR using average heights, and how can AR be utilized before designing a factory?**

Testing with VR using average heights may be economically feasible, and AR can be used before designing a factory for assessing existing conditions.

15. **How do you anticipate the evolution of VR technology impacting multi-user VR assessment in the next 5-10 years?**

The evolution of VR technology may improve software usability and increase adoption, but the direction and extent of these changes remain uncertain.

16. **What advancements in VR technology are needed to improve its effectiveness for ergonomics assessments?**

Advancements such as improved body and hand tracking are needed to enhance effectiveness for ergonomics assessments.

17. **How do you envision AI and machine learning enhancing VR-based ergonomic assessments?**

AI and machine learning could enhance VR-based ergonomic assessments by improving natural behaviour modelling, although this isn't directly related to VR technology itself.

18. **Are there any regulatory or safety considerations when using VR for ergonomic assessments in production environments?**

Regulatory and safety considerations include ensuring user comfort and safety, as VR systems become lighter and more comfortable over time. Additionally, advice is given regarding headset purchases and committing to the purpose of the thesis.

CONCLUSIONS OF THE MEETING

- The collaboration benefit will give a **good sense of scale, role-based interactions, and ability to involve different stake holders**. (Asymmetric XR collaboration)
- There's **friction** in the use of this technology for this purpose, due to the time that needs to be spent to know to get the workflow.
- Need to **find the real value** of implementing VR in this kind of tasks.
- The multi-user VR for ergonomic assessments is more focused in the **collaboration** rather than in the simultaneous task execution.
- Simulation of **weight sensation** is a problem that the VR technology has nowadays.
- Ergonomic methods give out scores out of **observational methods**, therefore they may be inaccurate sometimes if something has not been considered or not seen.
- There is no competition in using **VR or AR**, one is better than the other when doing a certain task, and the other way round. AR has better sense of reality, and you can interact with the physical world, on the other side, VR is better when working with things that have not been done yet.
- The **evolution of the multi-user VR technology** depends on software providers, the more they work on it, the easier it will get, and more people will use it and overtime it will improve.
- Improvement in **body and hand tracking** needs to be done to improve ergonomic assessments with VR technology.

STATED LIMITATIONS:

- Usability Friction
- VR is not for every task (value)
- Weight sensation
- Ergonomic scores fidelity
- Body and hand tracking
- Comfort of VR headsets

Interview to Dan Högberg

<table>
<tr><td>DAN HÖGBERG
dan.hogberg@his.se
Professor at University of Skövde</td><td>Date: 01/03/2024 from 13:00 till 15:00

• Prof. Human centric production and ergonomics</td></tr>
<tr><td colspan="2">• BACHELOR'S DEGREE: Product design Engineering
• MSC DEGREE: Engineering Design
• PHD: Deign Ergonomics
• He has been a lecturer and a professor at University of Skövde for 23 years</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://www.his.se/mot-hogskolan/medarbetare/dan.hogberg/
- https://www.linkedin.com/in/dan-h%C3%B6gberg-814a9223/
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- Using VR and Smart Textiles to Assess the Design of Workstations à https://his.diva-portal.org/smash/record.jsf?pid=diva2%3A1510514&dswid=-6346
- The Use and Usage of VR Technologies in Planning and Implementing New Workstations à https://his.diva-portal.org/smash/record.jsf?pid=diva2%3A1464503&dswid=5657</td></tr>
</table>

QUESTIONS TO ASK

1. **What are the potential benefits of collaboration in designing a factory using multi-user VR comparing it to the non-collaborative single user VR?**

Bringing different stakeholders into the assessment process enhances evaluations through rapid feedback and diversified perspectives.

2. **What are some limitations found on actual single user VR (any kind of assessment not only ergonomic)? Multi-user VR will solve these limitations?**

The inability to collaborate in single user VR hinders effective communication and cooperation among stakeholders. Multi-user VR addresses this limitation by enabling real-time collaboration and interaction.

3. **What are the limitations of multi-user VR environments for ergonomic assessments?**

Multi-user VR environments must accurately simulate human interactions to be effective, presenting challenges in replicating realistic interactions between virtual entities.

4. **If multi-user VR is used, we think that the VR assessment work can be done faster, is it like that? If so, will it be advantageous while designing a factory?**

Yes, multi-user VR facilitates faster assessments not only due to simultaneous evaluations but also because of streamlined communication among stakeholders. This advantage can significantly benefit factory design by accelerating decision-making processes and reducing time and cost.

5. **Given the inherent limitation of VR environments in simulating the sensation of weight, I am interested in understanding the approaches and technologies currently employed to address this challenge. How do you replicate or simulate the experience of weight and other physical properties within your VR systems to enhance realism and efficacy in multi-user assessments?**

Replicating weight in VR is challenging, but biomechanical solutions involve integrating object weight into the system and calculating its effects on virtual human bodies, enhancing realism and efficacy in assessments.

6. **After designing a factory in VR, what problems can still occur related to ergonomics? (Which postures are most difficult to cover using VR)**

Finger movement poses challenges in VR motion tracking systems, potentially leading to issues related to ergonomics despite designing the factory in VR.

7. **What are the ergonomic benefits that will be there with multi-user VR assuming that the software graphics will be the same as single user VR?**

Different stakeholders collaborating in multi-user VR environments can enhance ergonomic assessments through diverse perspectives and real-time feedback, irrespective of software graphics similarities with single user VR.

8. **Are there specific scenarios or tasks where multi-user VR is particularly advantageous or disadvantageous?**

Multi-user VR is advantageous in tasks requiring diverse stakeholder input and real-time collaboration. However, its effectiveness may vary depending on the specific ergonomic assessment tasks undertaken.

9. **What are the cost implications of integrating VR into ergonomics assessments, and how can those be mitigated?**

The cost implications of VR integration into ergonomics assessments vary across companies, as do the potential uses of VR tools. Clear understanding and efficient utilization of VR technology can help mitigate associated costs.

10. **Has multi-user VR been used in some other company, can you tell us about the improvement in ergonomics, quality etc.?**

Companies like CEVT and BMW have utilized multi-user VR, leading to improvements in ergonomics, time efficiency, cost reduction, and environmental impact, as seen through platforms like IPS IMMA and NVIDIA's Omniverse.

11. **What is the quantitative data that is calculated to see the efficiency of the current ergonomic methods?**

Quantitative data to evaluate different ergonomic methods may be different between different companies, we should ask directly to companies, not professors.

12. **In which cases can AR, be used instead of VR for ergonomic assessment (Is multi-user AR better than multi-user VR, for both renovating and designing a factory)**

When designing a non-existing factory, AR cannot be used, so for theses cases VR is the most adequate tool to be used, while if the need is to modify an existing workstation, AR may be more appropriate due to the fact that you can actually see and feel the real thing, therefore it´s much easier to understand the problems that may occur and address the assessment better.

13. **What advancements in VR technology are needed to improve its effectiveness for ergonomics assessments?**

Advancements in biomechanics, AI-driven motion prediction for virtual entities, accuracy enhancement, and responsiveness improvement are essential for enhancing VR effectiveness in ergonomics assessments.

14. **How do you envision the role of AI and machine learning in enhancing VR-based ergonomic assessments?**

AI and machine learning can play crucial roles in predicting virtual entity movements, ensuring accurate representation of human bodies, and addressing environmental factors affecting ergonomic assessments, thus enhancing VR-based assessments.

15. **How much is ManusVR used in companies and research nowadays?**

ManusVR is not extensively utilized in companies and research currently, primarily serving motion capture purposes rather than active VR movement.

16. **Can ergonomic assessments be compared? If so, how can they be compared?**

Comparing ergonomic assessments requires qualitative data due to significant variations between companies and their specific ergonomic needs.

CONCLUSSIONS OF THE MEETING

- It´s crucial for the multi-user VR tool for ergonomic assessments to really be useful, that the **interactions between manikins are as natural and close to real human interactions**. If not, the problems in communication and understanding of the situations will reduce the engagement and utility of the whole thing.
- Other benefits apart from the collaboration ability of multi-user VR environments for ergonomic assessments, are the **cost reduction** for the company by doing the assessments properly and therefore fewer problems to be found in the future. The **time gained** by have real-time interaction between the different stake holders that enables the assessment to be quicker. Finally, the **environmental load** reduction of not having to perform a real simulation of the assessment.
- **Bio-mechanical solutions** can be implemented to solve the absence of **weight sensation** for ergonomic assessments, whereby putting the weight of the object that is being lifted or interacted with, the system will calculate the effects on virtual human manikins, and from that give an ergonomic score that considers the weight sensation problem.
- Advancements in **biomechanics, AI-driven motion prediction** for virtual entities, **accuracy enhancement and responsiveness** are needed for the multi-user VR for ergonomic assessments to improve.

STATED LIMITATIONS:

- Inability to collaborate (single-user VR)
- Weight sensation
- Finger and hand movements in VR
- External factors like heat, lighting
- Accuracy enhancement
- Responsiveness

Interview to Cecilia Berlin

<table>
<tr><td rowspan="2">CECILIA BERLIN
cecilia.berlin@chalmers.se
Associate Prof. at Chalmers University of Technology</td><td>Date: 04/03/2024 from 10:30 till 12:30</td></tr>
<tr><td>• Prof. Human design and factors (Chalmers)</td></tr>
</table>

- MSC's: Industrial Design Ergonomics
- PHD: Ergonomics Evaluation on Companies
- Associate professor at Chalmers University of Technology
- **Certified European ergonomist**
- She has won several prices for her research being the last one in 2019 "The Levi Prize"

LINKS OF INTEREST
- https://research.chalmers.se/person/berlin
- https://sv.wikipedia.org/wiki/Cecilia_Berlin
- https://www.linkedin.com/in/cessie/?originalSubdomain=se

INTERESTNG PAPERS
- Book: Production Ergonomics à https://www.ubiquitypress.com/site/books/m/10.5334/bbe/
- Ergonomics of Office Work in a VR Environment: A State-of-the-art Literature Review à https://research.chalmers.se/en/publication/538254
- Production ergonomics evaluation - needs, procedures and digital human modelling tools à https://research.chalmers.se/en/publication/91919
- SIMTER: a Multi-Aspect Virtual Production System Evaluation Tool. à https://research.chalmers.se/en/publication/103286

QUESTIONS TO ASK

1. **What are the potential benefits of collaboration in designing a factory using multi-user VR comparing it to the non-collaborative single user VR?**

Basically, the live action evaluation and having direct feedback of other stake holders as they are evaluating the same thing, at the same time, from different points of view. It will also save time by the response time gained with the collaboration and rapid feedback from everyone involved in the assessment.

2. **What are some limitations found on actual single user VR? Multi-user VR will solve these limitations?**

In general, VR problems from the perspective of and ergonomist can be.

