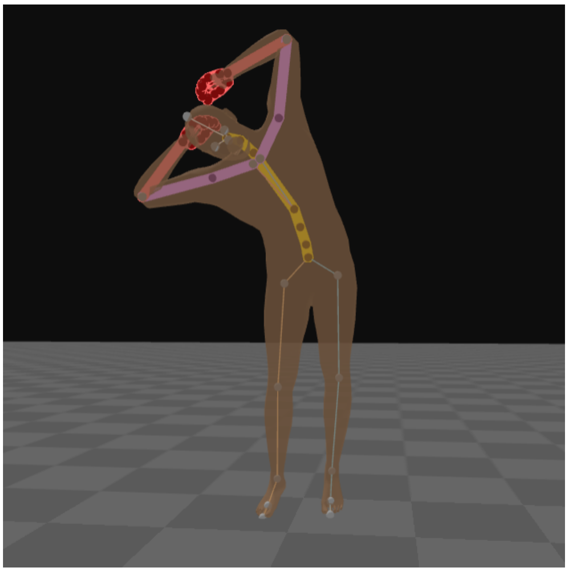 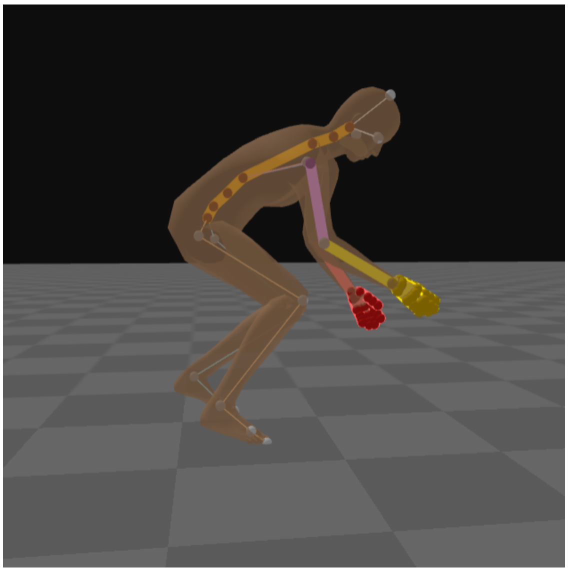

Body Tracking Technologies for Ergonomic Evaluation

Technical and Socio-Technical Evaluation of Markerless Systems for Ergonomic Assessment in Truck Assembly

Master's Thesis in Production Engineering

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Gothenburg, Sweden 2026
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MASTER'S THESIS 2026

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CHALMERS
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Department of Industrial and Materials Science
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Cover: Illustrative body tracking visualizations showing human postures relevant to ergonomic assessment in industrial work environments. The images were captured from the Occurrence Ergo software and are used for illustrative purposes only.

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Abstract

Ergonomic evaluations at Volvo Trucks Tuve are currently performed manually using an internal video-based assessment method, which is time-consuming and difficult to scale across a large number of workstations. This thesis evaluated whether currently available body tracking systems, with a focus on markerless solutions, can support ergonomic assessment in truck assembly. The study combined technical evaluation with socio-technical analysis by considering posture detection capability, evaluation time, workflow compatibility, transparency, data handling, and user acceptance. The investigated systems showed potential to reduce parts of the manual analysis workload and provide quantitative posture data, but their performance and practical usefulness varied between systems, body regions, and recording conditions. The results also showed that successful implementation depends on more than technical accuracy, as the systems must fit existing work practices and be trusted by users. Occurrence Ergo was selected as the most suitable candidate for further evaluation. Overall, body tracking technologies show potential as decision-support tools, but should not currently be regarded as fully autonomous ergonomic assessment systems.

Keywords: Body tracking, motion capture, ergonomic evaluation, markerless motion capture, truck assembly.

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Jacob Martinsson, Joel Svensjö
Gothenburg, June 2026

List of Acronyms

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

3D	Three-dimensional
AI	Artificial Intelligence
ATC	Actual Threshold Crossings
DTC	Detected Threshold Crossings
GDPR	General Data Protection Regulation
IMU	Inertial Measurement Unit
MAD	Mean Absolute Deviation
MEC	Manufacturing Ergonomics Checklist
RAMP	Risk management Assessment tool for Manual handling Proactively
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
TRL	Technology Readiness Level
UI	User Interface
UX	User Experience
WMSDs	Work-related Musculoskeletal Disorders

Contents

List of Acronyms **ix**

Nomenclature **xi**

List of Figures **xv**

List of Tables **xvii**

1 Introduction **1**
1.1 Aim and Objective 2
1.2 Scope and Delimitations 2
1.3 Research Questions 3
1.4 Stakeholder Analysis 3

2 Theoretical Background **7**
2.1 Ergonomics in Industrial Work Environments 7
2.2 Body Tracking Technology 8
2.3 Socio-Technical Aspects of Technology Implementation 10

3 Methodology **13**
3.1 Literature Study 13
3.2 Qualitative Study 14
3.3 Preliminary Technology Screening 15
3.3.1 Justification of Qualitative Ratings 15
3.4 Market Research 16
3.5 Requirement Specification 18
3.6 Testing of Body Tracking Solutions 18
3.6.1 Pilot Test 19
3.6.2 Comparison to Expert Evaluation Test 19
3.6.3 Threshold Crossing Test 20
3.6.4 Evaluation Time Analysis 21
3.7 Socio-Technical Analysis 21
3.8 Final Solution Selection 22

4 Results **23**
4.1 Literature Study 23
4.1.1 Optical Marker-based Body Tracking 23

4.1.2 Optical Markerless Body Tracking 24
4.1.3 Sensor-based Body Tracking 25
4.1.4 Hybrid Systems 26
4.2 Qualitative Study 26
4.2.1 Current Ergonomic Assessment Practices and Opportunities for Body Tracking 27
4.2.2 Technological Considerations 27
4.2.3 Implementation Considerations 28
4.3 Preliminary Technology Screening 29
4.4 Market Research 30
4.4.1 Sensor-based Technologies 30
4.4.1.1 Fluxpose 30
4.4.1.2 QSense 31
4.4.1.3 Wergonic 31
4.4.1.4 Xsens 31
4.4.2 Markerless motion capture technologies 32
4.4.2.1 ErgoPlus 32
4.4.2.2 Gemba Lens 33
4.4.2.3 Kimea 33
4.4.2.4 Occurrence Ergo 33
4.4.2.5 SoterAI 34
4.4.2.6 Theia 35
4.4.2.7 TuMeke Ergonomics 35
4.4.3 Technological Maturity Assessment 36
4.5 Requirement Specification 37
4.5.1 Screening with aspects of Requirement Specification 38
4.6 Testing of Body Tracking Solutions 39
4.6.1 Pilot Test 39
4.6.2 Comparison to Expert Evaluation Test 40
4.6.3 Threshold Crossing Test 41
4.6.4 Evaluation Time Analysis 44
4.7 Socio-Technical Analysis 45
4.7.1 Workflow Compatibility and Integration into Existing Ergonomic Evaluation 45
4.7.2 Practical Usability and Operational Feasibility 47
4.7.3 Organizational Acceptance, Trust, and Data Handling Considerations 48
4.8 Final Solution Selection 49
4.8.1 Modified Ergonomic Evaluation Workflow 51

5 Discussion **53**
5.1 Overall Feasibility of Body Tracking for MEC-Based Ergonomic Evaluation 53
5.2 Technical Performance 54
5.3 Comparison to Ergonomics Expert Evaluation 55
5.4 Body Tracking as Decision-Support 56

5.5 Evaluation Time and Workload Redistribution 56
5.6 Workflow Compatibility 57
5.7 Transparency, Trust, and User Acceptance 58
5.8 Socio-Technical Limitations 59
5.9 Methodological Limitations 60
5.10 Future Work 61
5.10.1 System Reliability and Broader Validation 61
5.10.2 Risk Classification and Longer Work Cycles 62
5.10.3 MEC-Specific System Adaptation 62
5.10.4 UI/UX and Socio-Technical Pilot Implementation 63

6 Conclusion 65

References 72

A Requirement Specification I

B Summary of information from company ergonomists Michael Schröder and Elin Algurén V

C Summary of interview with Jörgen Eklund, Professor Emeritus VII

D Summary of interview with Liyun Yang, Assistant Professor Karolinska Institutet IX

E Summary of interview with Lars Hanson XI

F Summary of interview with Health and Safety Ambassadors and Environmental Technician XIII

G Summary of interview with the Union and Safety Representatives XV

H Summary of interview with Volvo Employees responsible for Gemba lens in France XVII

I Detailed System–Expert Comparison Tables Used for MAD Calculations XIX

List of Figures

1.1 MEC category 1, 2, 8, 9, 10, and 11. Adapted from Volvo Group internal documentation. 3

2.1 Illustration of the four main categories of body tracking technologies. The images were generated using ChatGPT and are intended for illustrative purposes only. 9

3.1 Flowchart over the project. 13

4.1 Example of output from ErgoPlus software. 32
4.2 Example of output from Occurrence Ergo software. 34
4.3 Example of output from SoterAI software. 35
4.4 Example of output from TuMeke software. 36
4.5 Modified ergonomic evaluation workflow. 51

List of Tables

3.1 TRL scale and description of each level. 17

4.1 Preliminary technology screening of body tracking technologies based on operational burden criteria. 29
4.2 The preliminary technology screening outcome 30
4.3 Output of market research 30
4.4 Estimated TRL of identified body tracking solutions. 37
4.5 MAD for production videos captured from Angle 1. 40
4.6 MAD for production videos captured from Angle 2. 40
4.7 MAD for simulated production videos. 40
4.8 MEC threshold crossing test results, ErgoPlus 41
4.9 MEC threshold crossing test results, Occurrence Ergo 42
4.10 MEC threshold crossing test results, SoterAI 43
4.11 MEC threshold crossing test results, TuMeke 44
4.12 Approximate evaluation time for the investigated systems compared with manual ergonomic evaluation 45
4.13 Summary of decision-relevant differences between the investigated markerless systems. 50

A.1 Requirement Specification I
A.1 Requirement Specification II
A.1 Requirement Specification III

I.1 Comparison between the investigated systems and ergonomics expert evaluation for Production Video 1 XIX
I.2 Comparison between the investigated systems and ergonomics expert evaluation for Production Video 2 XX
I.3 Comparison between the investigated systems and ergonomics expert evaluation for Production Video 3 XX
I.4 Comparison between the investigated systems and ergonomics expert evaluation for Production Video 4 XXI
I.5 Comparison between the investigated systems and ergonomics expert evaluation for Production Video 5 XXI
I.6 Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 1. The workstation was designed primarily to affect the shoulders and includes repetitive arm movements. XXII

I.7 Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 2. The workstation was designed to involve a combination of different tasks to target the upper-body. XXII
I.8 Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 3. The workstation involved lifting and carrying and was designed primarily to affect the trunk and shoulders. XXIII
I.9 Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 4. The workstation was designed to involve repetitive arm and wrist movements. XXIII

1 Introduction

Ergonomic evaluations are an important part of industrial production environments, where they are used to identify work-related musculoskeletal risk factors and support improvements in workstation design and work organization. At Volvo Trucks Tuve, ergonomic assessments are currently performed manually using video recordings analyzed according to the internal Manufacturing Ergonomics Checklist (MEC) methodology. During the evaluation process, ergonomists manually identify and count predefined high-risk postures and movements and tasks associated with ergonomic risk. While the current evaluation procedure provides structured ergonomic assessments, it is also highly time-consuming. According to ergonomics specialists at the Tuve plant, the evaluation of a single workstation video may require up to two hours of manual analysis. This challenge is further amplified by the large number of workstations at the factory, approximately 600, and by the recurring nature of the evaluations. Consequently, the current workflow limits the ability of ergonomists to perform frequent assessments and allocate time toward preventive and improvement-oriented activities.

To address these challenges, Volvo Trucks Tuve proposed investigating whether body tracking technologies could support or partially automate parts of the existing ergonomic evaluation workflow. Recent developments in motion capture, wearable sensors, computer vision, and AI-based pose estimation have increased the industrial interest in technologies capable of capturing and analyzing human movement automatically. Such systems may offer opportunities to reduce manual workload, shorten evaluation lead times, and improve the consistency of ergonomic assessments. However, the practical applicability of body tracking technologies in industrial environments depends not only on posture tracking capability, but also on factors such as usability, workflow compatibility, robustness in production environments, and organizational acceptance.

This thesis therefore investigated the feasibility of applying body tracking technologies to support ergonomic evaluation at Volvo Trucks Tuve. The study includes identification and evaluation of commercially available body tracking systems, comparison of selected technologies against ergonomics expert evaluation, and analysis of socio-technical factors influencing practical implementation in an industrial production environment.

1.1 Aim and Objective

The aim of this thesis was to investigate whether body tracking technologies can support and partially automate ergonomic evaluations at Volvo Trucks Tuve. More specifically, the study aimed to identify and evaluate body tracking systems capable of supporting the existing MEC-based ergonomic assessment workflow by detecting and quantifying predefined high-risk postures and movements. In addition to technical performance, the study also investigated the practical feasibility of implementing such technologies within an industrial production environment. This includes aspects related to usability, workflow integration, data accessibility, operational constraints, and organizational acceptance. To achieve this, commercially available body tracking systems were identified, evaluated, and tested against ergonomics expert assessment in both controlled and production-related scenarios. Based on the technical evaluation and socio-technical analysis, the study further assessed the suitability of the investigated systems for practical ergonomic evaluation at Volvo Trucks Tuve.

1.2 Scope and Delimitations

The thesis aimed to facilitate the work involved in evaluating items No. 1 and 2 under MEC-chapter "Workstation Design", as well as items No. 8, 9, 10, and 11 under MEC-chapter "Upper Body" of the MEC, covering assessments of working reach (distance of hand movements relative to the workbench and body) and upper-body joint angles including wrist, shoulder, back, trunk, and neck postures (see Figure 1.1). Furthermore, the study focused exclusively on body tracking technologies that are currently available on the market, in order to ensure the feasibility of delivering a functional and implementable solution within the scope and timeframe of the project. However, the project did not consider the work associated with evaluating other MEC items beyond those specified above. Additionally, the project did not aim to update, develop, or improve the existing MEC Excel spreadsheet or redesign the overall ergonomic evaluation system. Although the project adopts a socio-technical perspective, it was not within the scope to reorganize roles, responsibilities, or implement organizational change processes. Instead, the study analysed these aspects only to the extent necessary to assess the feasibility and implications of introducing body tracking technology. Furthermore, the thesis did not include an evaluation of user interface (UI) or user experience (UX) design. While usability and workflow compatibility were considered as part of the socio-technical analysis, the study focused primarily on the functional suitability of the investigated systems. Consequently, aspects such as visual interface design, interaction design, and the broader user experience of the systems were outside the scope of the project. Lastly, time was also a limitation, as this project was conducted during the spring semester and was therefore limited to approximately 20 weeks, with an estimated workload of 8 hours per working day.

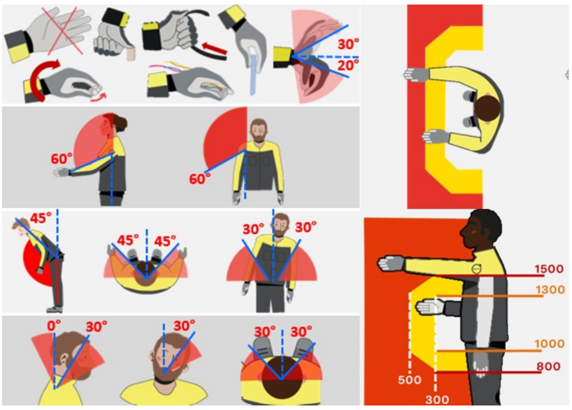


Figure 1.1: MEC category 1, 2, 8, 9, 10, and 11. Adapted from Volvo Group internal documentation.

1.3 Research Questions

Since the project addresses both technical performance and the integration of such technology into existing work practices, the research questions focus on efficiency, assessment capability, and socio-technical feasibility. The questions therefore examine not only how well body tracking systems perform in relation to current manual methods, but also the contextual factors that may influence their practical use in an industrial environment. Consequently, this study aims to answer the following research questions:

- **RQ1:** To what extent can body tracking technologies support ergonomic evaluation while reducing evaluation time and workload compared to current ergonomic assessment at Volvo Trucks?
- **RQ2:** To what extent do selected body tracking technologies detect MEC-defined high-risk postures in agreement with ergonomics expert evaluation?
- **RQ3:** To what extent can body tracking evaluation be limited by socio-technical aspects?