- The weight of the headset, that adds an extra torque to the neck, and may cause ergonomic problems to the ones evaluating the ergonomic assessments.
- The field of view of the headset, if no additional hand tracking tools are being used, when the cameras cannot see the arm or the hand, the manikin will drop the arm down, when maybe it´s reaching somewhere up where the cameras cannot see. This problem also applies with legs, their representation it´s not accurate and their movement is worse.
- Depending on the developer of the VR headset being used, there might be some friction problems with using apps / functionalities that are not inherent of this company. Ex: Meta accounts with the Oculus 2
- Scepticism of ergonomist: not trusting the VR representation of the human body

3. **What are the limitations of multi-user VR environments for ergonomic assessments?**

Companies may not like a lot of people in doing the assessment, so if multi-user VR helps in optimizing the number of people doing the job, it will be great.

4. **Given the inherent limitation of VR environments in simulating the sensation of weight, I am interested in understanding the approaches and technologies currently employed to address this challenge. How do you replicate or simulate the experience**

of weight and other physical properties within your VR systems to enhance realism and efficacy in multi-user assessments?

It´s an actual limitation, but it´s addressed through biomechanics systems that need a lot of calculating power, and after some inputs it gives you some outputs, like some ergonomic scores based on those calculations.

5. **What is the quantitative data that is calculated to see the efficiency of the current ergonomic methods?**

We need a baseline for this KIPs to be compared, but some of the questions that should be asked, considering that this quantitative data may vary between companies are:

- How long it takes to make and analysis?
- Is the result useful?
- Counting the number of steps in other to do the assessment (flow chart)
- Look at the trade-offs.
- Look at the bottle necks of the process.

6. **In which cases can AR, be used instead of VR for ergonomic assessment (Is multi-user AR better than multi-user VR, for both renovating and designing a factory)**

As said in other interviews, AR is more useful in the assessments that are being done on actual existing workstations, and VR for the design and ergonomic assessments of future factories.

7. **What advancements in VR technology are needed to improve its effectiveness for ergonomics assessments?**

Improvements in the usability of the VR technology where the friction is deleted and there will be improvements in the headset comfort, because, for now, they are heavy and not comfortable. You cannot work with them for hours.

8. **Are there any regulatory or safety considerations that need to be addressed when using VR for ergonomic assessments in production environments?**

There are not any regulations for working environments with the VR headset. For general use, there are some recommendations that manufacturers make, but in working environments you may be forced to use this tech when there are no rules or established regulations to protect workers form long exposures using the VR technology.

9. **Can ergonomic assessments be compared? If so, how can they be compared?**

Ergonomic methods are scientifically proven methods, but the certificate of being an ergonomist it´s not protected and people with different degrees, all within the study of the human body, can end up being an ergonomist, so for that reason the valuations been made from one or another ergonomist may vary. This makes us thick if we should trust ergonomists or computers based on ergonomic methods.

10. **How can VR be improved for ergonomic purposes?**

The fidelity of the body movement and body postures is one the actual concerns in using VR for ergonomic purposes, so this should be a thing to consider.

11. **Why is there friction in using VR or multi-user VR for ergonomics.**

New technologies like VR, are not for everybody. There will always be early enthusiast that will be willing to take the risk of buying the first-generation products of a new technology. From this point until it gets user-friendly for everybody, a lot of improvements need to be made by developers so that all the friction impeding the use for more industrial applications are eliminated. This development is not always easy, because for the same reason that there are early adopters, there are also, sceptical people on new tech, who are not willing to spend or lose their time in dealing with the early problems of these new products, and giving feedback on how it should be improved.

CONCLUSIONS OF THE MEETING

- Benefits from the multi-ser VR tool is the **direct feedback** of other stakeholders that are evaluating the same thing at the same time from different point of views, and this way, **time is saved**.
- **Weight sensation** limitation can be solved through **biomechanics systems**.
- Some KIPs suggested for the experimental part of the thesis may be:
    - How long it takes to make and analysis?
    - Counting the number of steps in other to do the assessment (flow chart)
    - Look at the trade-offs.
    - Look at the bottle necks of the process.
- There might be some **fidelity problems** with the **finger and hand postures** in the VR when grip and force is needed to be applied in the task.
- There are **no regulatory or safety considerations** for work environments nowadays.
- The difference between ergonomists may happen due to the **non-protected ergonomic certificate**.
- Advancements in the **usability of the VR** technology and the **fidelity of the human body postures**

STATED LIMITATIONS:

- Weight of the headset
- FoV
- Usability Friction
- Body and hand tracking
- Software Friction (software developer VS confidential data)
- Collision problem in the VR environment

Interview to Roland Örtengren

<table>
<tr><td>ROLAND ÖRTENGREN
roland.ortengren@chalmers.se
Prof. of Ergonomics / Human factors Engineering</td><td>Date: 8/3/2024 from 12:00 till 13:30

• Senior Prof. Human factors engineering and ergonomics (Chalmers)</td></tr>
<tr><td colspan="2">• MCS: Physics Engineer with specialization in Medical Engineering
• PHD: Medical Engineering
• He has been professor at Chalmers university of Ergonomics / Human Factor Engineering</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://research.chalmers.se/person/orten
- https://www.linkedin.com/in/roland-%C3%B6rtengren-aa286617/?originalSubdomain=se
- https://www.researchgate.net/profile/Roland-Oertengren/6
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- Avenues of entry: how industrial engineers and ergonomists access and influence human factors and ergonomics issues à https://research.chalmers.se/en/publication/198334
- The Influence of Poor Assembly Ergonomics on Product Quality: A Cost-Benefit Analysis in Car Manufacturing à https://research.chalmers.se/en/publication/78282
- Digital human modelling simulation results and their outcomes in reality: A comparative study within manual assembly of automobiles à https://research.chalmers.se/en/publication/93327
- Simulation of Ergonomic Assembly Through a Digital Human Modelling Software https://research.chalmers.se/en/publication/537684</td></tr>
<tr><td colspan="2">QUESTIONS TO ASK
12. From your background, how do you envision the role of VR and specially the multi-user VR tools for ergonomic assessments? How important is to be able to have more than one person’s opinion in the ergonomic assessment?
13. What may be some limitations that you may think VR technology has to help performing ergonomic assessments?
14. Do you see any benefit in the statement that with multi-user VR tools, the ergonomic assessment will be done faster, but is that beneficial?
15. Can you talk about do you think the environmental load reduction that may be gained with the multi-user VR tool for ergonomic assessments?
16. One current limitation that VR has is to not be able to simulate actual weight of objects or any kind of physical interaction between the manikin and the environment, how do you think this VR limitation can be solved.
17. Which postures are most difficult to cover using VR?
18. Are there specific scenarios or tasks where multi-user VR can be particularly advantageous or disadvantageous?
19. Has multi-user VR has been used in some other company, can you tell us about the improvement in ergonomics, quality etc.
20. What is the quantitative data that is calculated to see the efficiency of the current ergonomic methods?
21. In which cases can AR, be used instead of VR for ergonomic assessment (Is multi-user AR better than multi-user VR, for both renovating and designing a factory)
22. How do you see evolution of VR technology impacting multi-user VR assessment in the next 5-10 years?
23. What is needed for ergonomic assessments to be better? If there are improvements to be made, is VR involved? What other technologies may be more useful than VR?
24. How do you envision the role of AI and machine learning in enhancing VR-based ergonomic assessments?</td></tr>
</table>

25. Are there any regulatory or safety considerations that need to be addressed when using VR for ergonomic assessments in production environments?
26. How much is ManusVR used in companies and research now a days?
27. We got to know from different interviews that, ergonomic scores change from ergonomists to ergonomists, can you talk a bit about that.
28. Can ergonomic assessments be compared? If so, how can they be compared?
29. How can developers address the challenge of discrepancies between expected and actual interactions, specifically the mismatch between simulated grips and controller grips, in VR
30. Is there anyway ROI can be calculated after using the multi-user VR for ergonomic assessments?
31. Being one of the pioneers of the IPS software, how do you envision the new implementation of the multi-user VR for ergonomic assessments?
32. Do you see a possible collaboration between Emulate 3D software of Rockwell Automation and IPS IMMA?
33. Do you know anybody whom that you think can help us in our research, so that we can interview them?

NOTES OF THE MEETING

1. Pros: Faster
2. Cons: Subjective opinion of ergonomists
3. Save time:
4. Limitations of IPS: the movement of the operator
5. IPS has been used successfully in several operations
6. Try to do a couple of work simulations
7. Complicated postures: He does not know that finger movements are difficult
8. Throughout and ergonomic should be addressed at the same time, because they are related.
9. Try to find simulations with IPS software to see how it looks
10. Weight: In IPS its possible,
11. Suggestions: you chose an ergonomic evaluation depending on the situation...?
12. Change from manual to IPS
13. Contacts: Mikel Struger - responsible for ergonomics

Read chapter of the book recommended - evaluation of ergonomic assessments
Should we rely in the subjective opinion of an ergonomists
Design into the software the evaluations made from ergonomists
The important thing is to do a good design of the experiment

CONCLUSIONS OF THE MEETING

- One problem in doing ergonomic assessments is to **choose the ergonomic method** that best suits the task that is being assessed.
- The **weight sensation** limitation can be addressed through the **IPS IMMA software**.
- IPS is lacking the **natural movement** of the operator.
- **Throughput and ergonomics** should be addressed at the same time because they have a very close relationship.

STATED LIMITATIONS:

- Weight sensation – IPS software
- Natural body movements IPS
- Body and hand tracking

Interview with Dan Lämkull, Maciej Zdrodowski and Puranjay Mugur

<table>
<tr><td>DAN LÄMKULL
dan.lamkull@volvocars.com</td><td>Date: 12/3/2024 from 9:00 till 12:00
Prof. Ergonomic Assembly (Chalmers + Volvo Cars)</td></tr>
<tr><td colspan="2">

MSC’S: Mechanical engineering, industrial design engineering specialization in product design
PHD: Ergonomics and Virtual manufacturing
AREAS OF WORK: Virtual manufacturing, virtual developer for more than 30 years
JOBS: application engineer, consultant manager, method developer, teacher/tutor, Certified European Ergonomist and researcher and research leader.
He has been working in Volvo cars corporation for almost 25 years

</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://se.linkedin.com/in/dlamkull
- https://kunskapsformedlingen.se/forskare/dan-lamkull/
- https://research.chalmers.se/person/dlamkull
INTERSTING PAPERS
- Digital Human Modelling Simulation Results and Their Outcomes in Reality: A Comparative Study within Manual Assembly of Automobiles à https://research.chalmers.se/publication/93327
- Reduction of ergonomics design flaws through virtual methods à https://research.chalmers.se/en/publication/?id=62038</td></tr>
<tr><td>MACIEJ ZDRODOWSKI
maciej.zdrodowski@volvocars.com</td><td>Date: 12/3/2024 from 9:00 till 12:00
Ergonomist, Human Factors Expert, Volvo Cars, Certified European Ergonomist</td></tr>
<tr><td colspan="2">

Master of science in physiotherapy
Postgraduate in ergonomics, work safety and environment protection
Certified European ergonomist
Working as an ergonomic architect in Volvo Cars

</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://www.linkedin.com/in/maciej-zdrodowski-1167051/?originalSubdomain=se</td></tr>
<tr><td>PURANJAY MUGUR
puranjay.mugur@volvocars.com</td><td>Date: 12/3/2024 from 9:00 till 12:00
Simulation Engineer at Volvo Cars.</td></tr>
<tr><td colspan="2">

Bachelor’s degree in mechanical engineering
Master’s degree in production engineering
Master thesis at Volvo Cars
Working in Volvo Cars as a simulation engineer
MATLAB and Siemens simulation software’s certificates

</td></tr>
<tr><td colspan="2">LINKS OF INTEREST
- https://www.linkedin.com/in/puranjay-mugur/?originalSubdomain=se</td></tr>
<tr><td colspan="2">MAIN QUESTIONS</td></tr>
</table>

1. **Can you give us a brief overview about the paper of VR for ergonomic assessments from your perspective and background?**

Volvo Cars leverages global manufacturing engineering, where the designing, developing, implementing, and optimizing practices of manufacturing processes and systems it being done on a global scale. It involves the coordination and standardizing manufacturing practices, technologies, and strategies across multiple locations worldwide. On the other side, they also use a product driven development way of working, focusing on manufacturing high quality products that meet user needs. Considering these two aspects of the way of working in Volvo Cars, makes VR, as a tool for development, and the study of the ergonomics, two pivotal elements in the development of the company.