1.4 Stakeholder Analysis

As part of this master's thesis, a stakeholder analysis was conducted to identify the stakeholders affected by the project (Berlin et al., 2022). The analysis revealed several groups that are directly or indirectly connected to the development, implementation, and potential impact of the proposed body tracking–based solution. Volvo Group is the primary stakeholder and project client. The company has defined the problem context and provided the industrial environment in which the solution is to be evaluated. Volvo's interest lies in improving the efficiency, scalability, and objectivity of ergonomic assessments, while ensuring that any proposed solution is compatible with existing workflows, safety requirements, and production constraints. The company will also act as the main decision-maker regarding potential future implementation.

The ergonomics team and personnel conducting ergonomic evaluations at the Tuve plant represent the primary end users of the solution. Their work currently involves manual and time-intensive evaluation procedures. The proposed system may significantly influence their work processes by reducing repetitive analysis tasks and enabling a shift toward more preventive and improvement-oriented activities. Their practical experience is essential for defining functional requirements and for assessing the usability and relevance of the developed solution.

Production operators constitute an important stakeholder group, as they are directly affected by both the ergonomic risks being assessed and any changes resulting from improved evaluation methods. Although they are not primary users of the body tracking system, their work tasks and movements form the basis of the data being analysed. The implementation of more efficient ergonomic assessments may lead to improved workstation design, reduced physical strain, and a lower risk of work-related musculoskeletal disorders (Hosseini et al., 2025). At the same time, considerations related to worker acceptance, transparency, and data handling are important, as the technology involves recording and analysing human motion in the workplace (Jacobs et al., 2019; Schall et al., 2018).

The project team (thesis authors) is an operational stakeholder responsible for investigating, evaluating, and recommending suitable technological solutions. Through daily collaboration with engineers and ergonomists at the Tuve plant, the team ensures that the work remains aligned with industrial needs while contributing technical expertise in production engineering and digital technologies.

Chalmers University of Technology, represented by the examiner of the project team, is an academic stakeholder. Their role is to ensure scientific quality, methodological rigor, and ethical compliance. While not directly affected by the technical outcome, they influence how the study is conducted and validated. The industrial supervisors at Volvo Trucks also represent an important stakeholder group. Their role is to guide the project from an industrial perspective, ensuring that the work remains aligned with the company's needs, constraints, and operational realities. They contribute practical knowledge of production processes and organizational conditions, influencing the direction, feasibility, and relevance of the proposed solution. Although they are not direct users of the system, their involvement is essential in bridging the academic work with industrial implementation considerations. Technology suppliers of body tracking systems are also stakeholders, as their products are evaluated within the project. Their interest lies in demonstrating the applicability of their systems in an industrial context, potentially opening new market opportunities. However, this creates a need for critical and independent evaluation, as vendors may present their technologies in an overly favourable manner.

Regulatory and societal stakeholders, including EU occupational health and safety regulations and industry standards, indirectly influence the project by shaping the requirements for ergonomic risk management. Regulations and initiatives are increasingly providing companies with stricter requirements regarding ergonomics and worker health across the European Union. This development encourages Volvo and other companies to place greater focus on ergonomics and the human aspects of the work environment. In addition, various rankings and certifications related to workplace environment and sustainability provide companies with marketing opportunities and can enhance their employer brand and public reputation.

Finally, other industrial companies may be considered potential future stakeholders. If successful, the project outcomes could be transferable to other production environments where swifter ergonomic evaluation is needed.

2
Theoretical Background

This chapter presents the theoretical foundation relevant to the study, including ergonomics in industrial work environments, body tracking technologies, and socio-technical aspects of technology implementation. The chapter further introduces technical and organizational factors influencing the applicability of body tracking systems for ergonomic evaluation in industrial production environments.

2.1 Ergonomics in Industrial Work Environments

Work-related musculoskeletal disorders (WMSDs) represent one of the most common occupational health challenges in industrial production environments (Ding et al., 2023). Such disorders are commonly associated with repetitive motions, awkward postures, static work positions, and excessive physical loads (Da Costa & Ramos Vieira, 2010), and frequently affect areas such as the back, neck, shoulders, and upper limbs (Yang et al., 2023). In manufacturing and assembly operations, where several ergonomic risk factors often coexist, the risk of developing WMSDs is therefore particularly pronounced (Occupational Safety and Health Administration, 2024). In addition to their impact on worker health and well-being, inadequate ergonomic conditions may also contribute to reduced productivity, increased absenteeism, higher healthcare costs, and long-term workforce sustainability challenges (Mokhasi, 2022). Consequently, systematic ergonomic evaluation and continuous workstation improvement play an important role in modern industrial production. Previous research has shown that ergonomic interventions may reduce injury rates, improve worker well-being, and support operational performance (Hosseini et al., 2025; Zare et al., 2016). From an organizational perspective, ergonomics has increasingly become associated not only with occupational safety, but also with productivity, operational continuity, and sustainable production systems (Płaza et al., 2025; Smagacz, 2025).

However, achieving systematic ergonomic evaluation requires reliable methods for assessing human movement, posture, and physical workload. Traditional ergonomic assessment methods often rely on observational techniques, manual video analysis, or self-reported data, which may be time-consuming, subjective, and difficult to scale in complex industrial environments. Several studies have also highlighted limitations related to reliability and consistency in observational ergonomic assessment methods. For example, Schwartz et al. (2019) reported high intra-rater reliability but only moderate inter-rater reliability when using the REBA method in field conditions, indicating that different ergonomists may not fully agree when evaluating the same working posture. Similarly, Bao et al. (2009) demonstrated that reliability differs significantly between posture types and is influenced by factors such as camera angle, video quality, rater training, and posture categorization strategy. The study further suggested that observational methods are generally more suitable for broad ergonomic risk categorization than for precise joint angle measurement. Additionally, observational assessments often capture only short observation periods rather than complete work cycles, potentially leading to underestimation of cumulative exposure and peak loads (Abd Jalil et al., 2025).

These limitations have contributed to increasing interest in objective and automated technologies capable of continuously quantifying human movement and biomechanical loading. This development aligns with broader trends in industrial digitalization and data-driven decision-making (Chiappe et al., 2018). Body tracking technologies have therefore emerged as a promising approach for objective ergonomic assessment by enabling digital reconstruction and analysis of human movement in three-dimensional space. Compared with traditional observational methods, body tracking systems may offer improved measurement repeatability, higher measurement resolution, and the ability to capture dynamic movement patterns across complete work cycles (Rybnikár et al., 2023). Advances in wearable sensors, computer vision, and real-time processing have additionally enabled motion analysis outside laboratory environments, increasing the industrial interest in body tracking technologies for occupational ergonomics applications (Chiappe et al., 2018).

2.2 Body Tracking Technology

Body tracking technologies capture and digitally reconstruct human movement using sensing principles such as optical tracking, wearable inertial sensors, and computer vision-based pose estimation (Roggio et al., 2024; Salisu et al., 2023). These technologies are used across application areas including virtual reality, sports science, healthcare, rehabilitation, and ergonomics. Depending on the underlying sensing principle, body tracking systems differ considerably in terms of measurement accuracy, robustness, infrastructure requirements, ease of implementation, and accessibility of generated motion data (Adlou et al., 2025; Gutierrez et al., 2024; Suo et al., 2024).

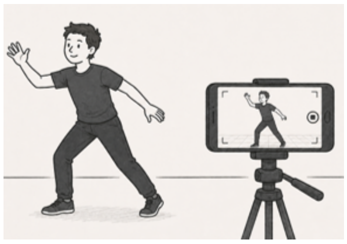
In the context of industrial ergonomic evaluation, such differences become particularly important since production environments often involve practical constraints related to setup time, worker mobility, occlusion, environmental disturbances, and workflow integration. Consequently, evaluating the applicability of body tracking technologies for ergonomic assessment requires consideration not only of posture tracking capability, but also of implementation-related factors associated with industrial use.

The principal technological approaches used for body tracking can generally be categorized as follows:

- **Optical Marker-based Body Tracking:** Systems using reflective or active markers tracked by external cameras to reconstruct human movement, as seen in Figure 2.1a.
- **Optical Markerless Body Tracking:** Systems relying on computer vision and artificial intelligence to estimate human pose directly from video data without physical markers, as seen in Figure 2.1b.
- **Sensor-based Body Tracking:** Systems using wearable sensors containing accelerometers, gyroscopes, and/or magnetometers to estimate body segment motion, as seen in Figure 2.1c.
- **Hybrid / Sensor Fusion Systems:** Systems combining multiple sensing principles to improve robustness and measurement performance, as seen in Figure 2.1d.

These technological categories represent the main approaches currently used for digital human motion capture. Since each approach is associated with different strengths and limitations regarding measurement performance, usability, robustness, and operational complexity, their suitability for industrial ergonomic evaluation may differ substantially depending on the intended application context.

(a) Marker-based



(b) Markerless

(c) Sensor-based

(d) Hybrid

Figure 2.1: Illustration of the four main categories of body tracking technologies. The images were generated using ChatGPT and are intended for illustrative purposes only.

2.3 Socio-Technical Aspects of Technology Implementation

The implementation of new technologies in industrial environments does not solely depend on technical performance, but also on how well the technology interacts with existing work practices, organizational structures, and user needs. Socio-technical systems theory describes organizations as systems consisting of interconnected technical and social subsystems that must function together in order to achieve successful system performance (Baxter & Sommerville, 2011). Within this perspective, the technical subsystem includes technologies, tools, and work processes, while the social subsystem includes workers, competencies, organizational structures, communication, and workplace culture. Consequently, the successful implementation of a new technology depends not only on whether the system performs its intended technical task, but also on whether it can be integrated into the existing organizational and human context. This is further supported by previous research showing that technically functional systems may still fail during implementation if social and organizational aspects are not sufficiently considered. Eason (1988) argues that technology adoption is influenced not only by technical functionality, but also by organizational conditions, user acceptance, and how the technology affects existing work routines and responsibilities. According to Eason's three-level model, implementation outcomes are shaped by factors related to the primary task, the organizational context, and the external environment. In industrial contexts, this may include factors such as compatibility with existing workflows, required competence, organizational support, and regulatory requirements.

Within manufacturing environments, increasing digitalization has led to growing interest in technologies capable of automatically collecting and analyzing production and worker-related data (Chiappe et al., 2018). In ergonomics, technologies such as motion capture systems, wearable sensors, and AI-based posture analysis have shown potential to support more objective and efficient ergonomic evaluations (Roggio et al., 2024; Salisu et al., 2023). However, the implementation of such systems may also introduce socio-technical challenges related to usability, worker acceptance, trust in automated measurements, and concerns regarding monitoring and privacy (Jacobs et al., 2019; Schall et al., 2018). Several studies have highlighted that worker acceptance is an important factor when introducing wearable or monitoring technologies in occupational environments. Schall et al. (2018) reported that workers' perceptions of comfort, usability, autonomy, and trust may significantly influence acceptance of occupational technologies. Similarly, Jacobs et al. (2019) emphasize that technologies involving the collection of worker-related data may create concerns regarding surveillance, privacy, and how collected information could potentially be used by organizations. Such concerns may become particularly relevant in industrial production environments, where technologies continuously record worker movements and behaviors.

In addition to user acceptance, practical integration into existing work processes represents an important socio-technical consideration. Baxter and Sommerville (2011) argue that successful implementation requires alignment between technical systems and organizational workflows. Within ergonomic assessment, this may include aspects such as system usability, setup time, required training, compatibility with existing ergonomic methodologies, and the accessibility of generated data. Technologies requiring extensive calibration, advanced technical expertise, or substantial changes to established work routines may therefore face barriers to implementation despite strong technical performance.

In the context of ergonomic evaluation at Volvo Trucks Tuve, the introduction of body tracking technologies may influence not only the technical process of posture analysis, but also the work practices and responsibilities of ergonomists and production personnel. Factors such as usability, workflow compatibility, trust in generated ergonomic outputs, data management, and worker acceptance may therefore influence the feasibility of implementing body tracking technologies as part of the existing ergonomic evaluation system. Consequently, a socio-technical perspective is considered relevant in order to evaluate not only the technical capabilities of the investigated systems, but also their potential applicability within a real industrial production environment.

3

Methodology

This thesis adopted an applied engineering and socio-technical research approach. The purpose of the study was not only to evaluate the technical feasibility of body tracking technologies for ergonomic assessment, but also to examine how such a solution could be integrated into the existing ergonomic evaluation practices at Volvo Trucks Tuve. To address both technical and organizational aspects of this case, the methodology was structured as a sequence of coherent phases. A visualisation of the phases, and the order in which they were performed, can be seen in Figure 3.1. This structure helped ensure that the proposed solution was technically grounded, user-oriented, and realistic to implement in an industrial context.

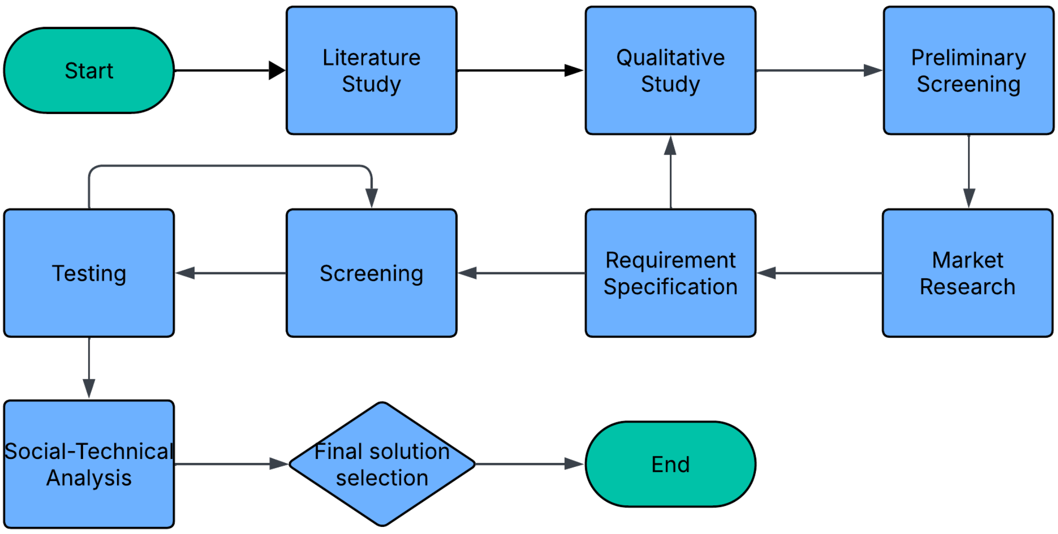


Figure 3.1: Flowchart over the project.

3.1 Literature Study

A literature study was conducted to establish the scientific and technical foundation of the project. The review focused on body tracking technologies based on optical, sensor, and hybrid sensing principles, as well as their use in ergonomic applications. Particular attention was given to methods for posture analysis, joint angle estimation, and detection of movement patterns associated with ergonomic risk.

In addition, the literature was used to identify known technical limitations of tracking systems in real-world environments, such as occlusion, sensor drift, and environmental disturbances. By linking these technological characteristics to ergonomic assessment tasks similar to those currently performed manually at the Tuve plant, the literature study supported the later evaluation and selection of suitable systems. Relevant studies were identified through searches in academic databases such as Scopus, the Chalmers Library, and the search engine Google Scholar. Examples of search keywords used in the literature review are presented below.

- ("body tracking" OR "motion capture") AND ("ergonomic assessment" OR ergonomics)
- ("body tracking" OR "motion capture") AND ("industrial ergonomics" OR manufacturing)
- ("motion capture" OR "body tracking") AND ("joint angle" OR "posture detection")
- ("ergonomic assessment" OR "occupational ergonomics") AND ("manual assembly" OR "production environment")

3.2 Qualitative Study

To ensure that the proposed solution addressed real operational needs, a qualitative study was conducted with stakeholders at Volvo Trucks Tuve and external experts in ergonomics, body tracking, and industrial technology implementation. The study consisted of iterative stakeholder dialogues with the industrial supervisors throughout the project, as well as semi-structured interviews with selected stakeholders and experts. The participants were selected based on their relevance to the project, including their experience of ergonomic evaluation, production work, technology implementation, or worker representation.