They are very aware of the need to work in ergonomics to improve the product quality, to keep up with the new laws regarding the safety of the workforce and to keep up the engagement of the workforce of the company. They focus mainly in physical ergonomics, but also in cognitive and organisational ergonomics. MSDs are the main associated injuries that they try to prevent with the study of physical ergonomics, where in Europe it represents a cost of 261 billion dollars per year for companies. Digging more into the MSDs, hand injuries represent the 41% of the injuries as the main part of the body that suffers from the ergonomics in the manufacturing process.

The design process of a new car, including ergonomics, from the first ideas till the first production unit, takes almost 3 years in the making, in which the virtual simulation part, takes a hole year in that process. They do the VR and simulation testing in the "Virtual Arena" where they can bring different stakeholders, people from the R&D team and other people that need to be in the development process.

2. **What kind of technology does this company use regarding ergonomics? Would it be possible to see it?**

They use what they call MR, where they use VR and AR depending on the task that is needed to be simulated. Regarding the software, over the years they have used different software's, but the last and actual software that Volvo uses to do the ergonomic assessments is IPS IMMA. In addition, when studying workstations and the production line, they combine scanned components with CAD models, and they can study ergonomics but also logistics.

3. **With this technology do you face any limitation to perform the ergonomic assessments?**

The main limitation is the fidelity of the simulation regarding real operator movements, where the computer may put the body in a certain posture, but the operator will do it in a completely different way. More in depth the representation of the fingers and wrists are the most difficult thing.

4. **One of the benefits we have thought from the beginning is that, adding this multi-user VR tool for ergonomic assessments in the design process of a new factory is that the assessment will be done faster. I this advantageous or economically beneficial?**

If the assessment can be done faster, ergonomic risks can be found faster, and the solving process starts earlier. Sometimes, not finding a solution in time for a certain problem in the design process of a car may lead to dismiss the product as non-viable.

5. **Thinking in why companies should invest in this kind of new technology, what are the cost implications of a multi-user VR tool for ergonomic assessments.**

The effectiveness can be measured through the amount of time that has been put into the assessment / simulation.

6. **If your company uses VR, how do you manage the learning curve associated with adopting VR for ergonomic assessments?**

Through training sessions of the employees

7. **For this kind of jobs how do you approach the difference between AR and VR, which one would you say is better for our field of study?**

They use MR, that means that they use both VR and AR, whenever they consider. Each one has its limitations, like in VR it's hard to predict the exact force for a certain task and AR might be better if you have a prototype that you can work with. Also, AR cannot be recorded and cannot give the immersion you may need to see a new design.

8. **Do you know of any safety regulations that exist regarding the use of VR technology for ergonomic assessment in production environments?**

They do not have any specific safety regulations, but they are aware that people may get dizzy after using VR for a long period of time, and employees are free to stop when they consider they need to do so. A transparency mode, where you can get to see your real environment would help in reliving this sense of feeling dizzy.

9. **Which postures are the most difficult to cover using VR regarding ergonomics?**

The most difficult postures are the hand movement, as some tasks may need a certain posture of the hand or to put the fingers in a tight space, and the accuracy of the hand and finger tracking is not that good yet. Smart gloves may be the solution, but they need to be more affordable. This problem can also be addressed through motion capture.

10. **What kind of KPIs are you currently using to measure the efficiency of the current ergonomic assessments?**

They do not have specific KIPs, they are in continuous touch with developers, where they ask what new tools / plug-ins / functionalities the software may have in the future. If they need to search for a new software, they will perform a market research and stick with the tool that suits them better.

11. **Do you know about ManusVR? If so, do you use it? How do you envision the potential of this technology?**

This will highly help in the tracking problems that they have with the wrists and fingers.

12. **Can you talk about how do you see the reduction of the environmental load thanks to multi-user VR for ergonomic assessment?**

It's crucial for them because as they develop a global manufacturing engineering, and the relationship between the cars produced in China and Sweden is very tight, so when there's the need to do an ergonomic assessment that concerns people from Sweden and Chine, all the transport needed its reduced to 0.

13. **Emulate 3D**

From the ergonomists point of view, the more relations that are stablished between different software companies and the easy these ergonomic assessments get, the better for their job, and for the output of these assessments.

QUESTIONS OF LIMITATIONS

14. **Weight and physical contact cannot be simulated through VR**

They do not consider weights under 3 Kg, anyway they do not use VR do ergonomic assessments that require weightlifting. For physical contact in VR simulation, like the structure of a car, they use easy building structures made up of aluminium profiles.

15. **Accuracy from the ergonomic methods, differences between ergonomists, fidelity of the computer-based scores.**

They believe that ergonomists within the same scenario, will perform a pretty similar evaluation. The assessments by real ergonomists are not done from scratch, they get into the process when the simulation in IPS IMMA gives a bad ergonomic score, and their job is to assess how it can be improved.

16. **Friction between all the apps / tools needed to perform an ergonomic assessment through VR.**

The main problem they find is the cybersecurity, because all the VR headsets available are associated to a certain company, like Meta, HTC and others, but if you are preforming a certain assessment with the VR set in Volvo cars that contain certain confidential information of new car that they may be working on, they want to have the security that there are no leaks of their information to this development companies that provide the software and the hardware.

17. **Fidelity of the VR world, difference between reality and the VR world**

That's why they also use AR when they need to perform a task that needs some sense of real environment. They think that the future in this technology is MR, where you can adjust the sense of immersion of the simulation.

18. **Not easy to use VR technology.**

They face this problem, and they think that the ease of use of the technology must be improved by the developers of the headsets, so that the use and implementation can get further. This tool must be used with operators that may not have any knowledge in technology, and for now, when they get involved, they are more impressed about the new experience, rather than in the task that they should be preforming.

19. **Robotic / non-natural body movement**

The natural body movement of the human body is one the most difficult things to simulate and needs to be improved.

20. **Lighting, heat, and other outside environmental factors that also affect ergonomics cannot be simulated in VR.**

These aspects are not being considered by Volvo because they assume that the work conditions regarding light, heat, noise, and other aspects are already optimal and are the best they can be.

21. **FoV of the VR headset may cause somebody tracking problems.**

It's been improving with the new models of the headsets.

CLOSING

22. **How do you see evolution of VR technology impacting multi-user VR for ergonomic assessment in the nest 5-10 years?**

One thing that the VR technology in ergonomic assessments needs to have it's a **built-in dynamic ergonomic method judgment**. For now, static ergonomic judgements scores are made, and see the evolution of the risk though the process / task will be very beneficial.

Access to raw data of the ergonomic assessment in the software will be also very beneficial, to be able to make decisions and judgments based on data that reflexed the time-exposure to the risk.

23. **Do you give us permission to use your name and/or companies name in our thesis report, and the notes we have taken?**

We can use the name of the people interviewed and the companies name, but not the photos taken.

CONCLUSIONS OF THE INTERVIEW

- Volvo does not focus on using **VR or AR**, they like to say that they use "**mixed reality**", where they consider both in their work, but use one or the other depending on the type of task that needs to be assessed. The reason behind this is that each one has its limitations, and they are aware of that. They believe that in the future, this technology will end up in a mix of both, where you will be able to graduate the level of immersion that you need in every scenario.
- When performing ergonomic assessments, they perform them through simulation in IPS and using VR or AR and while the **ergonomic scores** given by the software are not risky,

they won't need to call for an actual ergonomist for its point of view on a certain task. They will only call an **ergonomist** when bad ergonomic scores are given by the software and after trying different positions in the simulations where no improvement is found in that assessment. In that case, with all the data and information from the previous simulations, the ergonomists will try and find a solution for that specific task. The main point is that they do not call an ergonomist for every ergonomic assessment that they perform, and that implies a complete trust in the ergonomic scores given by the software that they use.

- Given the **weight sensation** problem, they use the simulation in the IPS IMMA software but do not use VR for this kind of ergonomic assessments.
- Regarding the **software friction** from a company's point of view, it is as big concern. VR solutions come from certain big companies like Meta or HTC, and you are forced to use their associated software to use the technology, and this implies that all your data will go through their systems. For Volvo Cars, when developing a new car with all the confidential information that comes with it, having to use this tool implies a certain risk that they are not willing to take, because they do not know how all their **data will be treated**. They would like to have control over their data all the time and protect it from any other company.
- One improvement that ergonomic software's should have and that is also compatible with the multi-user VR tool is, to have a **built-in dynamic ergonomic score** that reflects the ergonomic score of all the different postures that are being done when preforming the task, and have an average score based on all the movements. This way you can consider the **time** that takes to do the task and the number of **repetitions**, which is basic information that needs to be considered in ergonomic assessments. Nowadays, static ergonomic scores are given through ergonomic software's, which gives very little information.
- Ergonomic assessments in companies will be a **marketing trade-off** for the workforce of companies, as people do not want to suffer bad body-related consequences thanks to their jobs. In Volvo cars the average age of the workforce it's around 36 years old and in some years it will get higher. Working in a factory / production line is a very well-paid job in Sweden, but people are not willing to work in certain conditions where they can get injured, that's why ergonomics will be more considered and valued over time.

STATED LIMITATIONS:

- Fidelity of the simulation regarding the body movements and hands
- Confidential information
- Ease of use of the tool
- Robotic / non-natural body movement
- Static ergonomic scores
- Some people get dizzy when using VR

Interview with Johan Cruse

JOHAN CRUSE johan.cruse@volvo.com	**Date:** 13/3/2024 from 9:00 till 9:30
	Tools and Methods manager Retail Competence Development at Volvo Trucks

- Master's degree in biology / Biological sciences
- Working at Volvo Trucks as a tool and methods manager

LINKS OF INTEREST

- https://www.linkedin.com/in/johan-cruse-0070893/?originalSubdomain=se

NOTES OF THE MEETING

- He does not work in ergonomics, but he uses VR for other purposes, like training, change of layout of workstations and other things. He is very interested in the multi-user VR implementation.
- For them it will be a completely game changer
- In Volvo Trucks they use the Meta-quest 3

- BENEFITS OF TRAINIGN WITH MULTIUSER VR:
  - Rise the geometry
  - Electrical mobility – dangerous tasks
  - Seasick
  - Meta quest 3 (cheap)
- EASY-TO-USE:
  - Difficult in the beginning
  - VR way better than AR
- Software: UNITY
  - Not blurry
  - Internet speed requirements
- ERGONOMICS PROBLEMS WITH HEADSET:
  - Dizzy and tired (30 mins)
  - Very heavy
- Problems with the hands
- PROBLEMS WITH VR
  - Not having the sense of feeling
  - No sense of weight
- WHAT MADE THE COMPANY GO FOR VR
  - Covid
  - Electrical truck
- LEARNING COURVE
  - Every week they have a meeting where they share knowledge
- DIFFICULT TASK: small, delicate stuff
- GLOVES: It will be perfect, but they are aware that they are expensive.

Interview to Peter Mårdberg

PETER MÅRDBERG peter.mardberg@fcc.chalmers.se	**date:** 14/3/2024 from 10:00 till 11:30 • Geometry and Motion Planner working in FCC

LINKS OF INTEREST
- https://www.researchgate.net/profile/Peter-Mardberg
- https://www.fcc.chalmers.se/departments/geo/

INTERESTNG PAPERS
- Industrial Path Solutions – Intelligently Moving Manikins https://www.researchgate.net/publication/335397458_Industrial_Path_Solutions_-_Intelligently_Moving_Manikins
- DHM Based Test Procedure Concept for Proactive Ergonomics Assessments in the Vehicle Interior Design Process: Volume V: Human Simulation and Virtual Environments, Work With Computing Systems (WWCS), Process Control - https://www.researchgate.net/publication/326880014_DHM_Based_Test_Procedure_Concept_for_Proactive_Ergonomics_Assessments_in_the_Vehicle_Interior_Design_Process_Volume_V_Human_Simulation_and_Virtual_Environments_Work_With_Computing_Systems_WWCS_Process

MAIN QUESTIONS

1. **Can you give us a brief overview about the paper of VR for ergonomic assessments from your perspective and background?**

Coming from IPS IMMA (Intelligently moving manikins), the focus was more on the ergonomic side of our field of study, and, they focus more on the ergonomic assessment through simulations rather than preforming a motion capture VR assessment. Their software has capabilities of using VR and they will release a multi-user VR capability to preform ergonomic assessment soon.

INTRODUCTION TO IMMA

It uses inverse kinematics to do evaluations and the human bodies are formed out of rigid bones with a total of 162 degrees of freedom, that's why it's so complex to simulate a real human movement. With some inputs of different measurement of a certain body and with the help of regression models, they can recreate all the other parts of the body that's trying to be represented. They also consider the stability and balance of the manikin, the collision with objects but most important, they can consider all the anthropometric spreads of the human body, or manikin families, how they like to call it. This functionality enables the software to know how the ergonomic assessment of a certain task will affect all the possible different operators. With this they can see which people may have trouble by performing the task, and if needed they can evaluate a possible change in the workstation or whatever is being studied.

In addition, there's the ability to add different types of grips, if the task needs it, but only enables basic functions of the hands and finger movements. There's also a sequence editor that orders how the sequence will be performed by the manikin. Finally, an automatic ergonomic evaluation is done by the software so that the ergonomic assessment can be done, where different ergonomic methods are considered.

2. **One of the benefits we have thought from the beginning is that, adding this multi-user VR tool for ergonomic assessments in the design process of a new factory is that the assessment will be done faster. I this advantageous or economically beneficial?**

By doing the assessment faster the ergonomic evaluation is done in better way, because with the time you save, you can consider more different scenarios that lead to better conclusions.

3. **What are the potential benefits of being able to collaborate and bring different stakeholders while doing the ergonomic assessment? Eighter in the design process of a new factory or the modification of an actual one**

By collaborating at the same time with different people you can have a better discussion of different assemblies in the same meeting.

4. **For this kind of jobs how do you approach the difference between AR and VR, which one would you say is better for our field of study?**

The use of AR or VR depends on the task that needs to be done, if for example, a physical interaction with the real world is needed then AR might be better, but if for instance, you need another person into the job you are doing, VR will be better.

5. **Which postures are the most difficult to cover using VR regarding ergonomics?**

The most difficult postures and movements to be simulated in IPS IMMA are fine detailed movements, like hand and finger movements. Also, if the actual motion of the task needs to be assessed, it's also difficult but for static postures there are not a lot of limitations. Also leaning into a physical thing, like the structure of a car, it's difficult to represent how the body adapts to that structure.

6. **Do you know about ManusVR? If so, do you use it? How do you envision the potential of this technology?**

The potential of the technology is there, but for now a lot of calibration is needed and most of the times it's not done correctly, and you have to start again, so a lot of time is lost in the process using it.

7. **How can VR be improved for ergonomic assessments?**

A dynamic ergonomic method, where motion and time can be considered in the ergonomic assessment should be a thing that can be done.

QUESTIONS OF LIMITATIONS

8. **Weight and physical contact cannot be simulated through VR.**

It's a stated problem that sometimes is tried to be solved by adding external weight to the person who's performing the task.

9. **Accuracy from the ergonomic methods, differences between ergonomists, fidelity of the computer-based scores.**

DIFFERENCE BETWEEN ERGONOMISTS: The multi-user VR capability will solve this problem as it's natural to have a discussion from the ergonomic assessment within different people, and at the end a conclusion will be made.

10. **Comfort of the VR headset**

They have not taken the VR experience to the limit, so they have not been able feel the need to stop for an excessive use of it. But they believe that the technology will get more comfortable and lighter over time.

CLOSING

11. **How do you envision the role of AI and machine learning in enhancing VR-based ergonomic assessments?**

The actual problem with the AI is that they need a lot of training for them to perform how they are expected to, and the data needed for that is very limited and confidential for a lot of companies. For human motion, it can do some impressive human-like movements, but for the whole-body movement is still very far away for being able to be used properly.

12. **How do you see evolution of VR technology impacting multi-user VR for ergonomic assessment in the nest 5-10 years?**

For sure it will become a more used and better tool, but still has a lot of things that need to get fixed so that the experience gets more fluent and easier-to-use.

CONCLUSION OF THE MEETING

- By being able to perform the ergonomic assessment better and faster, the **time you have saved** can be used to **consider more scenarios** into the same assessment, that most certainly will lead to better conclusions.
- The **smart gloves** technology for motion capture is still very limited because it needs a lot of calibration which takes a lot of time, and sometimes an error may happen, which lead to more time spent in setting the tool, rather than performing the actual ergonomic assessment for instance.
- Improvement in the **dynamic ergonomic scores** in ergonomic software's.
- **AI** can be a great tool that is able to help in the improvement of the natural body movement of manikins, but there is a problem with the data that goes into the **training** of this AI. This data is very limited, and it needs a lot of training to get good results. For now, it cannot be used for hole body movements, but for some specific scenarios might be good enough.

STATED LIMITATIONS:

- Finger and hand movements
- Fidelity of body movement and interaction with physical objects
- Comfort of the headset

C. Appendix C - Validation case Study

C.I. Semi-structured interviews

Interview to Lars-Ola Bligård and Puranjay Mugur

QUESTIONS

1. **Can you describe your experience using each of the three platforms?**

Lars-Ola was not used to any of the three platforms proposed, on the other hand, Puranjay works on them all the time. This made obvious that the background skills in using every platform made a huge difference in the experience. They both agreed that using the VR, and specially the multi-user VR platform was much more intuitive and easier to navigate around. Being able to move around and to be yourself the reference point, it makes the ergonomic assessment much easier, and it lets you make better decisions.

2. **Were there any methods where you found it particularly challenging to assess a posture? What were the obstacles?**

There were no obstacles, they found it easy to get used to moving around in every platform, as everything in life it's all about practice.

3. **Which platform do you prefer for ergonomic assessments and why?**

It depends on the use case, if more than one stakeholder needs to take part in the assessment, then single-user VR or multi-user VR might be more suitable. But if you are working on your own, the desktop application might be enough.

4. **What obstacles did you see using multi-user VR platform?**

Considering that the multi-user VR platform was the better platform to perform the ergonomic assessment in their opinion, it should also be mentioned that a background knowledge is needed, and it can only be performed in a specific area with the current technologies, which might be a limitation. It is also true that the new headsets that are coming out in the market, are starting to be able to get used without the camera's setup, which allows you to use the VR anywhere. Another thing to mention is that experimenting the VR environment while you hear the real-world sounds or speaking of the people that are around you might be very confusing.

5. **Do you think seeing things in 3D and being more immersed is required to assess an ergonomic posture, or desktop application is good?**

Seeing things in 3D and being more immersed is not required to do an ergonomic assessment but it helps a lot in being more confident that you are making the right decision to improve the ergonomics of the task.

6. **Did it help having multiple stakeholders in a multi-user VR setting to assess and improve ergonomics of the operators?**

Although 1 ergonomist is enough to do an ergonomic assessment of a certain task, being able to collaborate and discuss about the assessment it's much better.

7. **How do you think the future of ergonomic assessments should be and why?**

Being able to adjust on real-time and be able to be the manikin and make yourself the positions that you suggest as an ergonomist will make the whole assessment faster. Another thing that could be extremely helpful would be to have a display in the VR world where you could see the ergonomic scores on real-time, this will enable to see the ergonomic zones of the hole motion of the task and make a better ergonomic assessment. Finally, if two people that are not in the same room could perform an ergonomic assessment remotely, that would also be a huge step into the future of ergonomic assessments.

8. **Is there anything else you want to share about using each of these three methods?**

Having a little bit of more background on the task that is being assessed, like how many tasks are being done in that area of the car or what kind of attachments are going to be used to fix the part that is being assembled can help in being sure of the decision.

9. **Family question**

Manikin families are crucial in ergonomic assessments, and seeing how the experiment has gone, we could have had the time to at least have the shortest and highest family manikin in the tasks. This way we could have taken more information out of the assessments.

CONCLUSION FROM THE INTERVIEW

- Having someone how works daily with all the platforms that are used in the experiment and someone who does not, made very clear that the difference in knowledge in using the software and the platforms was something that influenced a lot when testing the usability of things.

- They both agreed that multi-user VR was a step forward when doing ergonomic assessments. It added that little bit more of realism to the assessment that enables ergonomists to make better and more confident decisions.

- Also, it was noticed that the technology has plenty of room to improve, as there were a lot of limitations and features that they wished, if there, they would be able to perform better assessments.

- It should also be mentioned that, even if the technology improves, multi-user VR will not be the solution to everything. It is very useful, but depending on the situation and how many people is working on the assessment, working on a desktop application might be enough if the ergonomist is working on its own.

Interview to Dan Lämkull and Maciej Zdrodowski

QUESTIONS

1. **Can you describe your experience using each of the three platforms?**

The multi-user VR platform offers significant collaborative benefits and is quite like other platforms from a technical perspective. Desktop applications (DA), however, display robotic behaviours and are time-consuming, with a common issue being the misinterpretation of CAD models' scale.