The interviews followed an interview guide with predefined topic areas, while still allowing the participants to elaborate freely on issues they considered important. Topics included current ergonomic evaluation practices, limitations of manual video analysis, technical and practical requirements for body tracking systems, usability, workflow compatibility, trust, worker acceptance, and data handling. The iterative dialogues with the company supervisors were used to continuously clarify the MEC-based workflow, refine requirements, and validate whether emerging findings were relevant in the industrial context. Notes were taken during interviews and discussions and were condensed into summaries, presented in Appendices B–G. The material was analysed by grouping recurring statements and observations into themes such as current evaluation challenges, technical requirements, implementation constraints, workflow compatibility, transparency, and trust.

3.3 Preliminary Technology Screening

Based on insights obtained from the literature study and the qualitative investigation with ergonomics experts and industrial stakeholders, a preliminary screening of body tracking technology categories was conducted. The purpose of this step was to identify technology principles that were considered operationally feasible for the industrial production environment at Volvo Trucks Tuve before proceeding with a more detailed market investigation and requirement-based screening. At this stage of the project, the screening focused on technology categories rather than individual commercial solutions. The objective was therefore to filter out technology principles that would be difficult to implement in a dynamic production environment where ergonomic evaluations may be conducted across multiple workstations.

The selection of screening criteria was guided by the primary objective of the project, which was to reduce ergonomic evaluation lead time while maintaining operational feasibility. Since current evaluations at the Tuve plant are time-intensive and sometimes performed within active production environments, operational feasibility was considered a key factor during the early stages of technology selection.

Consequently, the screening criteria focused on operational aspects related to system deployment and usability rather than detailed performance metrics. Four operational feasibility criteria were defined:

- **Deployment time per workstation:** The estimated time required to prepare and initiate measurement at a specific workstation.
- **Infrastructure dependency:** The extent to which fixed environmental setup (e.g., multiple cameras or defined capture volumes) is required.
- **Relocation effort across workstations:** The degree of effort required to move and redeploy the system between different workstations.
- **Operational setup complexity:** The level of preparation, calibration, and technical expertise required to configure and operate the system in daily ergonomic evaluation practice.

These criteria reflected constraints directly related to the industrial context and the intended practical implementation of the system.

3.3.1 Justification of Qualitative Ratings

The qualitative ratings presented in Table 4.1 were derived from a contextual assessment informed by findings from the literature study, qualitative study, and analysis of the production environment at Volvo Trucks Tuve. The ratings represent the relative operational burden associated with each technology category in relation to the defined screening criteria.

- **Low** indicates limited operational burden and minimal impact on deployment time, infrastructure requirements, relocation effort, or setup complexity.
- **Medium** indicates moderate operational burden that can be managed within production constraints but requires some preparation, configuration, or adaptation.

- **High** indicates substantial operational burden, such as extensive infrastructure requirements, prolonged deployment time, significant relocation effort, or high setup complexity.

The ratings represent relative qualitative assessments made by the project team (thesis authors) within the specific context of the Tuve production environment and should therefore not be interpreted as quantitative performance measurements.

3.4 Market Research

Following the preliminary technology screening, a market research was conducted to identify commercially available body tracking solutions still deemed applicable to the industrial production environment at Volvo Trucks Tuve. The market research included a review of supplier documentation, comparison of technical specifications, and, when relevant, communication with technology suppliers. The purpose of this phase was to map existing systems and identify potential solutions that could be applicable within the industrial production environment at Volvo Trucks Tuve. The outcome of the market research was a set of candidate technologies and suppliers that were considered suitable for further evaluation within the scope of the project. As part of the market research phase, the identified technologies were also evaluated using the Technology Readiness Level (TRL) framework. The TRL model, originally developed by NASA, is used to estimate the maturity of technological solutions and consists of nine levels ranging from basic research to fully operational systems (National Aeronautics and Space Administration, 2023). The TRL scale and its levels are presented in Table 3.1.

Table 3.1: TRL scale and description of each level.

TRL	Description
1	Basic scientific principles are observed and reported. Research is focused on understanding fundamental phenomena without specific technological applications.
2	A technology concept and possible applications are formulated based on the identified scientific principles.
3	Analytical and experimental studies are performed to demonstrate proof of concept for key functions or components of the technology.
4	The technology is validated in a laboratory environment through initial testing of components or early prototypes.
5	The technology is validated in a relevant environment, meaning conditions that begin to resemble the intended application context.
6	A prototype or system model is demonstrated in a relevant environment to evaluate system performance and functionality.
7	A system prototype is demonstrated in an operational environment, representing a realistic use case.
8	The technology is complete and has been fully tested and qualified to meet operational requirements.
9	The technology has been proven through successful operation in its intended real-world environment.

In this project, TRL assessments were used to evaluate whether the identified body tracking technologies had reached a sufficient level of maturity for realistic industrial implementation within the scope of the project. Consequently, the estimated TRL levels were compared against a minimum required maturity level defined in the requirement specification. Furthermore, the estimated TRL levels were assessed specifically in relation to the applicability of the technologies for ergonomic evaluation and biomechanical assessment in industrial environments, rather than for their general technological maturity across all application domains. Consequently, technologies that are commercially mature within other application areas, such as gaming or virtual reality, could still receive lower estimated TRL levels if their ergonomic assessment capabilities within industrial environments were considered insufficiently validated. The estimated TRL levels for each solution were assessed by the project team based on available supplier documentation, published studies, and information obtained through communication with technology providers.

3.5 Requirement Specification

Based on findings from the qualitative study and the industrial conditions at Volvo Trucks Tuve, a requirement specification was developed to support the evaluation of suitable body tracking technologies. The purpose of the requirement specification was to translate identified user needs, ergonomic assessment tasks, and practical implementation constraints into structured technical and operational evaluation criteria.

The requirement specification was developed iteratively from the current MEC-based ergonomic evaluation procedure at Volvo Trucks Tuve, stakeholder input, and practical constraints identified in the industrial production environment. Technical requirements, such as posture tracking capability, joint angle estimation, and detection of MEC-defined risk postures, were primarily based on the MEC items included within the scope of the thesis. Operational and implementation-related requirements, such as setup time, workflow compatibility, and data accessibility, were informed by discussions with stakeholders, observations from the production context, and findings from the market research and preliminary screening. Socio-technical literature was used to support the interpretation of broader implementation aspects, including trust, user acceptance, data handling, and integration into existing work practices.

The requirement specification distinguished between mandatory requirements (R) and desirable features (D). Requirements represented conditions that had to be fulfilled for a technology to be considered relevant within the scope of the project, while desires represented additional features considered beneficial for practical implementation and usability. Desires were assigned qualitative weights between 1 and 3, where higher values represented higher importance. The was based on the perceived relevance of each feature for practical ergonomic evaluation at Volvo Trucks Tuve.

3.6 Testing of Body Tracking Solutions

Several tests and experiments were conducted to evaluate the applicability of body tracking technologies for ergonomic assessment at the Tuve plant. The testing phase included both exploratory pilot testing in a real production environment and more structured comparison experiments performed under controlled conditions. Representative work tasks relevant to the MEC framework were recorded and analyzed using the investigated systems. The collected motion data were used to evaluate aspects such as posture tracking capability, threshold crossing detection, practical usability, and the time required to perform ergonomic assessments. In addition, the system outputs were compared with ergonomics expert evaluations to assess agreement and identify practical limitations.

3.6.1 Pilot Test

A pilot test was conducted at the Tuve plant to gain practical experience of using body tracking systems in a real production environment before the main experiments. The pilot included the systems that were available for early practical testing and was carried out during a series of real production tasks on the assembly line. The purpose was not to formally evaluate system accuracy or compare system performance, but to understand how the systems functioned in practice under industrial conditions. The pilot was used to observe practical aspects such as initialization procedures, recording workflow, camera placement, occlusion, tracking stability, and the influence of confined working positions. These observations provided early insight into factors that could affect data collection and usability in later testing. The experience from the pilot was therefore used to refine the recording strategy and experimental setup for the subsequent comparison tests.

3.6.2 Comparison to Expert Evaluation Test

A comparison experiment was conducted to compare the ergonomic risk zone detections generated by different body tracking technologies with evaluations performed by an ergonomics expert using the MEC methodology. The experiment included both recordings from a real production environment and simulated workstations designed to emphasize different body regions and movement patterns relevant to the MEC framework.

Five recordings were collected from an ergonomically demanding workstation at the Tuve production line. The workstation involved physically demanding and varying assembly tasks performed in confined working positions. The work required movements ranging from kneeling positions to substantial forward bending and overhead work. Each recording was captured simultaneously from two different camera angles: one more favorable angle from the front or side of the operator, and one less favorable angle captured from behind the operator.

In addition, four simulated workstation videos were created to isolate and emphasize different types of movements and body regions. One station focused primarily on arm and shoulder movements, one involved a combination of movements targeting the upper-body, one focused primarily on trunk- and shoulder-related movements, and one involved repetitive arm and wrist movements. The recordings were conducted using the same overall procedure as for the real production recordings, with the primary difference being the performed work tasks.

The recordings were thereafter processed using the investigated body tracking systems. After each video had been processed, the generated ergonomic outputs were extracted and noted in its own spreadsheet. To be able to compare the generated outputs with the corresponding ergonomics expert evaluations, the mean absolute deviation (MAD) was used to summarize the average difference between the system outputs and the ergonomics expert evaluation. MAD was calculated according to Equation 3.1.

$$MAD = \frac{\sum_{i=1}^{n} |S_i - E_i|}{n} \quad (3.1)$$

where S_i represents the number of risk-zone occurrences reported by the body tracking system for video i, E_i represents the corresponding number of occurrences identified by the ergonomics expert, and n represents the number of videos included in the comparison. The MAD values were calculated separately for each body region available in each system, and an overall MAD was calculated as the mean of the available MAD values for each system. Since the systems did not report identical output categories, missing or unsupported categories were excluded from the overall MAD calculation rather than treated as zero.

3.6.3 Threshold Crossing Test

The comparison with ergonomics expert evaluations demonstrated how the systems performed during realistic work tasks. However, since work cycles are not performed identically between repetitions, differences between systems could potentially originate from variations in task execution rather than from the systems themselves. A supplementary threshold crossing test was therefore conducted to evaluate the systems under more controlled movement conditions. In this test, predefined isolated body motions were performed to angular positions corresponding to selected MEC threshold values. The threshold angles were measured beforehand using a goniometer and represented the decision boundaries between the green and red zones defined within the MEC framework.

For each motion, the MEC threshold position were marked on a whiteboard positioned behind the test subject. These markings were used both as visual guidance during the movements and as a reference during subsequent video review to verify that the intended threshold angles had been reached.
The following motions were included in the test:

- Right and left shoulder abduction
- Right and left shoulder flexion
- Trunk flexion and extension
- Trunk right and left tilt
- Trunk right and left twist
- Neck flexion and extension
- Neck right and left tilt
- Neck right and left rotation
- Wrist flexion and extension

Each motion was performed ten times. The test subject started from a neutral position and exceeded the threshold angle with a clear margin before briefly holding the posture and returning to the neutral position. All movements were recorded using a mobile camera with in a fixed angle and an unobstructed view of the subject. The recordings were thereafter analyzed using the investigated body tracking systems.

For each motion and system, the number of Detected Threshold Crossings (DTC) was compared with the Actual Threshold Crossings (ATC) observed in the video recordings. DTC represents the number of times the system identified that a predefined angular threshold had been exceeded, while ATC represents the number of threshold crossings actually performed during the repetitions. In addition, qualitative observations were made regarding the reported joint angles, including whether the systems appeared to systematically underestimate certain movements or failed to detect specific postures. Since no direct quantitative comparison with goniometer measurements was performed, these observations were primarily used to support interpretation of discrepancies between DTC and ATC.

3.6.4 Evaluation Time Analysis

An evaluation time analysis was conducted to estimate the potential reduction in ergonomic assessment lead time when using the investigated body tracking systems compared with the current manual evaluation workflow used at Volvo Trucks Tuve. The analysis focused on the time required to process a recorded workstation video and obtain ergonomic outputs that could be used as input for the MEC-based assessment procedure. For each investigated system, the measured duration included the time required to upload the video, process the recording, and access the generated ergonomic outputs. In addition to the measured processing time, the need for additional manual interpretation was also considered, since some systems required further manual counting or interpretation of joint angle graphs before the outputs could be used in relation to the MEC workflow.

The measured system times were compared with the reported time required for the manual ergonomic evaluation process. To achieve this, based on input from the ergonomics specialists, this value was linearly scaled to an approximate one-minute reference of up to 20 minutes in order to enable comparison with the investigated systems, which were evaluated using videos of approximately one minute. Furthermore, to estimate the potential implications of the observed time differences in a large-scale industrial application, the measured evaluation times for one-minute videos were extrapolated to six-minute videos and further scaled to 600 workstations, corresponding to the approximate number of workstations reported for the factory. The resulting values therefore served as indicative estimates rather than exact implementation times.

3.7 Socio-Technical Analysis

Following the technical evaluation, a socio-technical analysis was conducted to assess factors influencing the practical implementation of body tracking technologies within the ergonomic evaluation workflow at Volvo Trucks Tuve. While the technical experiments provided insight into posture tracking capability and evaluation performance, the socio-technical analysis focused on aspects related to workflow integration, usability, organizational compatibility, user acceptance, and practical implementation constraints. The analysis was based on information collected throughout the project, including findings from the qualitative study, observations made during testing and system evaluation, discussions with ergonomists and production personnel, supplier interactions, and organizational constraints identified during the project. Particular attention was given to factors considered important for realistic industrial implementation, such as setup complexity, calibration requirements, portability between workstations, accessibility of generated ergonomic data, compatibility with existing MEC-based workflows, and the extent to which the systems reduced or redistributed ergonomic evaluation workload. In addition, the analysis included considerations related to worker acceptance, trust in automated measurements, data handling, and concerns associated with recording and analyzing worker movements in production environments. Practical limitations related to production conditions, including occlusion, environmental disturbances, and safety considerations were also considered as part of the implementation analysis.

The socio-technical analysis was structured using concepts from socio-technical systems theory (Baxter & Sommerville, 2011) and Eason's (Eason, 1988) three-level model of technology implementation. The framework was used to support interpretation of how technical system characteristics interacted with existing organizational structures, work practices, and operational conditions. Particular emphasis was placed on understanding whether the investigated technologies could realistically support and integrate into the current ergonomic evaluation process rather than only demonstrating technical posture tracking capability.

3.8 Final Solution Selection

The final solution selection was based on the preceding evaluation steps. The investigated systems were compared based on their fulfilment of the requirement specification, results from the testing phase, and findings from the socio-technical analysis. Based on this combined assessment, the system considered most suitable for further evaluation and potential implementation at Volvo Trucks Tuve was selected.

4
Results

This chapter presents the results from the different phases of the study. The results are presented in the same overall sequence as the methodology, moving from identification and screening of body tracking technologies to testing and implementation-related evaluation. The chapter concludes with a final solution selection based on the combined findings from the preceding sections.

4.1 Literature Study

The literature study revealed findings regarding body tracking technologies based on optical, sensor, and hybrid sensing principles, as well as their use in ergonomics and occupational health applications.

4.1.1 Optical Marker-based Body Tracking

Optical marker-based body tracking, or marker-based systems for short, capture human movement by placing reflective or active markers on the body, which are then tracked by one or several cameras to reconstruct joint positions, body segments, and postures in a digital environment (Adlou et al., 2025; Roggio et al., 2024). Due to their ability to capture detailed kinematic data with high spatial resolution, these systems are widely used in applications such as sports science, rehabilitation, and ergonomic assessment (Adlou et al., 2025; Gutierrez et al., 2024). In ergonomic contexts, marker-based systems have been used to analyse working postures, joint angles, and movement patterns in order to identify risk factors associated with work-related musculoskeletal disorders (Gutierrez et al., 2024; Salisu et al., 2023). Compared to wearable sensors and markerless systems, marker-based optical systems are generally reported to offer superior measurement accuracy and richer motion data, particularly in controlled environments (Gutierrez et al., 2024; Suo et al., 2024).

However, their suitability for industrial use is limited by several practical constraints. Factors such as marker occlusion, fixed capture volumes, and environmental conditions can reduce their effectiveness in complex production settings (Scataglini et al., 2025). Additionally, marker-based systems typically require time-consuming setup and calibration procedures compared to markerless alternatives (Scataglini et al., 2025). For similar reasons, another study report that both wearable sensor-based and markerless systems are increasingly investigated for industrial ergonomic applications (Salisu et al., 2023). Lastly, Salehi et al. (2026) note that these systems require substantial expertise in data processing and extensive training for marker placement, which limits their suitability for field applications.

4.1.2 Optical Markerless Body Tracking

Optical markerless body tracking, or markerless systems for short, estimate human pose and joint kinematics directly from video data using trained machine learning models, eliminating the need for physical markers or any wearable equipment (Roggio et al., 2024). The technology has shown promising results in applications such as posture analysis, ergonomic risk assessment, and movement monitoring (Roggio et al., 2024; Salisu et al., 2023). In one study, the authors concluded that these types of systems have strong potential to reduce the resources required for ergonomic assessment while improving measurement objectivity and consistency (Bortolini et al., 2018). In this industrial case study, conducted in an automotive assembly environment, it was demonstrated that a markerless depth camera system could identify high-risk ergonomic conditions and provide detailed breakdown analysis of contributing task elements, without requiring operators to wear sensors or specialized suits. Furthermore, Taleb-Salah et al. (2025) concluded that markerless solutions enable non-intrusive measurement using standard video recordings and offer improved scalability and cost efficiency compared to sensor-based systems. Recent developments in deep learning–based pose estimation models also demonstrate strong potential for industrial ergonomic monitoring without requiring body-mounted sensors (Taleb-Salah et al., 2025).

A systematic review by Scataglini et al. (2025) compared marker-based and markerless camera-based motion capture systems found that markerless systems have reached a level of accuracy and reliability sufficient for many industrial ergonomic risk assessment applications. While marker-based systems still provide the highest measurement precision, markerless systems demonstrate moderate to high accuracy while offering significant practical advantages since they eliminate the need for body-mounted sensors, reduce setup time, and minimize interference with natural worker movement, making them more suitable for real-world production environments (Scataglini et al., 2025). Complementing this, Bonakdar et al. (2025) conducted a controlled comparative study directly validating a markerless system against both marker- and sensor-based systems during a standardized lifting task. The study found strong correlation between the markerless system and the marker-based system for back and knee joint angles. Furthermore, the study found that ergonomic risk scores derived from the markerless system matched those from the marker-based system for 87% of participants, providing direct empirical support for the suitability of markerless systems for automated ergonomic risk assessment.

Despite the promising performance mentioned above, challenges still remain. Scataglini et al. (2025) mentions that reliability testing is inconsistently reported across studies, and long-term measurement stability has not been extensively validated, highlighting the need for further research in real production environments. Moreover, performance remains highly dependent on factors such as camera placement, lighting conditions, occlusions, and the complexity of the surrounding environment (Roggio et al., 2024; Salisu et al., 2023). Furthermore, markerless approaches rely heavily on algorithm performance, which can influence both measurement reliability and data accessibility (Roggio et al., 2024). Challenges in occlusion and depth estimation have also been reported, although the measurement robustness is expected to improve as the technology continues to develop (Taleb-Salah et al., 2025). While markerless systems offer clear practical advantages over marker-based approaches in terms of setup simplicity and non-intrusiveness, their accuracy and robustness in real industrial environments require careful consideration when evaluating their suitability for ergonomic assessment applications.

4.1.3 Sensor-based Body Tracking

Sensor-based body tracking systems are wearable alternatives to optical tracking, where human movement is tracked using body-mounted sensors that typically combine accelerometers, gyroscopes, and in some cases magnetometers (Adlou et al., 2025; Suo et al., 2024). By measuring linear acceleration, angular velocity, and orientation, sensor-based systems are able to estimate body segment motion without the need for external cameras (Adlou et al., 2025). As a result, sensor-based systems are particularly suited for applications in dynamic real-world environments (Adlou et al., 2025; Suo et al., 2024).

Sensor-based systems are widely used in fields such as sports science, rehabilitation, and ergonomics, where portability and flexibility are critical (Adlou et al., 2025; Salisu et al., 2023). In ergonomic assessments, wearable inertial sensors have been applied to analyse working postures, joint angles, and manual handling tasks in order to identify risk factors associated with work-related musculoskeletal disorders (Gutierrez et al., 2024; Salisu et al., 2023). Compared to optical tracking systems, sensor-based solutions are reportedly easier to deploy, have lower setup complexity, and do not suffer from visual occlusions, making them an attractive alternative for use in industrial production settings (Gutierrez et al., 2024). These systems have also shown promising results in terms of accuracy. One study reported measurement errors below 1° in static conditions and below 2° in dynamic conditions (Ancans et al., 2021). In the same study, the systems demonstrated the ability to operate without data loss in scenarios where optical systems suffer from marker occlusion. Another study demonstrated that automated ergonomic assessment systems based on sensor data can achieve strong agreement with expert evaluations (Senjaya et al., 2022). In this study, automated RULA scoring based on sensor-based motion tracking data has demonstrated similarity levels exceeding 80% compared to manual ergonomic evaluation.

However, sensor-based tracking systems also have some noticeable drawbacks that must be considered, such as drift and noise originating from the usage of sensors (Gutierrez et al., 2024). Furthermore, the accuracy of sensor-based motion capture can be affected by sensor placement, calibration procedures, and magnetic disturbances in industrial environments (Adlou et al., 2025; Suo et al., 2024). Therefore, while sensor-based systems provide a flexible solution for ergonomic data collection, their suitability for ergonomic evaluation depends on the required level of precision, robustness, and data accessibility for the specific application.

4.1.4 Hybrid Systems

Hybrid, or sensor fusion, tracking systems combine multiple technologies in order to leverage the strengths of each approach while lowering the effect of their individual limitations. In many hybrid systems, sensor-based data are integrated with optical or vision-based tracking to compensate for occlusions, temporary loss of visual information, or limited capture volumes (Menolotto et al., 2020).

More recently, advances in machine learning–based pose estimation have enabled the integration of markerless computer vision with sensor-based tracking in hybrid frameworks. In these systems, pose estimates derived from deep learning models are combined with inertial or electromagnetic sensor data to improve robustness, reduce sensitivity to occlusions, and increase tracking reliability in complex environments (Adlou et al., 2025; Roggio et al., 2024). Such hybrid approaches might be highly relevant in applications that require motion capture outside of controlled laboratory settings.

Within ergonomics, hybrid tracking systems have been proposed as a solution for achieving reliable motion data in real-world conditions (Salisu et al., 2023). By combining multiple sensing principles, these systems can better handle challenges such as occlusions, environmental disturbances, and sensor-errors compared to single-technology solutions. However, hybrid systems also introduce increased complexity in terms of data management, calibration, and implementation (Gutierrez et al., 2024; Salisu et al., 2023). Overall, hybrid and sensor fusion systems could be a suitable solution for automated ergonomic evaluation, however their suitability depends on factors such as implementation, calibration, and data accessibility.

4.2 Qualitative Study

The qualitative study provided insights into current ergonomic evaluation practices, limitations of existing methods, and requirements for potential body tracking solutions in industrial environments. Interviews with ergonomists, academic researchers, production personnel, and union representatives revealed several consistent themes related to measurement practices, technological feasibility, organizational constraints, and worker acceptance. Detailed summaries of the individual interviews are presented in Appendices B-G, while the main findings are synthesized in this section.

4.2.1 Current Ergonomic Assessment Practices and Opportunities for Body Tracking

This section is primarily informed by the empirical findings documented in Appendices B, F, and G.

Across multiple production sites, ergonomic risk assessments are currently conducted using the internal observational method MEC. This approach relies on manual observation of body postures, joint angles, and movement frequencies, often during relatively short observation periods. While widely used across the company, several limitations were identified. Observational assessments are time-consuming, difficult to scale across large numbers of workstations, and subject to variability between assessors. Short observation windows may also fail to capture representative exposure patterns over longer work cycles. In addition, observational video recordings may not always capture all relevant body movements due to obstructed camera views.

Body tracking technologies were generally viewed as promising tools for improving the objectivity and efficiency of ergonomic assessments. Automated measurement systems were perceived as having potential to reduce subjectivity and provide quantitative data describing body angles and movement frequencies. Such data could strengthen decision-making processes and support investments in ergonomic improvements. However, stakeholders consistently emphasized that body tracking technologies should function as decision-support tools rather than fully autonomous assessment systems, with professional ergonomic expertise remaining essential for interpreting results. Furthermore, several stakeholders highlighted the importance of transparency and traceability in how ergonomic results are generated. Systems that allowed users to visually follow and verify the assessment process, for example through synchronized video recordings or visualized posture tracking, were generally preferred over “black-box” solutions that only provided summarized numerical outputs without insight into how the results had been derived.

4.2.2 Technological Considerations

This section is primarily informed by the empirical findings documented in Appendices C, D and E.

Several technological considerations were identified. Marker-based optical motion capture systems were widely regarded as impractical for industrial production environments due to high infrastructure requirements, calibration complexity, and susceptibility to occlusion. Wearable sensor-based systems were considered more feasible for real-world implementation, although they introduce challenges related to calibration procedures, sensor attachment, magnetic interference, and connectivity stability. Measurement accuracy was reported to typically range between approximately 3–10 degrees under appropriate conditions, which was considered sufficient for many ergonomic risk assessments. However, reliability and robustness were emphasized as more critical than achieving maximum technical precision. Markerless systems based on video analysis were also discussed as promising alternatives due to their lower intrusiveness and the widespread availability of camera devices such as smartphones. Nevertheless, these approaches were also mentioned to be sensitive to occlusion and reconstruction errors.

4.2.3 Implementation Considerations

This section is primarily informed by the empirical findings documented in Appendices B, F and G.

Operational constraints in production environments were identified as an important factor influencing technology adoption. Measurement systems must require minimal setup and calibration time, preferably on the order of a few minutes, and should be easy to relocate between workstations. The technology should integrate smoothly with existing evaluation workflows and support standardized assessments across different evaluators and production areas. Reliability, ease of use, and compatibility with existing safety procedures were consistently highlighted as key requirements.

Organizational and socio-technical factors were also identified as critical for successful implementation. Worker acceptance was generally considered achievable, particularly in environments where wearing protective equipment is already common. However, transparency regarding the purpose and use of collected data was emphasized as essential to avoid concerns about performance monitoring or time studies. Participation in assessments should remain voluntary, and collected data should remain within the company's internal infrastructure in accordance with GDPR and internal data governance requirements. Early involvement of operators and other stakeholders, combined with pilot testing and clear communication about how the technology functions, were described as important strategies for building trust and facilitating adoption.

Several functional requirements for potential body tracking systems were also identified. These included the ability to reduce manual counting of movements in defined risk zones, support longer measurement periods to capture representative exposure patterns, and enable structured analysis of work tasks. The possibility to segment work activities into identifiable phases and filter relevant data for deeper analysis was considered particularly valuable for supporting ergonomic evaluations. Flexibility to apply the technology across different occupational roles and workstations was also regarded as advantageous.

Overall, the qualitative study indicated that body tracking technologies have strong potential to enhance ergonomic risk assessment in industrial environments, provided that the systems are reliable, easy to use, integrated with existing workflows, and implemented with careful consideration of organizational, regulatory, and worker-related factors.

4.3 Preliminary Technology Screening

The qualitative assessment of each technology category against the screening criterion are presented in Table 4.1. This resulted in the exclusion of marker-based and hybrid body tracking systems from further evaluation as seen in Table 4.2.

Marker-based optical systems typically require multiple calibrated cameras, reflective markers, and a predefined capture volume. In the context of the Tuve production environment, these characteristics were considered difficult to implement due to the high infrastructure requirements and operational setup complexity. As a result, marker-based systems were not considered suitable for further investigation in this study.

Hybrid systems combine multiple sensing modalities to improve measurement robustness and accuracy. However, these systems generally require additional calibration procedures and integration of both wearable and environmental components. In an industrial production environment where measurements may need to be performed across several workstations, these characteristics were considered to result in high deployment effort and operational complexity. Consequently, hybrid systems were also excluded from further investigation.

In contrast, sensor-based systems and optical markerless systems were identified as having greater potential feasibility in the Tuve production environment. These technologies generally require less fixed infrastructure and can be deployed more flexibly across different workstations. Despite known limitations, such as sensor drift in sensor-based systems and occlusion sensitivity in markerless systems, both technologies were considered compatible with the operational constraints of the production environment for further investigation.

Table 4.1: Preliminary technology screening of body tracking technologies based on operational burden criteria.

Screening Criterion	**Sensor-based**	**Markerless**	**Marker-based**	**Hybrid**
Deployment time per workstation	Medium	Low	High	High
Infrastructure dependency	Low	Low	High	High
Relocation effort across workstations	Low	Low	High	Medium
Operational setup complexity	Medium	Low	High	High

Table 4.2: The preliminary technology screening outcome

Technology	Sensor-based	Markerless	Marker-based	Hybrid
Further Investigation	Yes	Yes	No	No

4.4 Market Research

Following the preliminary technology screening, a market research was conducted to identify commercially available body tracking technologies considered applicable to the industrial production environment at Volvo Trucks Tuve. Several companies and solutions were identified through review of supplier documentation, comparison of technical specifications, and communication with technology providers. The identified technologies are presented below, separated into sensor based and markerless motion capture solutions, and are thereafter assessed using the TRL framework. The market research identified 25 solutions across the sensor-based and markerless technologies. The most relevant of these are discussed in more depth later in this chapter and summarised in Table 4.3 below. Relevance was determined by recurring mentions in academic literature, recommendations from interviewed stakeholders and experts, or different technical approaches considered worth examining.

Table 4.3: Output of market research

Sensor-based technologies	**Markerless technologies**
221e, AMFITRACK, Cometa, dorsaVi, Fluxpose, KNOXLABS, Motio, Noraxon, QSense , Rokoko, SlimeVR, Vicon, Wergonic, Xsens	ART, Azure Kinect DK, DeepLabCut, Ergoplus, Gemba Lens, Kimea, Occurrence, OpenCap, OpenPose, Soter, Theia, TuMeke Ergonomics

4.4.1 Sensor-based Technologies

The subsections below present the sensor-based technologies identified during the market research phase of this project.

4.4.1.1 Fluxpose

FluxPose is a wearable electromagnetic tracking system that provides real-time 6DoF tracking of body-mounted sensors relative to a local beacon. Unlike many other sensor-based systems, the technology does not primarily rely on inertial estimation, but instead calculates tracker position and orientation from controlled electromagnetic fields. The system exports raw positional and rotational tracking data rather than predefined ergonomic metrics or skeletal visualisations. As a result, ergonomic evaluation workflows would need to be developed separately using external analysis pipelines and inverse kinematics models. Furthermore, it was reported that the lack of an ergonomic analysis workflow would require a high degree of custom and internal development. (FluxPose, 2026. Personal communication, 2026)

4.4.1.2 QSense

QSense is a wearable inertial measurement unit (IMU) motion tracking system that captures body movements using synchronized accelerometer, gyroscope, and magnetometer sensors. After calibration, the system continuously tracks body segment orientations and motion data in real time. The platform primarily provides raw kinematic and orientation data rather than predefined ergonomic evaluations. Motion data can be exported in multiple formats for further analysis through external software and custom processing pipelines, allowing ergonomic metrics and threshold-based assessments to be developed separately. Compared to AI-based ergonomic platforms, QSense offers full access to detailed motion data, but also requires additional calibration, technical expertise, and data processing. Furthermore, potential challenges related to magnetic disturbances and sensor placement in industrial production environments were highlighted during discussions with company representatives. (QSense Motion, 2026. Personal communication, 2026)

4.4.1.3 Wergonic

Wergonic is a wearable ergonomic assessment system based on IMU sensors integrated into tight-fitting garments worn underneath regular work clothing. The system combines body-mounted sensors, a mobile application, and a cloud-based analysis platform to generate ergonomic data and statistical results based on worker movements and perform ergonomic risk assessments. The platform supports established ergonomic methods such as MEC, RULA, REBA, and RAMP, and provides processed ergonomic outputs including risk classifications, posture analysis, and suggested improvements. Unlike raw motion capture systems, Wergonic is designed as a more application-oriented ergonomic workflow solution. The system aims to minimize disruption to workers by integrating sensors directly into clothing. However, reliable measurements depend on correct sensor placement, garment fit, and calibration procedures, while environmental disturbances and sensor movement may affect tracking accuracy in industrial settings. In addition, information obtained during the market research and from previous experiences of using the system within Volvo Group indicated that sensor connectivity and system stability could occasionally be affected during operation, potentially resulting in temporary loss of connection between sensors. Such disturbances may influence robustness and practical usability in industrial production environments where reliable and uninterrupted measurements are required. (Wergonic AB, 2026. Personal communication, 2026)

4.4.1.4 Xsens

Xsens is a wearable IMU-based motion capture system where multiple body-mounted sensors are attached directly to the operator using straps. After calibration, the system continuously tracks body segment orientations and joint kinematics in real time. Unlike AI-based video systems, Xsens primarily functions as a motion capture platform that provides detailed kinematic data rather than ready-made ergonomic assessments. Joint angles, segment positions, and raw motion data can be exported for further analysis through external software or custom workflows. The system has been widely used in biomechanics research and industrial ergonomics and was frequently described as a reference-quality solution. However, the need for multiple wearable sensors, calibration procedures, and technical data handling increased the operational complexity compared to simpler AI-based video solutions. (Xsens, 2026. Personal communication, 2026)

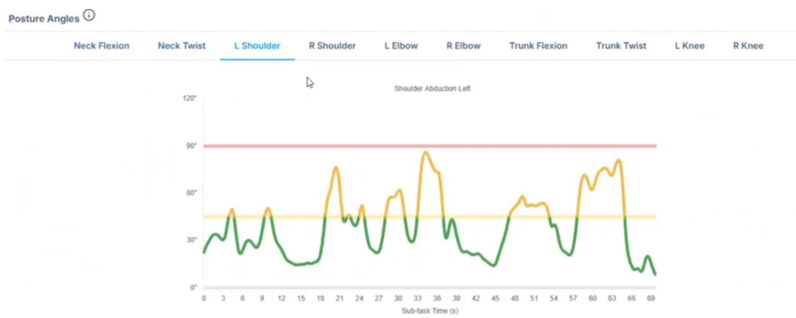
4.4.2 Markerless motion capture technologies

The subsections below present the markerless technologies identified during the market research phase of this project.