2. **Which platform do you prefer for ergonomic assessments and why?**

They preferred the multi-user VR platform because it also allows for single-user operations. This flexibility is crucial because you can mimic and physically feel the tasks being performed by the manikins, which is essential for accurate ergonomic assessment.

3. **What obstacles did you see using multi-user VR platform?**

Key challenges in multi-user VR include the necessity for a transparency mode, the ability to see real avatars or manikins, and the integration of haptic feedback or any kind of vibration and colour indications during collisions with VR objects. There's also a need to simulate physical contact more realistically, like having a surface to mimic real-world interactions could be helpful.

4. **Do you think seeing things in 3D and being more immersed is required to assess an ergonomic posture, or desktop application is good?**

Both VR environments and Desktop Applications have their place in ergonomic assessments. VR is essential for confirming and understanding situations that desktop applications outline but can't immerse you in. Knowing when to use each is key.

5. **Did it help having multiple stakeholders in a multi-user VR setting to assess and improve ergonomics of the operators?**

Having multiple stakeholders like ergonomists is not typical in the everyday life of companies like for example Volvo but can be crucial when needed. Typically, one ergonomist is sufficient if engineers are asking the right questions. However, two are necessary when two operators are simultaneously active, such as in many cases in automotive assembly tasks.

6. **How do you think the future of ergonomic assessments should be and why?**

The future of ergonomic assessments should incorporate built-in ergonomic feedback and advanced tools like smart gloves. Another thing that needs to get fixed or simplified is the amount of calibration that is needed to use the VR, as well calibration issues that come in the process. It's also essential to be able to record and assess full body motions, offer support for simulated leaning in VR, and facilitate remote collaboration in the same virtual environment across different global locations. Adding cycle time to simulations will also enhance their utility.

7. **Will ergonomic methods be faster in multi-user VR**

The efficiency of ergonomic assessments depends on the specific task and user familiarity with the technology. Multi-user VR can speed up the process for less skilled individuals by offering an intuitive and immersive environment.

CONCLUSION FROM THE INTERVIEW

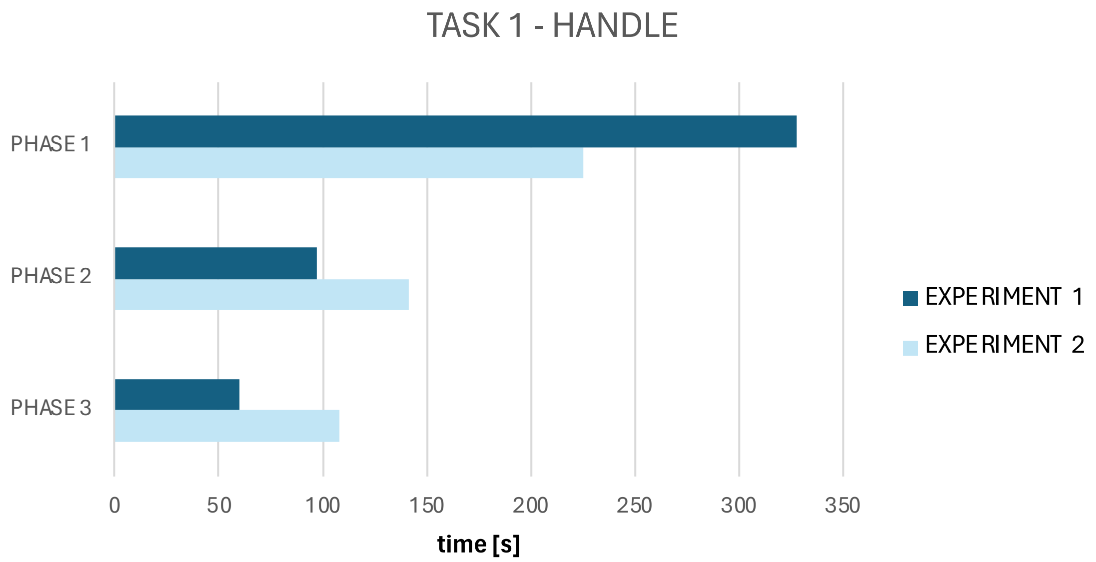
- Interviewees discussed the benefits and preferences for multi-user versus single-user VR platforms, emphasizing the flexibility of multi-user VR that also accommodates single-user functionality, which is essential for detailed ergonomic assessments.

- Participants highlighted several technical challenges related to VR, including issues with body and hand tracking, field of view limitations, and the comfort and usability of VR equipment, which affect the overall effectiveness of ergonomic assessments.
- The discussions included the importance of collaboration in multi-user VR environments and how current VR technology handles multiple stakeholders, indicating the need for features like transparency mode, realistic avatars, and effective collision feedback.

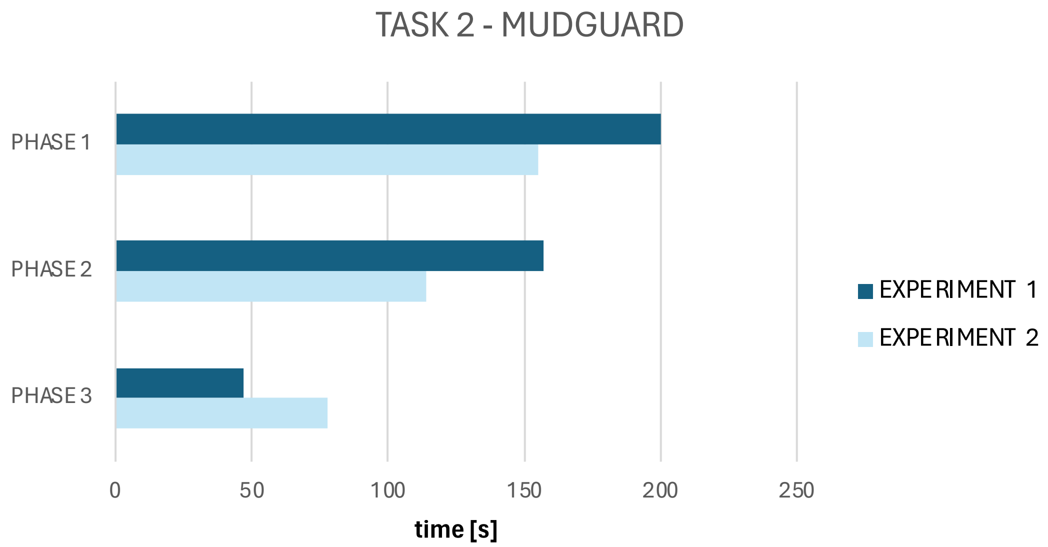
- The interviewees shared insights on the future of ergonomic assessments using VR, such as the need for built-in ergonomic feedback, improved motion tracking, and the potential for VR environments to support remote collaboration and more comprehensive simulations.

C.II. Platforms time-efficiency analysis

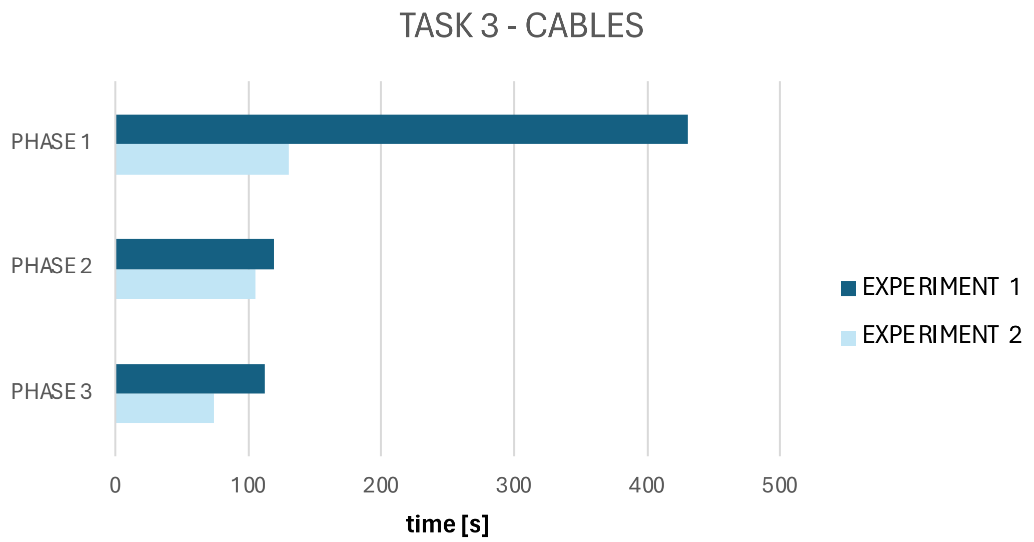
TASK 1 - HANDLE	EXPERIMENT 1	PLATFORM	EXPERIMENT 2	PLATFORM2
PHASE 3	60	DA	108	MU
PHASE 2	97	SU	141	DA
PHASE 1	328	MU	225	SU
TOTAL	485		474	



TASK 2 - MUDGUARD	EXPERIMENT 1	PLATFORM	EXPERIMENT 2	PLATFORM
PHASE 3	47	MU	78	SU
PHASE 2	157	SU	114	DA
PHASE 1	200	DA	155	MU
TOTAL	404		347	



TASK 3 - CABLES	EXPERIMENT 1	PLATFORM	EXPERIMENT 2	PLATFORM
PHASE 3	112	MU	74	DA
PHASE 2	119	SU	105	MU
PHASE 1	431	DA	130	SU
TOTAL	662		309	



C.III. Usability Survey

System Usability Scale (SUS)

	Strongly disagree 1	2	3	4	Strongly agree 5
1. I think that I would like to use this system frequently					
2. I found the system unnecessarily complex					
3. I thought the system was easy to use					
4. I think that I would need the support of a technical person to be able to use this system					
5. I found the various functions in this system were well integrated					
6. I thought there was too much inconsistency in this system					
7. I would imagine that most people would learn to use this system very quickly					
8. I found the system very cumbersome to use					
9. I felt very confident using the system					
10. I needed to learn a lot of things before I could get going with this system					

Usability Survey Results

QUESTION 1: I think I would like to use this system frequently

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	4	3	4
P2	3	3	3
P3	4	3	3
P4	5	4	5
Average	**4**	**3,25**	**3,75**

QUESTION 2: I found the system unnecessarily complex

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	1	1	1
P2	3	3	3
P3	3	3	3
P4	2	2	3
Average	**2,25**	**2,25**	**2,5**

QUESTION 3: I thought the system was easy to use

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	5	5	5
P2	2	4	4
P3	4	3	3
P4	4	4	4
Average	**3,75**	**4**	**4**

QUESTION 4: I think that I would need the support of a technical person to be able to use this system

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	2	2	2
P2	5	5	5
P3	1	5	5
P4	2	3	4
Average	**2,5**	**3,75**	**4**

QUESTION 5: I found the various functions in this system were well integrated

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	5	5	4
P2	2	2	2
P3	4	3	3
P4	4	3	3
Average	**3,75**	**3,25**	**3**