4.4.2.1 ErgoPlus

ErgoPlus is a video-based ergonomic assessment platform designed to support workplace risk evaluation and ergonomic improvement processes. Work tasks are recorded and uploaded to the web-based platform, where ergonomic assessments can be performed using established methods such as RULA and REBA. In addition, the platform allows implementation of customized methodologies and assessment criteria tailored to specific industrial needs. Similar to other AI-assisted ergonomic assessment systems, the platform provides graphs containing joint angles over time, skeletal visualizations, and ergonomic analysis of worker postures as seen in Figure 4.1. The platform also includes features such as optional face blurring of recorded workers and the possibility for ergonomists to manually review and adjust automatically generated ergonomic outputs when needed. The system also includes tools for root-cause analysis, intervention tracking, and evaluation of ergonomic improvements over time. ErgoPlus also place a great emphasis on workflow support, reporting, and continuous improvement processes. During discussions with the company, the platform appeared particularly focused on organizational ergonomics management and implementation of corrective actions in industrial environments. (ErgoPlus, 2026. Personal communication, 2026)

(a) Visualizations from ErgoPlus software.



(b) Joint angle graph from ErgoPlus software.

Figure 4.1: Example of output from ErgoPlus software.

4.4.2.2 Gemba Lens

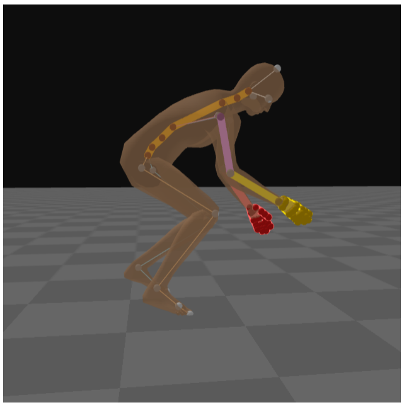
According to the Vovlo employees in France (Appendix H) is Gemba Lens a markerless digital analysis platform developed within Volvo in collaboration with the startup DataTimeSpace. The system uses mobile devices to scan and create 3D representations of production environments and analyze worker movement within the workspace. Through meetings and discussions with the developers responsible for the platform, the primary focus of the system was identified as process analysis based on the 3M framework (Muri, Mura, Muda), where movement patterns and workspace flow can be visualized through tools such as 3D spaghetti diagrams. Furthermore, some basic ergonomic functionality was also available, including counting occurrences of some risk postures and simplified posture analysis. However, unlike dedicated ergonomic assessment systems, Gemba Lens is primarily oriented toward production flow optimization and workplace digitalization rather than detailed ergonomic evaluation. At the time of this study, the platform was still under active development and was not yet commercially available as a finished product. The ergonomic functionality was considered to be in an early stage of development, with limited support for exposure duration analysis, ergonomic scoring, and other features required for comprehensive MEC-based ergonomic assessment.

4.4.2.3 Kimea

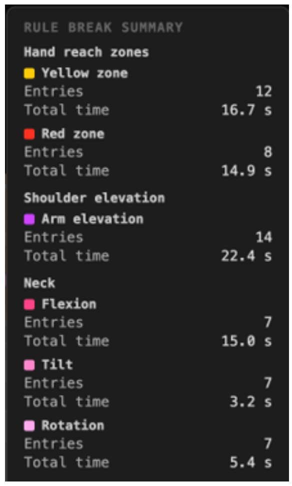
Kimea is a markerless ergonomic assessment platform based on computer vision and AI-driven posture analysis. Video recordings captured using either a smartphone or a dedicated depth camera are uploaded to the platform, where the system automatically generates ergonomic scores, skeletal visualizations, exposure metrics such as time and frequency in risk positions, as well as a 3D avatar representation of the operator movement. The platform supports several established ergonomic methods, including REBA and RULA, while also allowing customization of thresholds and analysis parameters. In addition, selected segments of recordings can be excluded from the analysis to remove non-value-adding activities. However, quantitative joint-angle data could not be directly visualized within the platform itself and instead required export of raw motion data for further external analysis (Moovency, 2026. Personal communication, 2026).

4.4.2.4 Occurrence Ergo

Occurrence Ergo is an ergonomic analysis tool from Occurrence AB, configured to work from a standard camera or smartphone recording. The tool produces outputs needed for MEC-style evaluation such as the amount of movements into MEC-defined risk zones for the upper body, as well as yellow and red zones for reaching (see Figure 4.4b). The tool is supplemented by a 3D avatar visualisation of the operator next to the original video of the work task, where specific body parts are lit up when entering into the different risk zones (see Figure 4.2a). During consultation with the company it was revealed that data handling follows a privacy-by-design approach, including optional face blurring of recorded workers. Video is not stored, only anonymised positional and pose data are retained, and the platform is designed for GDPR compliance. Deployment is possible either on-premises or in a cloud environment, which is relevant to the requirement that data must remain within Volvo Trucks internal network (Occurrence, 2026. Personal communication, 2026).



(a) Visualizations from Occurrence Ergo software.



(b) Output from Occurrence Ergo software.

Figure 4.2: Example of output from Occurrence Ergo software.

4.4.2.5 SoterAI

SoterAI is a broader AI-driven safety platform focused on workplace safety and ergonomic risk management. The system allows ergonomic evaluations to be performed from smartphone video recordings, where AI-based posture analysis is used to identify hazardous movements and calculate ergonomic risk scores. In addition to conventional posture assessment, the platform emphasizes AI-assisted interpretation, automated reporting, and predictive safety analysis intended to support proactive safety management at a larger organizational scale. During discussions with the company, the system appeared less focused on detailed biomechanical output, with no functionalities such as skeletal visualizations or movement reconstructions available, and more oriented toward AI-supported decision-making and high-level safety insights. However, MEC compatible outputs such as the amount of movements into risk zones and reaches into yellow and red zones of were still a functionality of the system as seen in Figure **??** (Soter Analytics, 2026, Personal communication, 2026)

Time	LEFT arm state	>60°?	Motion complet
t=19	Transitioning to side view	—	—
t=20	Swinging forward ~50°	❌	—
t=21	Raised ~65° ✅	✅	—
t=22	Returning ~20°	❌	Motion 1 ✓
t=23	Raised ~70° ✅	✅	—
t=24	Returning ~15°	❌	Motion 2 ✓
t=25	Raised ~65° ✅	✅	—
t=26	Returning ~20°	❌	Motion 3 ✓
t=27	Raised ~70° ✅	✅	—
t=28	Returning ~15°	❌	Motion 4 ✓
t=29	Raised ~65° ✅	✅	—
t=30	Returning ~20°	❌	Motion 5 ✓

Figure 4.3: Example of output from SoterAI software.

4.4.2.6 Theia

Theia3D is a markerless motion capture system designed for research-grade biomechanical analysis. The system uses synchronized multi-camera video recordings together with deep learning and inverse kinematics to generate detailed 3D skeletal models and joint kinematics. Unlike workflow-oriented ergonomic assessment platforms, Theia primarily functions as a motion capture and raw data extraction system. The platform exports pose and kinematic data that can be further processed using external analysis pipelines to calculate ergonomic metrics, threshold crossings, and exposure measures. The system requires a calibrated multi-camera setup, with at least eight cameras recommended for reliable full-body tracking. Due to its dependence on controlled capture conditions, clear line of sight, and extensive infrastructure, deployment in active industrial production environments was described as potentially operationally challenging during communication with company representatives (Theia Markerless, 2025, Personal communication, 2026).

4.4.2.7 TuMeke Ergonomics

TuMeke is an AI-based ergonomic assessment platform where work tasks are recorded using a smartphone and uploaded to a cloud-based analysis platform. The system automatically generates a digital skeleton visualization together with ergonomic risk scores, posture classifications, and graphs with joint angles over time (see Figure 4.4). The platform also includes features such as optional face blurring of recorded workers and the possibility for ergonomists to manually review and adjust automatically generated ergonomic outputs when necessary. The platform is designed to support rapid ergonomic evaluations without requiring wearable sensors, calibration procedures, or advanced technical expertise. During communication with the company, it was confirmed that custom methodologies can be implemented to align with company-specific ergonomic frameworks such as MEC. The workflow and user interface were considered highly relevant for the context of this project due to the low deployment complexity and compatibility with the existing video-based ergonomic evaluation process at Volvo Trucks Tuve (TuMeke, 2026, Personal communication, 2026).

(a) Visualizations from TuMeke software.

(b) Output from TuMeke software.

Figure 4.4: Example of output from TuMeke software.

4.4.3 Technological Maturity Assessment

The technological maturity of the identified solutions was estimated using the TRL framework. The resulting TRL assessments, accompanied by a short motivation for each rating, are presented in Table 4.4.

Table 4.4: Estimated TRL of identified body tracking solutions.

Technology	TRL	Motivation
Sensor-based Technology		
FluxPose	2	Sensor-based solution with ergonomic capabilities, that are not currently developed.
QSense	8	Sensor-based system seen in research and industrial applications.
Wergonic	6	Sensor-based system currently under development and tested in industrial contexts.
Xsens	9	Sensor-based system widely adopted in research and industry.
Markerless Technology		
ErgoPlus	8	Software platform used for ergonomic analysis based on computer vision.
Gemba Lens	5	Software platform in very early stages of ergonomic analysis.
Kimea	8	Software platform used for ergonomic analysis based on computer vision.
Occurrence Ergo	6	Software platform currently demonstrated and used for ergonomic analysis based on computer vision.
SoterAI	8	Software platform used for risk assessment and ergonomic analysis.
Theia	9	Markerless motion capture software widely used in biomechanics research.
TuMeke	8	Software platform used for ergonomic analysis based on computer vision.

4.5 Requirement Specification

The resulting requirement specification can be found in Appendix A.1. The specification included both technical and operational requirements and served as a basis for the continued technology screening process.

4.5.1 Screening with aspects of Requirement Specification

After the screening based on the requirement specification, the remaining systems were ErgoPlus, Occurrence Ergo, SoterAI, and TuMeke. These systems fulfilled the defined requirements and therefore proceeded to further investigation and testing. The systems that were excluded during the screening process are presented below together with the corresponding motivations for their exclusion in relation to the requirement specification presented in Appendix A

Theia was eliminated based on requirements 4.1, 4.2, and 4.5 of the requirement specification. The system relies on eight synchronized cameras that require calibration prior to use and recalibration when relocated. This was considered incompatible with the intended industrial use case, where ergonomic evaluations may need to be conducted rapidly across multiple workstations during ongoing production. The level of infrastructure dependency and setup complexity was therefore deemed impractical for routine ergonomic assessments within the Tuve factory environment.

FluxPose was eliminated based on requirements 1.2 and 4.4. Although the technology demonstrated interesting technical potential, the system was still in an early development phase and primarily oriented toward virtual reality applications rather than ergonomic assessment. As a result, substantial additional development and integration work would likely have been required before the system could support the intended MEC-based ergonomic evaluation workflow. This level of technical immaturity was considered outside the scope and intentions of the project.

Both Xsens and QSense were eliminated primarily based on requirements 2.2, 4.1, and 4.4. Both systems are highly capable sensor-based motion capture platforms and are widely regarded as technically advanced solutions for motion tracking. However, the systems primarily provide raw kinematic and orientation data rather than directly processed ergonomic outputs that can be transferred into the MEC workflow. As a result, additional processing, interpretation, or development of separate analysis workflows would likely be required to use the generated data for routine MEC-based ergonomic evaluation. Furthermore, both systems require multiple body-mounted sensors, calibration procedures, and relatively high levels of technical expertise to operate, which could increase the total evaluation time.

Gemba Lens was eliminated based on requirements 1.2 and 4.4. Although the platform demonstrated promising functionality related to production visualization and workflow analysis, its ergonomic assessment capabilities were considered insufficiently developed for the intended application. The system was primarily oriented toward process flow analysis and workplace visualization rather than detailed posture-specific ergonomic evaluation according to the MEC methodology. Since the ergonomic functionality was still at a relatively early stage, further development and adaptation would likely be required before the system could be used as a fully operational solution for routine ergonomic assessment.

Wergonic was not prioritized for further evaluation based on requirements 2.1, 3.2, and 4.1. The system is an application-oriented ergonomic assessment solution based on wearable sensor garments and body-mounted hardware. While the platform provides processed ergonomic outputs and supports established ergonomic methods, previous experiences and information obtained during the market research indicated that sensor connectivity and system stability could occasionally be affected during operation. Such disturbances could reduce measurement traceability and make it more difficult to maintain stable measurements in a dynamic production environment. In addition, the need for correct sensor placement, garment fit, and calibration procedures was considered likely to increase the total evaluation time.

Kimea was not selected for further evaluation primarily based on requirements 2.1 and 2.2. While the platform demonstrated promising posture tracking capabilities, the accessibility and transparency of the generated motion data were considered less compatible with the intended ergonomic evaluation workflow. Unlike several of the other investigated markerless platforms, joint angle data were not directly available within the software interface. Instead, motion data primarily had to be exported through extensive spreadsheet-based datasets containing large quantities of sequential numerical values and multiple variables. This additional processing and interpretation step was considered less suitable for supporting efficient and transparent ergonomic evaluations within the scope of the project.

4.6 Testing of Body Tracking Solutions

This section presents the findings from the pilot test, threshold crossing experiments, comparison tests against ergonomics expert evaluations, and the measured time required to perform ergonomic assessments using the investigated systems.

4.6.1 Pilot Test

The pilot test provided practical experience regarding the use of a markerless body tracking system in a real production environment and contributed to a better understanding of operational workflows and limitations. The test demonstrated the importance of recording conditions and camera placement when performing markerless motion capture in production environments. Situations involving partial occlusion of body segments appeared to affect the continuity of posture tracking, particularly when the operator worked inside confined areas of the cab. The pilot also indicated that the system could experience difficulties identifying which individual to track when multiple people appeared simultaneously in the recording. Furthermore, maintaining full-body visibility throughout the recording appeared important for stable pose estimation, as incomplete visibility occasionally resulted in unrealistic or incorrect body pose estimations. Initial observations also suggested that recordings captured from the front or side of the operator generally resulted in more stable pose estimation than recordings captured from behind the operator.

4.6.2 Comparison to Expert Evaluation Test

The following section presents the results from the comparison to expert evaluation test, where the outputs generated by the investigated systems were compared with ergonomics expert evaluations by calculating its corresponding MAD value. For the videos recorded in the real production environment, Angle 1 represents the more favourable recording angle, captured predominantly from the front or side of the operator. The resulting MAD values for the Angle 1 recordings are presented in Table 4.5.