QUESTION 6: I thought there was too much inconsistency in this system

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	2	2	3
P2	3	3	3
P3	2	2	2
P4	2	3	3
Average	**2,25**	**2,5**	**2,75**

QUESTION 7: I would imagine that most people would learn to use this system very quickly

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	2	4	4
P2	3	4	4
P3	4	3	3
P4	4	4	4
Average	**3,25**	**3,75**	**3,75**

QUESTION 8: I found the system very cumbersome to use

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	2	2	2
P2	4	3	3
P3	1	3	3
P4	2	2	3
Average	**2,25**	**2,5**	**2,75**

QUESTION 9: I felt very confident using the system

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	5	5	5
P2	2	2	2
P3	5	4	4
P4	4	4	4
Average	**4**	**3,75**	**3,75**

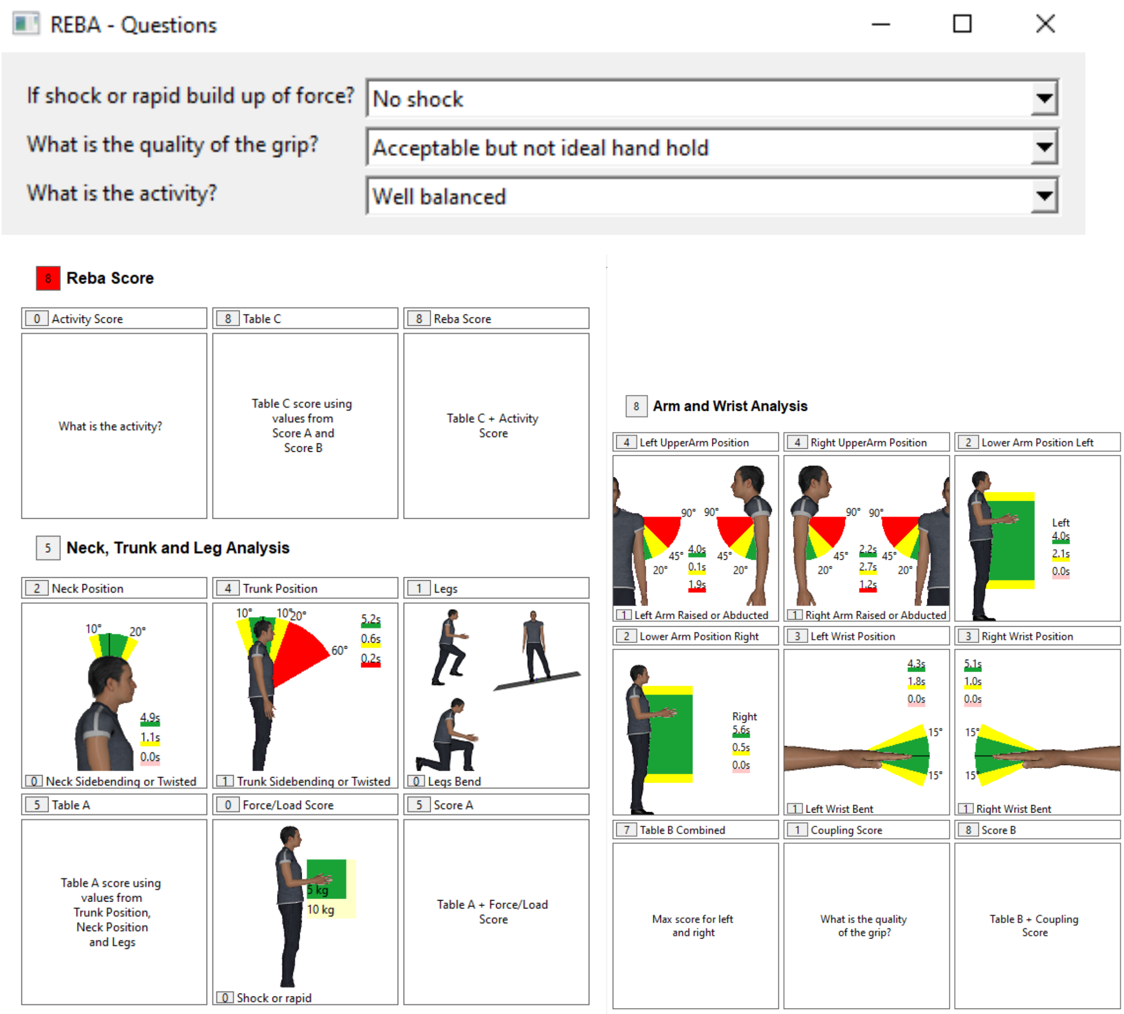
QUESTION 10: I needed to learn a lot of things before I could get going with this system

PEOPLE	Desktop Application	Single-User VR	Multi-User VR
P1	1	1	2
P2	4	3	3
P3	2	2	2
P4	4	3	3
Average	**2,75**	**2,25**	**2,5**

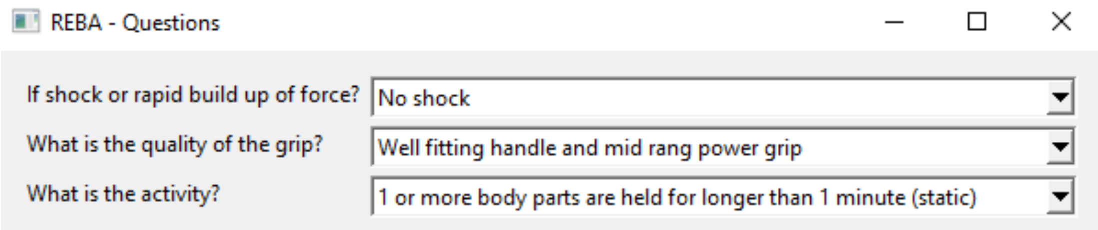
C.IV. Ergonomic improvement

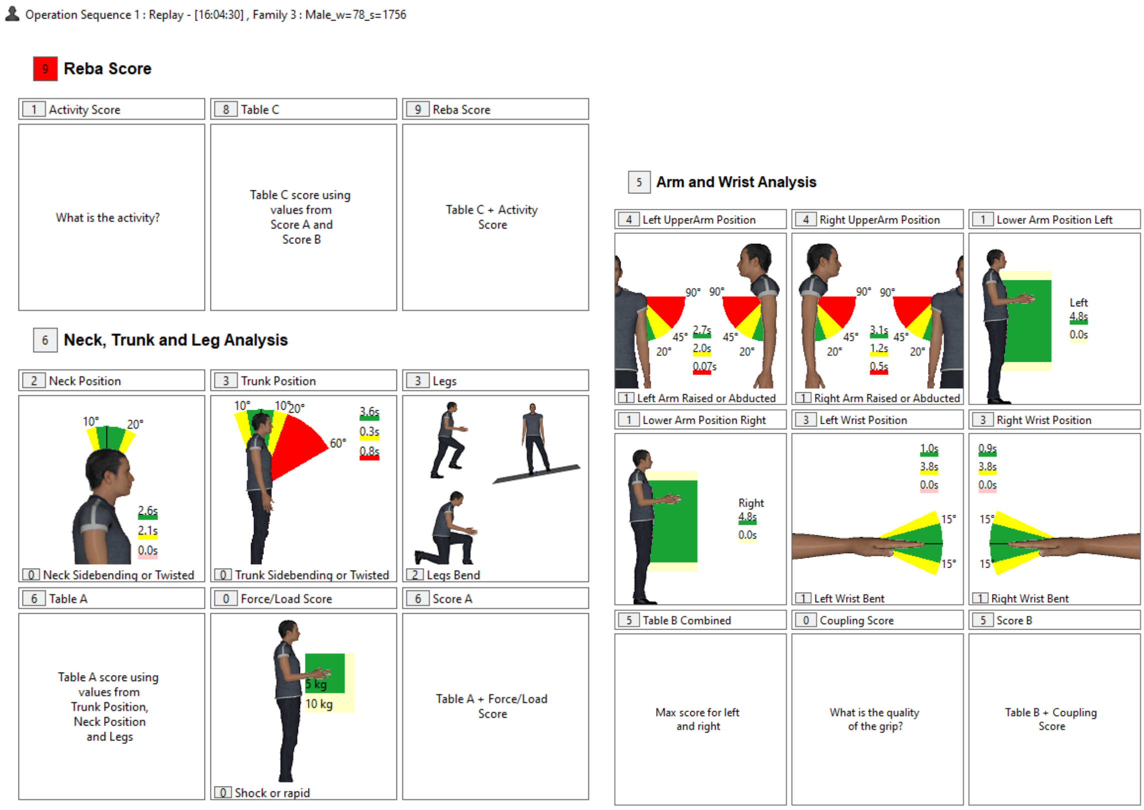
BASE SCENES

TASK 1 – HANDLE

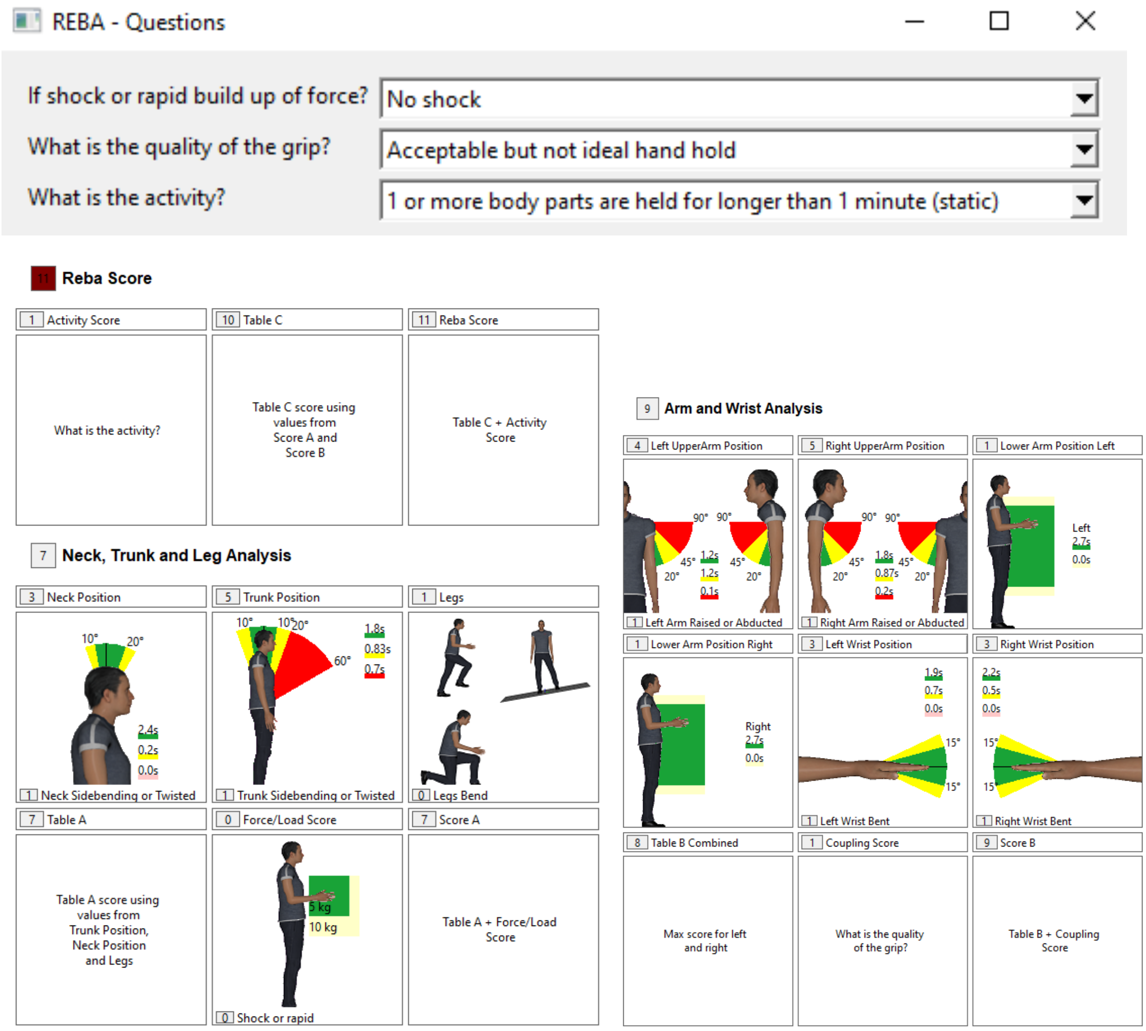


TASK 2 – MUDGUARD



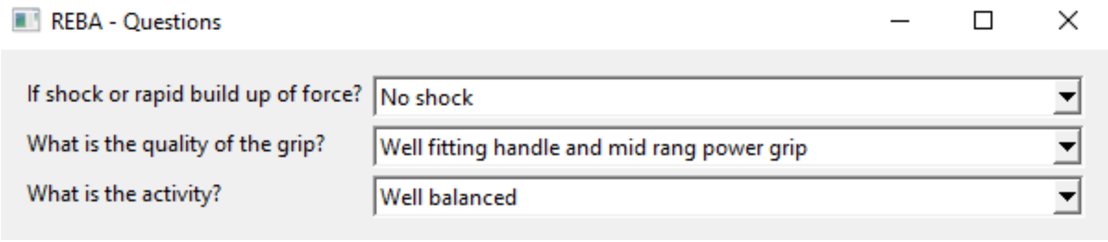


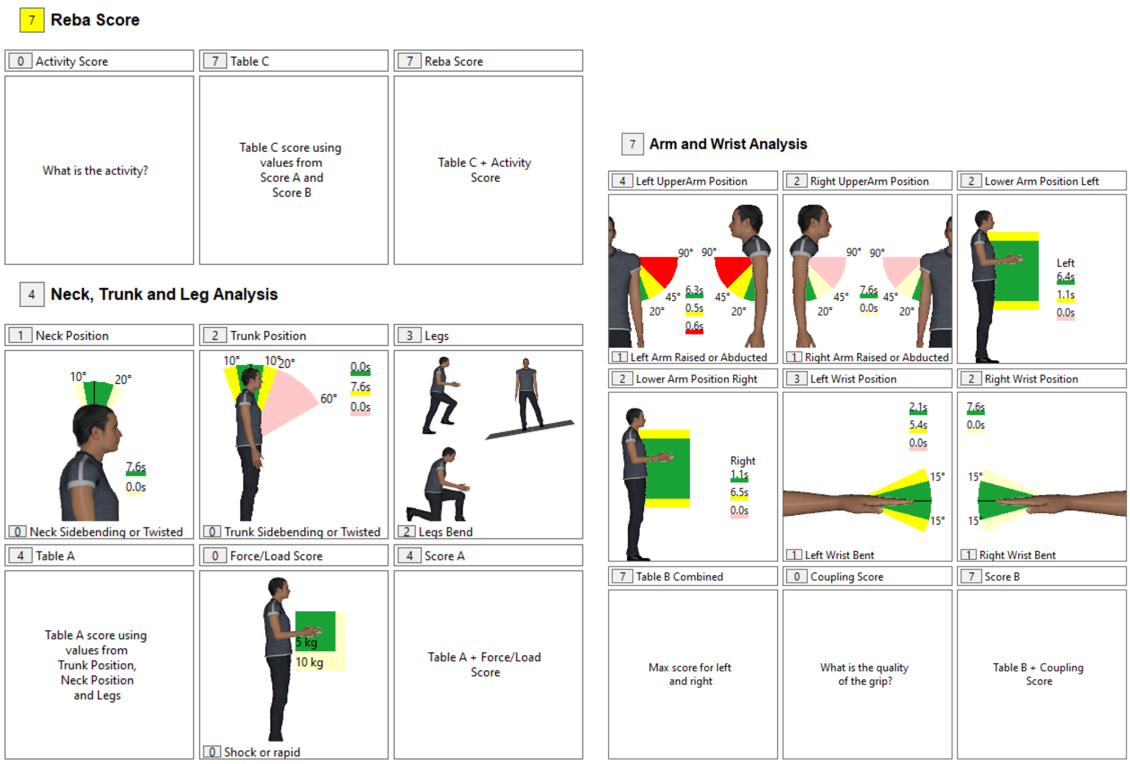
TASK 3 – CABLE


REBA - Questions
If shock or rapid build up of force?
No shock
What is the quality of the grip?
Acceptable but not ideal hand hold
What is the activity?
1 or more body parts are held for longer than 1 minute (static)
Reba Score
1 Activity Score
What is the activity?
10 Table C
Table C score using values from Score A and Score B
11 Reba Score
Table C + Activity Score
7 Neck, Trunk and Leg Analysis
3 Neck Position
1 Neck Sidebending or Twisted
5 Trunk Position
1 Trunk Sidebending or Twisted
1 Legs
0 Legs Bend
7 Table A
Table A score using values from Trunk Position, Neck Position and Legs
0 Force/Load Score
5 kg
10 kg
0 Shock or rapid
7 Score A
Table A + Force/Load Score
9 Arm and Wrist Analysis
4 Left UpperArm Position
1 Left Arm Raised or Abducted
5 Right UpperArm Position
1 Right Arm Raised or Abducted
1 Lower Arm Position Left
1 Lower Arm Position Right
3 Left Wrist Position
1 Left Wrist Bent
3 Right Wrist Position
1 Right Wrist Bent
8 Table B Combined
Max score for left and right
1 Coupling Score
What is the quality of the grip?
9 Score B
Table B + Coupling Score