Table 4.5: MAD for production videos captured from Angle 1.

System	Wrist	Shoulder	Trunk	Neck	Yellow	Red	Overall
ErgoPlus	–	2.4	5.2	4.2	–	–	3.9
Occurrence Ergo	–	3.0	20.0	13.0	4.2	4.2	8.8
SoterAI	13.0	9.0	12.2	5.6	5.6	12.4	9.6
TuMeke	23.8	3.4	5.6	3.8	–	–	9.2

Angle 2 represents the less favourable recording angle, captured predominantly from behind the operator. The resulting MAD values for the Angle 2 recordings are presented in Table 4.6.

Table 4.6: MAD for production videos captured from Angle 2.

System	Wrist	Shoulder	Trunk	Neck	Yellow	Red	Overall
ErgoPlus	–	13	3.8	7.6	–	–	8.1
Occurrence Ergo	–	2.4	16.8	15.4	3.8	4.8	8.6
SoterAI	11.6	7.0	7.2	10.2	9.2	7.8	8.8
TuMeke	33.2	1.8	1.0	4.4	–	–	10.1

Lastly, the resulting MAD values from the simulated workstation recordings are presented in Table 4.7.

Table 4.7: MAD for simulated production videos.

System	Wrist	Shoulder	Trunk	Neck	Yellow	Red	Overall
ErgoPlus	–	10.8	3.5	5.5	–	–	6.6
Occurrence Ergo	–	10.8	8.0	3.8	4.3	4	6.2
SoterAI	7.8	15.0	5.8	3.3	–	–	8.0
TuMeke	8.8	9.75	4.0	3.5	–	–	6.5

4.6.3 Threshold Crossing Test

The following section presents the results from the MEC threshold crossing test, where the number of DTCs identified by the investigated systems was compared with the ATCs performed during the controlled repetitions. Qualitative observations regarding movement detection and joint angle estimation were also documented in the tables.

The results from the MEC threshold crossing test for ErgoPlus are presented in Table 4.8. The DTC matched the ATC for eight of the eighteen tested movements, mainly for shoulder movements, but also for trunk and neck flexion/extension. For the remaining movements, deviations were observed or the relevant data were not accessible. Qualitative observations regarding underestimated angles and inaccessible movement categories are presented in the notes column.

Table 4.8: MEC threshold crossing test results, ErgoPlus

ErgoPlus			
Movement	**DTC**	**ATC**	**Notes**
Right Shoulder Abduction	10	10	
Left Shoulder Abduction	10	10	
Right Shoulder Flexion	10	10	
Left Shoulder Flexion	10	10	
Trunk Flexion	10	10	
Trunk Extension	10	10	
Trunk Right tilt	0	10	Measured angles substantially lower than the actual angles
Trunk Left tilt	0	10	Measured angles substantially lower than the actual angles
Trunk Right Twist	-	10	Category available, but only generated detections for trunk tilt
Trunk Left Twist	-	10	Category available, but only generated detections for trunk tilt
Neck Flexion	10	10	
Neck Extension	10	10	
Neck Right tilt	-	10	Not measured / Inaccessible data
Neck Left tilt	-	10	Not measured / Inaccessible data
Neck Right Twist	1	10	Measured angles often substantially lower than the actual angles
Neck Left Twist	0	10	Measured angles substantially lower than the actual angles
Wrist Flexion	-	10	Not measured / Inaccessible data
Wrist Extension	-	10	Not measured / Inaccessible data

The results from the MEC threshold crossing test for Occurrence Ergo are presented in Table 4.9. The DTC matched the ATC for fifteen of the eighteen tested movements, including all shoulder and trunk movements, as well as most neck movements. For the remaining movements, one neck movement was only partly detected, while wrist flexion and extension were not measured or accessible. Qualitative observations regarding incomplete detection and inaccessible movement categories are presented in the notes column.

Table 4.9: MEC threshold crossing test results, Occurrence Ergo

Occurrence Ergo			
Movement	**DTC**	**ATC**	**Notes**
Right Shoulder Abduction	10	10	
Left Shoulder Abduction	10	10	
Right Shoulder Flexion	10	10	
Left Shoulder Flexion	10	10	
Trunk Flexion	10	10	
Trunk Extension	10	10	
Trunk Right tilt	10	10	
Trunk Left tilt	10	10	
Trunk Right Twist	10	10	
Trunk Left Twist	10	10	
Neck Flexion	10	10	
Neck Extension	10	10	
Neck Right tilt	10	10	
Neck Left tilt	6	10	Failed to detect all threshold crossings
Neck Right Twist	10	10	
Neck Left Twist	10	10	
Wrist Flexion	-	10	Not measured / Inaccessible
Wrist Extension	-	10	Not measured / Inaccessible

The results from the MEC threshold crossing test for SoterAI are presented in Table 4.10. The DTC matched the ATC for two of the eighteen tested movements, including trunk right tilt and neck extension. For the remaining movements, deviations were observed in the form of missed detections, overestimations, or no detected threshold crossings. Qualitative observations regarding these deviations are presented in the notes column.

Table 4.10: MEC threshold crossing test results, SoterAI

SoterAI			
Movement	**DTC**	**ATC**	**Notes**
Right Shoulder Abduction	8	10	Failed to detect all threshold crossings
Left Shoulder Abduction	7	10	Failed to detect all threshold crossings
Right Shoulder Flexion	15	10	Overestimation of threshold crossings
Left Shoulder Flexion	7	10	Failed to detect all threshold crossings
Trunk Flexion	8	10	Failed to detect all threshold crossings
Trunk Extension	9	10	Failed to detect all threshold crossings
Trunk Right tilt	10	10	
Trunk Left tilt	11	10	Overestimation of threshold crossings
Trunk Right Twist	5	10	Failed to detect all threshold crossings
Trunk Left Twist	6	10	Failed to detect all threshold crossings
Neck Flexion	4	10	Failed to detect all threshold crossings
Neck Extension	10	10	
Neck Right tilt	0	10	No threshold crossings detected
Neck Left tilt	11	10	Overestimation of threshold crossings
Neck Right Twist	5	10	Failed to detect all threshold crossings
Neck Left Twist	6	10	Failed to detect all threshold crossings
Wrist Flexion	0	10	No threshold crossings detected
Wrist Extension	0	10	No threshold crossings detected

The results from the MEC threshold crossing test for TuMeke are presented in Table 4.11. The DTC matched the ATC for eight of the eighteen tested movements, primarily shoulder movements, as well as trunk flexion/extension, neck extension, and wrist flexion. For the remaining movements, deviations were observed or the relevant data were not accessible. Qualitative observations regarding underestimated angles and inaccessible movement categories are presented in the notes column.

Table 4.11: MEC threshold crossing test results, TuMeke

TuMeke			
Movement	**DTC**	**ATC**	**Notes**
Right Shoulder Abduction	10	10	
Left Shoulder Abduction	10	10	
Right Shoulder Flexion	10	10	
Left Shoulder Flexion	10	10	
Trunk Flexion	10	10	
Trunk Extension	10	10	
Trunk Right tilt	1	10	Measured angles often substantially lower than the actual angles
Trunk Left tilt	1	10	Measured angles often substantially lower than the actual angles
Trunk Right Twist	-	10	Not measured / Inaccessible data
Trunk Left Twist	-	10	Not measured / Inaccessible data
Neck Flexion	0	10	Measured angles substantially lower than the actual angles
Neck Extension	10	10	
Neck Right tilt	-	10	Not measured / Inaccessible data
Neck Left tilt	-	10	Not measured / Inaccessible data
Neck Right Twist	-	10	Not measured / Inaccessible data
Neck Left Twist	-	10	Not measured / Inaccessible data
Wrist Flexion	10	10	
Wrist Extension	9	10	One threshold crossing was not detected

4.6.4 Evaluation Time Analysis

Table 4.12 presents the approximate evaluation time ranges observed for the investigated systems when analysing video recordings of approximately one minute in duration. The measured times include the time required to upload and process the video and obtain the systems' generated ergonomic outputs, additional manual interpretation is indicated qualitatively and is not included in the hour estimate. The results were compared with the currently reported manual ergonomic evaluation process at Volvo Trucks Tuve.

Table 4.12: Approximate evaluation time for the investigated systems compared with manual ergonomic evaluation

System	Processing time for 1 minute of video	Additional manual processing	Notes	Indicative processing time for 600 evaluations
ErgoPlus	9–19 min	Medium	Current version requires manual counting of threshold crossings from joint angle graphs	540–1140 h
Occurrence Ergo	5–10 min	Low	Threshold crossing counts provided as numerical values	300–600 h
SoterAI	8–22 min	Low	Threshold crossing counts provided as numerical values	480–1320 h
TuMeke	1–3 min	Medium	Current version requires manual counting of threshold crossings from joint angle graphs	60–180 h
Manual Assessment	Up to 20 min	High	Manual video review and MEC counting	Up to 1200 h

4.7 Socio-Technical Analysis

The socio-technical findings showed that implementation feasibility within industrial ergonomic evaluation was influenced not only by technical posture tracking performance, but also by workflow integration, usability, interpretability, and the extent to which the systems reduced rather than redistributed ergonomic evaluation workload.

4.7.1 Workflow Compatibility and Integration into Existing Ergonomic Evaluation

A recurring theme throughout both the qualitative study and the testing phase was the importance of compatibility with the existing ergonomic evaluation workflow used at Volvo Trucks Tuve. Several stakeholders emphasized that a future body tracking solution should support and simplify this workflow rather than require additional processing. The findings therefore concerned not only whether the systems could identify ergonomic postures, but also how naturally the generated outputs could be integrated into the existing evaluation process.

The market research highlighted differences between the investigated markerless systems regarding how naturally the generated outputs aligned with the existing MEC workflow. Systems such as Occurrence Ergo and SoterAI, capable of directly generating threshold crossing counts, reduced the amount of manual interpretation required after recording. This was considered important since the current evaluation process was described as time-consuming and repetitive. Systems producing outputs that aligned directly with the existing MEC logic therefore appeared more compatible with current ergonomic evaluation work. In contrast, systems such as ErgoPlus and TuMeke, primarily relying on exported graphs with raw angle values, still required some manual counting of the threshold crossings before the results could be integrated into the MEC-based evaluation procedure. This showed that the output format influenced how much manual work remained after automated posture tracking.

The threshold crossing test further demonstrated differences regarding how comprehensively the investigated systems supported the movements and postures relevant to the MEC methodology. While both Occurrence Ergo and SoterAI were capable of identifying a broader range of ergonomic movements and postures, ErgoPlus and TuMeke provided more limited coverage. The latter systems therefore still required complementary manual assessment for specific parts of the ergonomic evaluation process within the Tuve context.

Ergonomic evaluators at Volvo also emphasized the importance of maintaining transparency and traceability throughout the evaluation process and highlighted the need to understand how outputs were generated and to retain the possibility of manually verifying posture events when necessary. Systems providing skeletal visualizations or visual movement reconstructions in combination with the posture data, such as ErgoPlus, Occurrence Ergo, and TuMeke, alongside the original workstation recordings were therefore perceived as more compatible with existing ergonomic work practices. Such visualizations made it easier for ergonomists to understand, verify, and interpret the generated ergonomic outputs in relation to the observed work task, compared with systems such as SoterAI which provided numerical ergonomic outputs with no ability for visual verification.

Since the investigated systems relied on standard video recordings captured using mobile phones, the practical data collection procedure remained relatively similar to the current ergonomic evaluation workflow already used at Volvo Trucks Tuve. No extensive calibration procedures, dedicated motion capture environments, or additional wearable equipment were required. The ergonomic workflow therefore remained largely unchanged, since the recordings could still be performed using standard mobile devices without requiring extensive external infrastructure. The introduction of the investigated markerless systems would therefore primarily affect the analysis stage of the ergonomic evaluation process rather than the recording procedure itself.

The comparison to expert evaluation test also indicated that human validation and contextual interpretation would likely remain important parts of the ergonomic evaluation workflow. While several systems demonstrated the ability to identify relevant ergonomic risk postures with relatively low deviation from expert evaluations, the results varied substantially throughout the conducted tests. The findings therefore showed that the investigated systems would still require ergonomic interpretation, validation, and contextualization of software-generated outputs.

Although the recording procedure remained relatively similar to the current workflow, the investigated systems introduced new forms of interaction with digital analysis software and generated ergonomic outputs requiring interpretation within the software environments. The role of the ergonomists would therefore partially shift from purely manual video assessment toward interpretation and validation of software-generated outputs. While this reduced certain repetitive aspects of the evaluation process, it also introduced new forms of analytical work associated with reviewing, validating, and interpreting automatically generated posture events.

4.7.2 Practical Usability and Operational Feasibility

In addition to workflow compatibility, practical usability and operational feasibility emerged as important implementation-related considerations throughout the testing phase. Since ergonomic evaluations at Volvo Trucks Tuve are conducted across a large number of workstations within an active production environment, stakeholders repeatedly emphasized the importance of systems being easy to use and scale up across the workstations. The findings therefore included not only posture tracking performance, but also how practically manageable the systems appeared during repeated everyday use within production environments.

Even though all remaining systems were based on markerless video analysis, practical differences were still observed regarding ease of use. ErgoPlus and TuMeke required additional manual counting and interpretation of joint angle graphs after the recording had been processed, while Occurrence Ergo and SoterAI provided directly MEC-compatible outputs. These differences influenced the total workload associated with completing an ergonomic evaluation with the aid of a body tracking system. The findings showed that workflow simplicity and output format differed between systems, even when the systems demonstrated relatively similar posture tracking functionality.

The evaluation time analysis further demonstrated considerable differences between the investigated systems' required time for uploading and processing of videos before ergonomic outputs became available. These differences directly influenced the practical lead time associated with completing ergonomic assessments. Occurrence Ergo and TuMeke generated ergonomic outputs relatively quickly after video upload. ErgoPlus and SoterAI occasionally required higher uploading and processing times, which increased the total lead time compared with the other tested systems.

The pilot test also highlighted practical limitations associated with markerless video-based tracking in industrial production environments. Factors such as recording angle and occlusion were observed to influence tracking quality and robustness in all of the systems, particularly during recordings involving confined workspaces or situations where body segments became partially obscured. These observations showed that systems capable of producing relevant ergonomic outputs under favourable conditions could still face practical limitations when applied within dynamic and constrained industrial production environments.

Overall, the practical usability findings were mainly associated with workflow simplicity, operational robustness, ease of interpretation, and compatibility with the practical realities of ergonomic evaluation work within an industrial production environment.

4.7.3 Organizational Acceptance, Trust, and Data Handling Considerations

The qualitative study also identified several socio-technical aspects related to organizational acceptance, trust, and data handling regarding the implementation of markerless body tracking technologies in industrial production environments. Although stakeholders generally expressed positive attitudes toward technologies capable of reducing repetitive manual work and improving ergonomic evaluation efficiency, concerns related to monitoring, privacy, and the handling of recorded material were also raised throughout the study. These findings showed that the investigated systems were evaluated not only in relation to technical functionality, but also in relation to how they were perceived by ergonomists, operators, and other stakeholders involved in the evaluation process.

Several stakeholders emphasized the importance of clearly communicating the intended purpose of the technology and ensuring that collected recordings and posture data would only be used for ergonomic improvement purposes. Concerns were raised that body tracking systems could potentially be perceived as tools for productivity monitoring or worker surveillance if the purpose of the system were not sufficiently transparent. Such concerns were considered particularly important in relation to worker trust and organizational acceptance. Systems such as Occurrence Ergo, capable of providing transparent and traceable ergonomic evaluations through clear MEC-related outputs and interpretable results, were therefore perceived as more aligned with the existing ergonomic evaluation workflow.

Issues related to personal data and handling of recorded workstation videos were also highlighted during discussions with ergonomists, health and safety representatives, and production personnel. Several stakeholders emphasized the importance of minimizing personally identifiable information and ensuring that recordings were managed according to existing company regulations and data protection requirements. Functions enabling anonymization, background blurring, or masking of workers and surrounding environments were therefore generally perceived positively, since such features were considered capable of reducing privacy-related concerns associated with workplace recordings. Data handling in line with company regulations was therefore identified as an important organizational consideration.