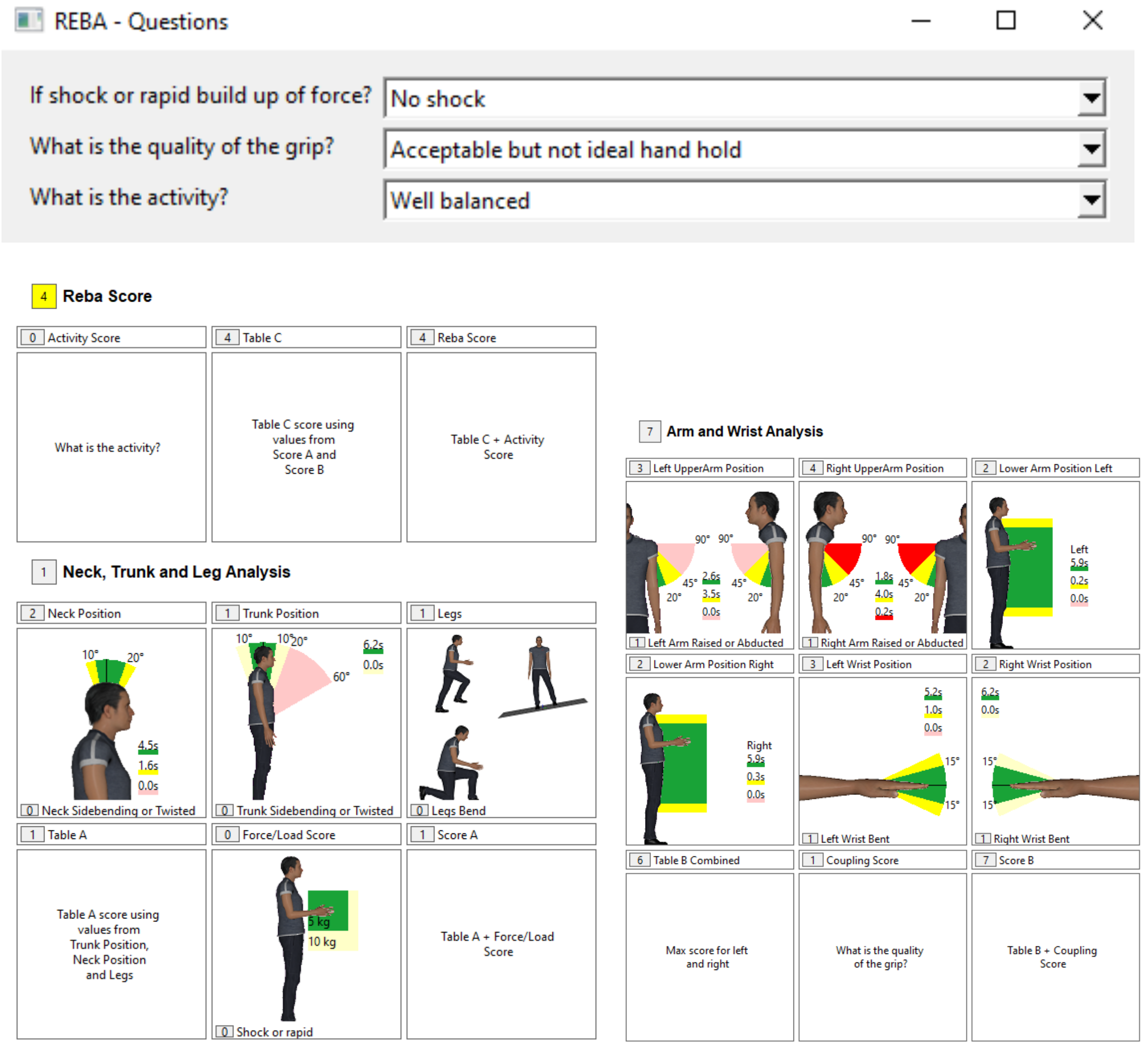
IMPROVED SCENES

TASK 1 – HANDLE EXPERIMENT 1

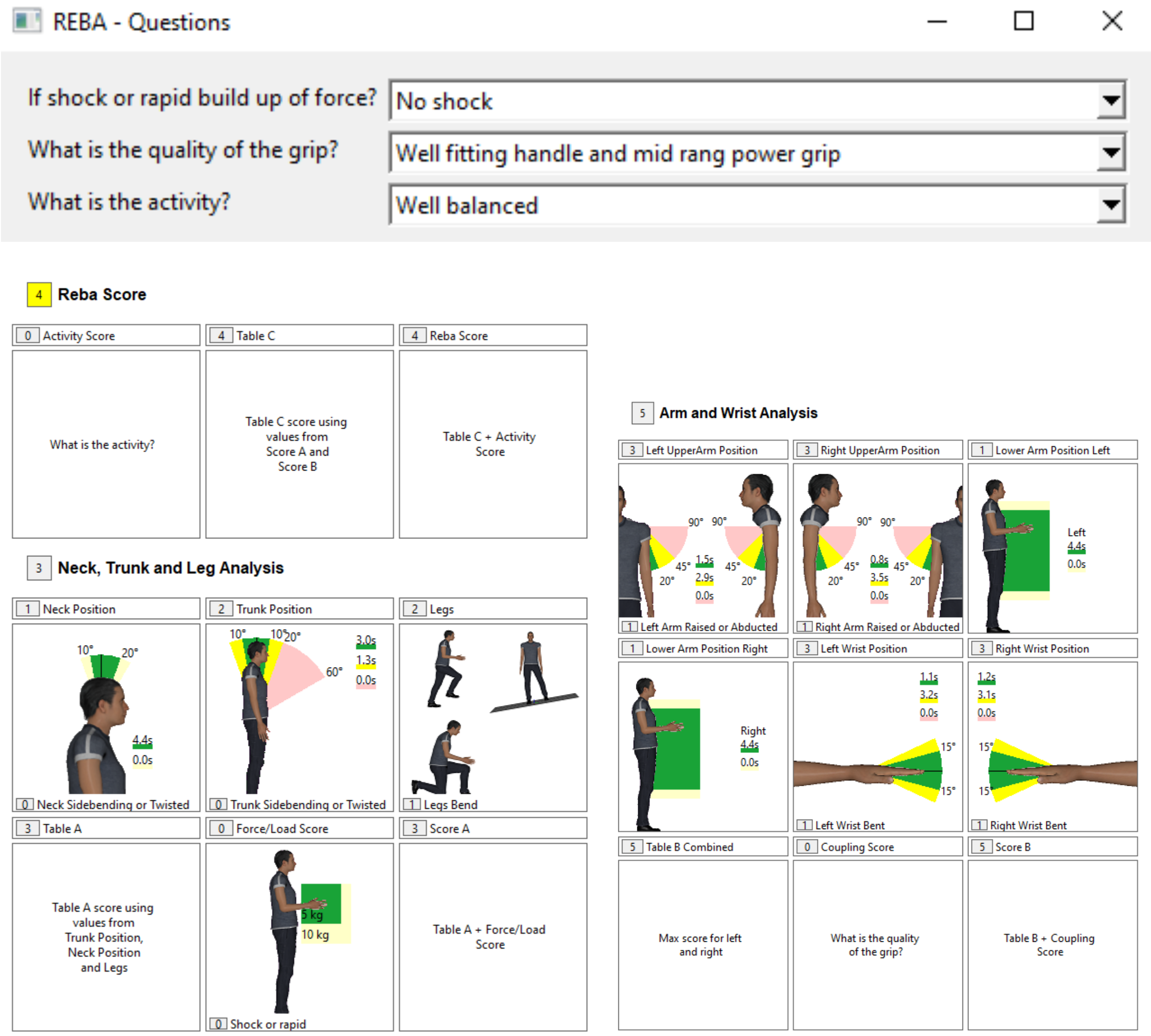




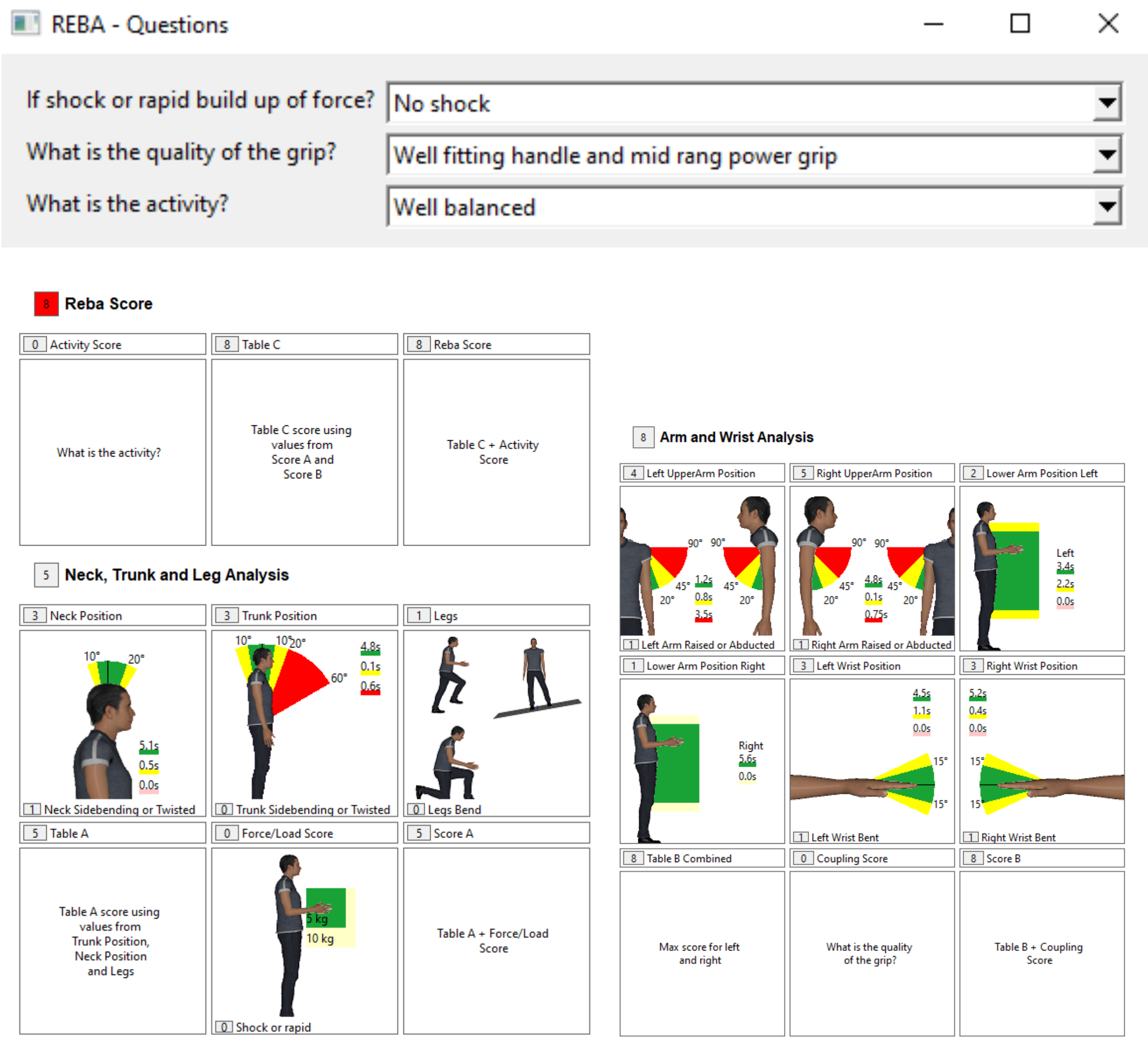
TASK 1 – HANDLE EXPERIMENT 2



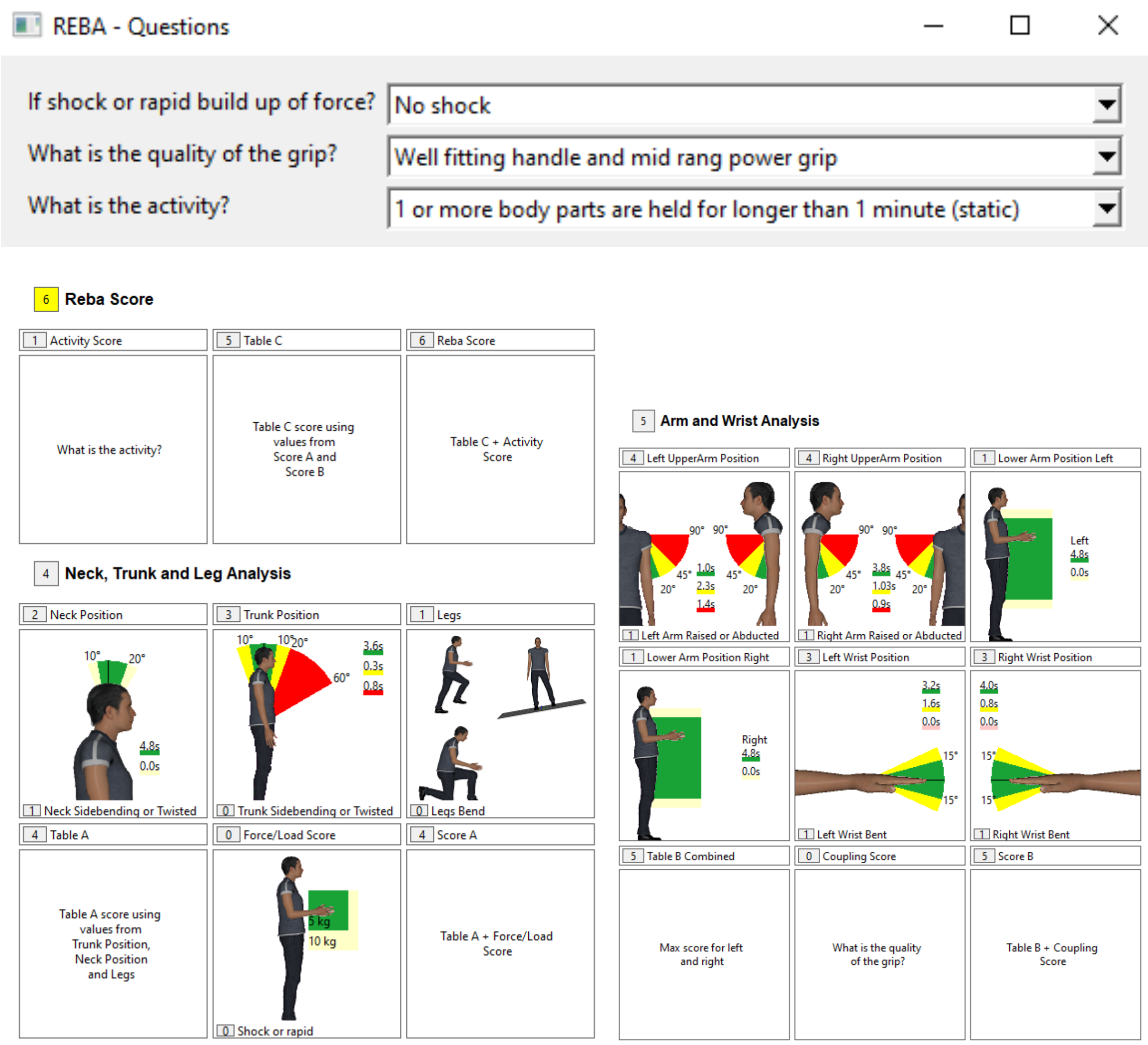
TASK 2 – MUDGUARD EXPERIMENT 1 & 2



TASK 3 – CABLE EXPERIMENT 1



TASK 3 – CABLE EXPERIMENT 2



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