The qualitative study indicated that ergonomists primarily viewed body tracking technologies as support tools intended to assist ergonomic evaluation rather than replace human expertise or professional judgement. The importance of retaining the possibility for manual review, contextual interpretation, and adjustment of generated ergonomic outputs during assessments was emphasized. Systems such as ErgoPlus and TuMeke, which allowed users to review, modify, or remove automatically generated posture events and results, were therefore generally perceived as more compatible with existing ergonomic work practices and professional evaluation procedures. This flexibility was considered important for maintaining trust in the generated outputs and reducing the risk of overreliance on automated system assessments.

Stakeholders also emphasized the importance of maintaining trust in the generated ergonomic outputs. During both testing and evaluation, systems such as ErgoPlus, Occurrence Ergo, and TuMeke, which were perceived as transparent and capable of providing traceable results, such as joint angle graphs, visual tracking, or animated posture reconstructions, generally increased confidence among the evaluators. In contrast, SoterAI, which provided numerical ergonomic outputs, but with no visual traceability, was perceived as more difficult to validate within the ergonomic evaluation workflow. Systems with lower transparency were therefore perceived as more difficult to integrate into the ergonomic evaluation process, despite demonstrating technically relevant posture tracking capabilities.

4.8 Final Solution Selection

Based on the combined results from the study (see Table 4.13), Occurrence Ergo was selected as the most suitable final solution candidate for further evaluation at Volvo Trucks Tuve. The selection was primarily based on the system's alignment with the existing MEC-based ergonomic evaluation workflow. Occurrence Ergo provided direct numerical outputs related to MEC-defined risk zones, including upper-body risk postures and yellow and red reaching zones. This reduced the need for additional manual interpretation compared to systems where the evaluator had to manually interpret joint angle graphs or count threshold crossings. In the threshold crossing test, Occurrence Ergo also showed the strongest overall alignment with the selected MEC thresholds among the investigated systems, although wrist movements and one neck movement category were not fully covered.

Table 4.13: Summary of decision-relevant differences between the investigated markerless systems.

Criterion	**ErgoPlus**	**Occurrence Ergo**	**SoterAI**	**TuMeke**
Direct MEC-compatible counts	Medium/Low	High	High	Medium/Low
Manual interpretation needed	Medium	Low	Low	Medium
Threshold-crossing alignment	Medium	High, except wrist and neck left tilt	Low/Medium	Medium
Transparency and traceability	High	High	Low	High
Workflow fit	Medium	High	Medium	Medium
Main limitation	Manual graph interpretation	Missing wrist detection	Low traceability and deviations from expected counts	Manual graph interpretation and missing outputs

Occurrence Ergo also fulfilled several practical and organizational requirements identified during the project. The system can be used with standard video recordings and does not require wearable sensors, extensive calibration procedures, or fixed motion capture infrastructure. This makes it compatible with the existing video-based evaluation workflow and supports use across multiple workstations. In addition, the 3D avatar visualization shown alongside the original video provided traceability by visually indicating when specific body regions entered risk zones. This was considered important for supporting trust and manual verification of the generated outputs. From an implementation perspective, the system's data handling approach was also considered suitable for the industrial context. The use of anonymized pose data, optional face blurring, and the possibility of either on-premises or cloud-based deployment aligned with the data handling and privacy-related requirements identified during the study.

TuMeke and ErgoPlus were considered relevant alternatives, particularly due to their visualizations and potential adaptability to company-specific ergonomic methodologies. However, the tested versions required more manual interpretation and did not provide the same level of direct MEC-compatible output as Occurrence Ergo. SoterAI provided direct numerical outputs for several ergonomic risk categories, but was not selected due to larger deviations in the threshold crossing test and lower transparency in how the results could be visually verified.

4.8.1 Modified Ergonomic Evaluation Workflow

Based on the final solution selection, the proposed use of body tracking technology would introduce a modified ergonomic evaluation workflow, as illustrated in Figure 4.5. The recording procedure would remain similar to the current video-based assessment workflow, since the proposed system can be used with standard video recordings. The main change would instead occur during the analysis stage, where the body tracking system would automatically process the video and generate MEC-related ergonomic outputs, such as posture classifications and threshold crossing counts.

In the proposed workflow, the system-generated outputs should not replace the ergonomist's professional judgement. Instead, the outputs should be used as decision-support material. The ergonomist would remain responsible for reviewing the original video, validating the generated results, considering contextual factors from the work task, and transferring relevant information into the existing MEC-based evaluation procedure. This means that the new technology would primarily reduce parts of the repetitive manual counting and video analysis work, while introducing a new step involving interpretation and validation of software-generated ergonomic outputs.

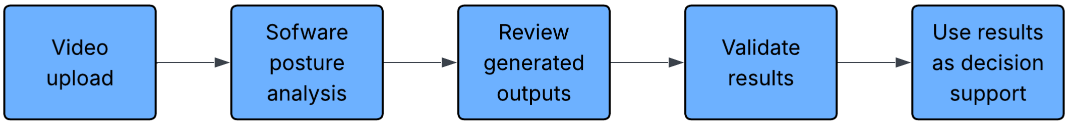


Figure 4.5: Modified ergonomic evaluation workflow.

5

Discussion

The previous chapter validated the fulfilment of the project aim and identified Occurrence Ergo as the most suitable candidate for further evaluation at Volvo Trucks Tuve. The discussion therefore focused on the implications of the findings rather than restating the selection outcome. The results are discussed in relation to the three research questions, previous literature, and the industrial context at Volvo Trucks Tuve, with particular attention to the technical, workflow-related, and socio-technical factors.

5.1 Overall Feasibility of Body Tracking for MEC-Based Ergonomic Evaluation

The findings suggest that body tracking technologies can support MEC-based ergonomic evaluation, particularly by reducing repetitive manual video analysis and generating quantitative posture-related data. This relates to RQ1, since the investigated systems showed potential to reduce the time and workload associated with the current manual ergonomic evaluation process at Volvo Trucks Tuve. The evaluation time analysis showed that ErgoPlus, Occurrence Ergo, and TuMeke generated ergonomic outputs faster than the scaled manual reference for the observed one-minute recordings. SoterAI also showed potential to reduce processing time in some cases, but its upper processing-time exceeded the manual reference, and the time-saving potential were therefore seen to vary between systems. These results are in line with previous research suggesting that body tracking technologies could improve the objectivity and efficiency of ergonomic assessment by their digital reconstruction and analysis of human movement (Salisu et al., 2023; Scataglini et al., 2025). The study's results also address limitations associated with traditional observational methods, which have been described as time-consuming, subjective, and affected by rater variability. For example, Schwartz et al. (2019) reported high intra-rater reliability but only moderate inter-rater reliability when using REBA in field conditions, indicating that different assessors may not fully agree when evaluating the same posture. Similarly, Bao et al. (2009) showed that observational reliability can be influenced by factors such as posture type, camera angle, video quality, rater training, and posture classification strategy.

However, the results also show that body tracking should not be interpreted as a complete replacement for manual ergonomic assessment. The investigated systems differed in movement coverage, threshold detection capability, output format, traceability, and agreement with ergonomics expert evaluation. Some systems provided direct numerical counts of MEC-relevant threshold crossings, while others required manual interpretation of joint angle graphs or exported data. Furthermore, some body regions were not available or not reliably detected in all systems. Therefore, feasibility depended not only on tracking capability, but also on whether the outputs could support the MEC-based evaluation process. The overall interpretation is therefore that body tracking technologies appear feasible as supportive tools for selected parts of the MEC-based evaluation process, rather than as complete automated assessment systems.

5.2 Technical Performance

The threshold crossing test was designed to evaluate whether the investigated systems could detect isolated MEC-defined risk posture thresholds under controlled conditions. This test was particularly relevant for RQ2, since it assessed the systems' ability to identify predefined high-risk postures corresponding to MEC threshold values. By comparing detected threshold crossings with actual threshold crossings, the test provided insight into the available outputs and detection capabilities of each system. The results showed clear differences between the investigated systems. Occurrence Ergo demonstrated strong threshold detection performance for nearly all of the movements included in the test, except for wrist movements and one neck movement category where some crossings were missed. The system therefore provided good coverage of MEC-compatible threshold crossing outputs. In contrast, SoterAI provided numerical output for all relevant upper-body regions and movements, but the number of detected threshold crossings often deviated from the actual number of performed crossings. This suggests that broad movement coverage does not necessarily imply reliable threshold detection. ErgoPlus and TuMeke detected several movements correctly, particularly for shoulder and some trunk movements, but also showed limitations for other movement categories, suggesting that additional manual interpretation would be required before their results could be used in an MEC-based evaluation.

A central interpretation of the threshold crossing test is that technical capability must be evaluated at two levels. First, the system must support the relevant body region or movement category. Second, it must detect the relevant MEC threshold crossing with sufficient reliability. This means that even though a system is able to provide posture tracking data, it may still be limited for practical MEC evaluation if relevant body regions are missing or if the system underestimates or overestimates certain movements. This distinction is important because MEC-based evaluation requires classification of specific risk-zone events, not only general motion capture.

Overall, the findings from the test are in line with previous literature on markerless body tracking. Markerless systems have been described as promising for industrial ergonomic applications because they reduce setup time, avoid body-mounted markers or sensors, and enable non-intrusive data collection (Salisu et al., 2023; Scataglini et al., 2025). At the same time, previous research emphasizes that markerless tracking performance remains dependent on body region, movement type, and algorithmic pose estimation quality (Bonakdar et al., 2025; Roggio et al., 2024). The threshold crossing results therefore support the literature by showing that several MEC-relevant movements could be detected, but also that performance varied depending on body region, movement type and system.

The test also demonstrated that controlled threshold detection is not equivalent to complete ergonomic assessment. The threshold crossing test isolated specific movements and therefore reduced the influence of task complexity, occlusion, and contextual interpretation. This made the test useful for evaluating basic detection capability, but real ergonomic evaluation involves combined postures, varying work strategies, exposure duration, and task context. Therefore, strong performance in this test should be interpreted as evidence of technical potential, rather than as proof of complete practical assessment accuracy.

5.3 Comparison to Ergonomics Expert Evaluation

The comparison to ergonomics expert evaluation provided a more realistic assessment of system performance in production-related work tasks. Unlike the threshold crossing test, this comparison included more complex postures, changing body orientations, varying camera angles, and work situations closer to the actual ergonomic evaluation context at Volvo Trucks Tuve. This made the test more relevant for practical application, but also more difficult to interpret as a pure measurement accuracy test.

The MAD results showed that there was no single superior system that consistently outperformed the others across the different scenarios and body regions. For the production videos captured from the more favourable camera angle, ErgoPlus showed the lowest overall MAD among the reported metrics, while TuMeke, Occurrence Ergo, and SoterAI showed different deviation patterns across body regions. For the less favourable camera angle and the simulated production videos, the differences between systems were more even. This indicates that each system depended on the evaluated body region in combination with the recording condition.

A key interpretation is that overall MAD values should not be used in isolation when judging system suitability. Overall MAD provides a useful summary of deviation from expert evaluation, but it may conceal body-region-specific weaknesses. For example, a system may show low deviation for shoulder or trunk postures but higher deviation for wrist or neck movements. Similarly, a system that reports fewer metrics may obtain a relatively low overall MAD based only on the metrics it supports. Therefore, the body-region-specific results are often more informative than the overall score when evaluating whether a system is suitable for MEC-based assessment. This is particularly important because the scope of this thesis focused on MEC items related to workstation design and upper-body postures, including reaching, wrist, shoulder, trunk, back, and neck-related movements. A system that performs well for some of these categories but lacks others may still require complementary manual assessment. Consequently, system selection should be based on the specific ergonomic risk categories that Volvo Trucks Tuve needs to evaluate, rather than on a single aggregated performance metric.

5.4 Body Tracking as Decision-Support

A recurring finding across the technical tests, qualitative study, and socio-technical analysis was that the investigated systems are currently more suitable as decision-support tools than as fully autonomous ergonomic evaluation systems. This synthesis relates to all three research questions, since the results showed time-saving potential, partial MEC detection capability, and socio-technical constraints affecting implementation.

In this case, full automation would imply that a system could independently record a work task, detect all relevant ergonomic risks, apply the MEC methodology correctly, and produce a final assessment without expert involvement. The findings do not support such a use case. Several systems required manual interpretation while others lacked relevant body-region data, and the comparison to expert evaluation showed deviations between system outputs and expert assessments. In addition, ergonomic assessment requires contextual understanding of the work task, including whether the observed posture is representative, how long exposure lasts, how frequently it occurs, and how it relates to other risk factors such as force, variation, recovery, and production constraints. Decision-support is therefore a more realistic and practically valuable role. In this role, body tracking systems can support ergonomists by providing quantitative posture data and highlighting tasks that require closer assessment. This could allow ergonomists to spend less time on manual video analysis and more time on interpretation, prioritization, and improvement-oriented activities. Such a shift is consistent with the socio-technical perspective, where successful technology implementation depends on how the technology supports existing work practices and professional roles rather than simply replacing human work (Baxter & Sommerville, 2011; Eason, 1988). This interpretation is also supported by the qualitative findings. Stakeholders generally viewed body tracking as promising for increasing objectivity and efficiency, but emphasized that ergonomic expertise should remain central in the assessment process.

5.5 Evaluation Time and Workload Redistribution

The evaluation time analysis showed one of the clearest benefits of the investigated systems. Compared with the manual reference, ErgoPlus, Occurrence Ergo, and TuMeke demonstrated shorter processing-time ranges for obtaining ergonomic outputs from a recorded video. SoterAI showed potential time savings in some cases, but not consistently, since its upper end exceeded the manual reference.

However, the results also show that evaluation time should not be interpreted only as upload and processing time. The practical workload depends on the complete workflow from recording to decision-ready ergonomic information. In the state as of this study, some systems generated threshold crossing counts directly as numerical outputs, while others required manual interpretation of joint angle graphs. Occurrence Ergo and SoterAI therefore appeared more directly aligned with the MEC counting logic, while TuMeke and ErgoPlus, in their tested versions, required additional manual work to translate system outputs into MEC-relevant counts. This means that automation did not always remove work, since in some cases, it redistributed work from manual video observation to software-based interpretation and validation. This distinction is important because a system may appear efficient when considering processing time alone, but still require substantial manual work before the results can be used in practice. In contrast, a system with slightly longer processing time may be more useful if the output is directly interpretable and aligned with the existing MEC workflow. The evaluation time results therefore showed that workload reduction depended on both processing time and the amount of remaining manual interpretation.

Furthermore, from a socio-technical perspective, workload redistribution is an important implementation issue. If a system reduces repetitive counting but introduces new tasks such as data or graph interpretation, the perceived usefulness may decrease. Successful implementation therefore depends on whether the new digital workflow is easier, faster, and more meaningful for ergonomists than the existing manual process. This aligns with socio-technical systems theory, where the fit between the technical subsystem and the social or organizational subsystem is central for successful implementation (Baxter & Sommerville, 2011). It also aligns with Eason's view that implementation outcomes depend not only on technical functionality, but also on the primary task, organizational context, and external environment (Eason, 1988).

5.6 Workflow Compatibility

Workflow compatibility emerged as one of the most important factors influencing practical implementation. Since the purpose of the thesis was to support the existing MEC-based evaluation process, a suitable system must produce outputs that can be used within that process without requiring major changes to established work routines. This is particularly relevant in the industrial context of Volvo Trucks Tuve, where ergonomic evaluations may need to be conducted across many workstations within an active production environment.

In this regard, the markerless systems investigated in the final testing phase had many practical advantages. Since they relied on standard video recordings captured with mobile phones, the data collection procedure remained relatively similar to the current ergonomic evaluation workflow. No wearable sensors, body-mounted markers, fixed capture volumes, or extensive calibration procedures were required. As a result, the main workflow change was not the recording procedure itself, but the analysis stage. Taken together, these findings align with previous research describing markerless systems as promising for real-world ergonomic assessment due to their non-intrusive nature, reduced setup time, and lower interference with natural worker movement (Scataglini et al., 2025). It also supports the preliminary screening logic used in the thesis, where technologies requiring extensive infrastructure, calibration, or body-mounted equipment were considered less suitable for rapid and scalable ergonomic evaluation in production environments.

However, workflow compatibility is not only about data collection. The investigated systems introduced new forms of interaction with digital analysis platforms, including uploading videos, reviewing tracking results, interpreting visualizations, and translating system outputs into MEC-compatible results. Therefore, the practical feasibility of implementation depended strongly on output accessibility and interpretability. Systems that provided directly usable MEC-relevant outputs were more compatible with the existing workflow than systems that primarily generated joint angle graphs requiring additional manual processing.

Industrial feasibility was also influenced by production-specific conditions. The pilot test and later system evaluations indicated that camera placement, occlusion, and full-body visibility affected tracking robustness. This is particularly relevant in truck assembly, where operators may work in confined spaces, bend into vehicle structures, or be partially obscured by tools, components, or other personnel. Similar limitations have been identified in previous studies, where markerless tracking performance has been shown to depend on camera placement, lighting, occlusion, and environmental complexity (Roggio et al., 2024; Salisu et al., 2023).

Therefore, successful implementation would require more than selecting a suitable software platform. It would also require clear recording guidelines, including recommendations for camera angle, distance, visibility, and procedures for handling partially occluded work. Without such guidelines, the same system may produce different levels of reliability depending on how the recording is performed.

5.7 Transparency, Trust, and User Acceptance

Transparency, trust, and user acceptance were central socio-technical factors influencing the feasibility of implementation. One recurring finding was the importance of being able to verify how ergonomic outputs were generated. Systems that provided skeleton overlays, avatar visualizations, synchronized video views, or joint angle graphs were generally easier to understand and validate. These features made it possible for ergonomists to compare the system interpretation with the original work task and determine whether the generated output appeared reasonable. In contrast, systems that produced summarized results without transparent intermediate information risked being perceived as non-verifiable "black-box" solutions. This is particularly important since the comparison to ergonomics expert evaluation showed that the systems deviated from the expert assessment. When deviations occurred, transparent outputs made it easier to assess whether the result was reasonable. Without transparent and traceable outputs, this validation becomes difficult. Therefore, transparency is not only a usability feature, but a necessity for trust in the automated ergonomic outputs. The importance of transparency and trust is also supported by socio-technical literature. Baxter and Sommerville (2011) emphasize that successful technology implementation requires alignment between technical systems and the social and organizational context in which they are used.

Furthermore, Eason (1988) argues that implementation outcomes depend on how the technology affects tasks, roles, and organizational conditions. In the context of this thesis, the technology changes the ergonomist's role somewhat from manually identifying every posture occurrence toward interpreting and validating software-generated outputs. For such a workflow to be accepted, the outputs must be understandable and trustworthy. User acceptance was also closely connected to privacy and monitoring concerns. Since the investigated systems involve recording and analyzing worker movements, stakeholders emphasized the importance of ensuring that the technology is used for ergonomic improvement rather than productivity monitoring or individual performance evaluation. This aligns with previous research on occupational monitoring technologies, where worker acceptance is influenced by comfort, perceived autonomy, trust, and concerns regarding how collected data may be used (Jacobs et al., 2019; Schall et al., 2018). For Volvo Trucks Tuve, this suggests that future implementation should include clear communication regarding the purpose and boundaries of the technology. Workers and stakeholders should understand that the system is intended to support ergonomic improvement, not time studies or individual monitoring. Data handling procedures should also be clearly defined, including, storage, anonymization, and whether features such as face blurring or similar functionalities are available.

5.8 Socio-Technical Limitations

The third research question asked to what extent body tracking evaluation can be limited by socio-technical aspects. The findings indicate that socio-technical aspects can substantially limit implementation, even when the underlying posture tracking technology is technically relevant.

One limitation concerns competence and training. In the current state, the systems require users to interpret joint angle graphs, numerical outputs, visualized skeletons, and risk classifications. If the system output does not directly correspond to the MEC workflow, ergonomists may require additional training or technical support. This can reduce practical usability and create dependency on specialists. In contrast, systems that generate clear MEC-compatible outputs and provide intuitive visualizations are more in line with the everyday ergonomic evaluation work.

Another limitation concerns organizational fit. Ergonomic evaluation is not an isolated technical task, but part of a broader improvement process involving ergonomists, production personnel, managers, safety representatives, and operators. A body tracking system may generate useful posture data, but if the organization lacks routines for validating, communicating, and acting on the results, the practical benefit may be limited. Therefore, implementation should focus not only on selecting a system, but also on defining how results will be reviewed, interpreted, documented, and translated into workstation improvements.

5.9 Methodological Limitations

Several methodological limitations should be considered when interpreting the findings. First, the comparison to ergonomics expert evaluation used the expert assessment as the reference. This was appropriate because the aim was to evaluate whether body tracking systems could support the existing practical MEC workflow at Volvo Trucks Tuve. However, expert evaluations should not be interpreted as absolute biomechanical ground truth. Observational ergonomic assessments involve professional judgement and may be influenced by assessor interpretation, camera angle, video quality, and posture classification strategy (Bao et al., 2009; Schwartz et al., 2019). Consequently, deviations between system outputs and expert evaluation should be interpreted as differences from the current practical assessment method rather than direct measurement error.

Another limitation concerns the version and configuration of the investigated software platforms at the time of testing. TuMeke and ErgoPlus were evaluated in the versions that were available during the project period, without being fully customized to the MEC methodology. During supplier interactions, both systems indicated possibilities for adapting or developing methodology-specific functionality, such as customer-specific ergonomic assessment logic. However, since this thesis was conducted within a limited timeframe and Volvo Trucks Tuve aimed to identify a solution that could be used directly within the existing ergonomic evaluation workflow, the systems were evaluated based on their available functionality rather than their potential future functionality after supplier-specific development. Consequently, the results for TuMeke and ErgoPlus should primarily be interpreted as reflecting their out-of-the-box applicability for MEC-based evaluation at the time of testing, rather than their possible performance if fully adapted to MEC. This also influenced the comparison between systems, since Occurrence Ergo and SoterAI provided more directly MEC-compatible outputs during the project, while TuMeke and ErgoPlus required additional interpretation or manual processing before their outputs could be translated into the MEC workflow.

Related to this, the systems did not report identical metrics. Some systems lacked wrist data, some did not provide reaching-zone classifications, and some provided relevant information only through graphs or exports. This complicates direct comparison between systems. Overall MAD values were calculated based on the metrics available for each system, which avoids treating unsupported metrics as zero but also means that the overall values are not based on identical information. Therefore, body-region-specific deviations should be interpreted alongside the overall MAD values.

Furthermore, the threshold crossing test was conducted under controlled conditions with isolated movements and clear visual references. This made the test useful for evaluating whether systems could detect selected MEC thresholds, but it does not fully represent real production work. In actual work tasks, movements are more complex, body segments may be occluded, camera angles may vary, and multiple joints may move simultaneously. Strong performance in the threshold crossing test therefore does not necessarily guarantee strong performance in real production scenarios.

The production and simulated video material was also limited in scope. The study included selected work tasks, recordings, and camera angles, but not the full variation of operators, workstations, lighting conditions, clothing, tools, movement strategies, and occlusion patterns that may exist across the factory. The findings should therefore be interpreted as indicative rather than definitive. A broader validation would be required before drawing firm conclusions about system performance across all relevant production contexts.

Another limitation was that the study primarily evaluated practical ergonomic assessment applicability rather than absolute kinematic measurement accuracy. The systems were compared with MEC-relevant thresholds and expert evaluations, but not against laboratory-grade reference systems such as marker-based optical motion capture. This was consistent with the industrial aim of the thesis, but it limits conclusions about absolute joint angle accuracy.

Finally, the socio-technical analysis was based on stakeholder input, qualitative observations, testing experiences, supplier interactions, and implementation-related reflections gathered during a limited project period. While this provided valuable insight into implementation feasibility, a long-term deployment study would be required to evaluate actual user adoption, organizational learning, trust development, and sustained use over time.

5.10 Future Work

Future work should focus on broader validation, reliability testing, and pilot implementation in real ergonomic evaluation workflows.

5.10.1 System Reliability and Broader Validation

One important direction is to investigate the repeatability of the systems themselves. While this study compared system outputs with ergonomics expert evaluation, it did not examine whether the same system produces consistent results when analyzing the same video multiple times or when similar tasks are recorded under slightly different conditions. Future studies could therefore investigate intra-system reliability and determine whether body tracking systems can function as stable reference tools.

Another important direction is to compare system outputs against evaluations from multiple ergonomists rather than a single expert reference. This would make it possible to distinguish system-related deviations from normal variation between human assessors. Since previous literature has shown that inter-rater reliability can be limited in observational ergonomic assessment (Schwartz et al., 2019), such a study would help clarify whether body tracking technologies reduce or introduce variability in ergonomic evaluation.

5.10.2 Risk Classification and Longer Work Cycles

Future work should also investigate whether the systems tend to overestimate or underestimate ergonomic risk compared with expert assessment. The MAD metric used in this thesis describes the magnitude of deviation, but it does not show whether a system is generally more conservative or less conservative than the ergonomist. This distinction is important in practical ergonomic evaluation. A system that systematically overestimates exposure may lead to unnecessary prioritization of low-risk tasks, while a system that systematically underestimates exposure may fail to identify relevant ergonomic risks. Future analysis of signed deviations, in addition to absolute deviations, could therefore clarify whether each system tends to classify postures on the safe side or whether it risks missing important exposures.

Future studies should also include longer recordings and complete work cycles. Ergonomic risk is influenced not only by posture occurrence, but also by frequency, duration, and variation. Short video clips may therefore not fully capture the ergonomic load of a workstation. Testing the systems on longer and more representative recordings would provide stronger evidence regarding their usefulness for practical MEC evaluation.

5.10.3 MEC-Specific System Adaptation

Future work should also evaluate systems such as TuMeke and ErgoPlus with MEC-specific functionality implemented. In this thesis, these systems were tested in their available versions rather than as fully MEC-customized platforms. Since several limitations identified during testing were related to output format, manual interpretation of joint angle graphs, and the lack of direct MEC-compatible threshold counts, a renewed evaluation after MEC adaptation could provide a more representative assessment of their potential suitability. This would also allow a fairer comparison with systems such as Occurrence Ergo and SoterAI, which provided more directly MEC-compatible outputs during the present study.

5.10.4 UI/UX and Socio-Technical Pilot Implementation

Although this thesis considered usability and workflow compatibility, future work should include a more detailed evaluation of UI and UX aspects. This could include how easily ergonomists can interpret system outputs, navigate the interface, extract relevant MEC-related information, and integrate the results into their existing assessment routines.

Finally, future work should include socio-technical pilot implementation. Such a pilot should involve ergonomists, operators, managers, union representatives, safety personnel, and IT or data governance stakeholders. The pilot should define recording guidelines, training needs, data handling procedures, acceptance criteria, and boundaries for how the technology may and may not be used. This would allow Volvo Trucks Tuve to evaluate not only whether the technology works technically, but whether it can become a trusted and useful part of the ergonomic evaluation system.

6
Conclusion

This thesis investigated whether body tracking technologies could support and partially automate MEC-based ergonomic evaluation at Volvo Trucks Tuve. The findings indicate that body tracking technologies can support ergonomic evaluation by reducing parts of the manual analysis workload and providing quantitative posture data. In relation to RQ1, several systems showed potential to reduce evaluation lead time compared with the manual workflow reference, particularly when the generated outputs were directly compatible with the MEC-based evaluation process and required limited additional manual interpretation. However, the actual workload reduction depended on how directly usable the system outputs were. Systems requiring additional manual interpretation shifted parts of the workload rather than fully reducing it.

In relation to RQ2, the technical evaluation showed that several MEC-relevant postures could be detected, but that performance varied between systems, body regions, and recording conditions. The threshold crossing test and comparison to ergonomics expert evaluation indicated that the systems could support detection of ergonomic risk postures, but none of them fully replicated expert assessment across all evaluated conditions. This suggests that the investigated systems are currently more suitable as support tools than as replacements for professional ergonomic judgement.

In relation to RQ3, the study showed that practical implementation is limited by socio-technical factors such as workflow compatibility, usability, transparency, data handling, worker acceptance, and trust in the generated outputs. These factors are important because the technology must not only detect postures, but also fit into the existing ergonomic evaluation workflow and be accepted in a production environment.

Based on the combined technical and socio-technical evaluation, Occurrence Ergo was selected as the most suitable final solution candidate for further evaluation at Volvo Trucks Tuve. The selection was mainly based on its direct MEC-compatible numerical outputs, use of standard video recordings, traceable 3D posture visualization, and alignment with identified data handling requirements. Overall, the study concludes that body tracking technologies can provide valuable support for MEC-based ergonomic evaluation, but should currently be implemented as decision-support tools where final interpretation and decision-making remain with qualified ergonomics personnel.

Declaration of Competing Interest

The thesis authors declare that they have no financial interests or personal relationships that could have influenced the work presented in this thesis. During the project, information was obtained from several technology suppliers and external experts, some of whom had professional, academic, or commercial involvement with body tracking technologies evaluated in the study. Such information was therefore treated with awareness of potential supplier bias or commercially motivated perspectives. To reduce the influence of such bias, supplier-provided information was compared with literature, stakeholder input, requirement-based screening, and practical testing where possible. The evaluation, interpretation of results, and final solution selection were conducted independently by the authors.

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A

Requirement Specification

Table A.1: Requirement Specification

ID	Requirement description	R/D	Target value /Definition	Weight (1-3)	Verification method
1. Functionality - Motion detection & ergonomic analysis					
1.1	Enable quantification of ergonomic risk postures	R	The system shall provide pose data that can be used to quantify worker postures and movements relevant for ergonomic assessment and support analysis of workstation risk zones according to the MEC framework.		Validation against expert assessment
1.2	TRL and availability	R	TRL score $\geq$ 6 & available for purchase and use in Sweden		Market research & literature study
2. Data processing & traceability					
2.1	Transparent and traceable motion data	R	The system shall provide transparent access to underlying motion tracking data and allow extraction of relevant variables. The data shall be traceable over the measurement sequence and presented in a way that enables interpretation within Volvo Trucks Tuve's existing ergonomic assessment practices.		Supplier documentation review

Table A.1: Requirement Specification

ID	Requirement description	R/D	Target value /Definition	Weight (1-3)	Verification method
2.2	Compatibility with MEC workflow	R	The system shall generate outputs that are transferable into the MEC Excel		Practical test
3. Robustness in a production environment					
3.1	Works with partially occluded body	R	Stable tracking without significant degradation compared to a controlled environment		On-site testing/measurement
3.2	Robust operation in dynamic production environments	R	The system shall operate reliably in a dynamic industrial production environment and not interfere with the surrounding.		On-site testing/measurement
4. Usability, Work Environment & Operational Requirements					
4.1	Reduction of total ergonomic evaluation time	R	The total time required to perform an ergonomic assessment, must be shorter than the current assessment method used at Volvo Trucks Tuve.		On-site testing/measurement
4.2	Follows Volvo's Health and Safety regulation	R	Non-obstructive equipment		Confirming with Supervisor and Health & safety regulations
4.3	Does not require a specialist	R	The system shall be operable by ergonomists without requiring specialist technical knowledge or ongoing IT support.		On-site testing/measurement
4.4	No internal technical development required	R	Delivered as a fully operational system without need for extensive development		Contract review / supplier documentation

Table A.1: Requirement Specification

ID	Requirement description	R/D	Target value /Definition	Weight (1-3)	Verification method
4.5	Mobile solution	R	Due to the amount of station in the production site the solution must be mobile to be able to make more than one evaluation each day		On-site testing
4.6	Provides visualisations that could be analysed after evaluation.	D	For transparency and traceability	3	On-site Testing
			5. Safety & ethics		
5.1	Compliance with Volvo internal data governance policies	R	All video and motion data shall be processed, stored, and transferred in accordance with Volvo's internal confidentiality, IT security, and data handling policies		Supplier documentation review / IT security validation
5.2	No machine interference	R	No EM/optical interference		Supplier documentation review
5.3	Anonymization possible	D	No identifiable video	2	Supplier documentation review

B

Summary of information from company ergonomists Michael Schröder and Elin Algurén

Michael Schröder and Elin Algurén are ergonomists working at Volvo Trucks Tuve. Both hold the title of Certified European Ergonomist (Eur.Erg.), a credential that reflects professional competence within the field. In addition to their ergonomic expertise, Michael and Elin serve as the industrial supervisors for this thesis project, giving the thesis authors insight into both the operational context and the practical constraints that potential solution must satisfy. Their experience within both ergonomics and Volvo's production makes them well-positioned to provide perspectives on how body tracking technologies could be integrated into existing assessment workflows at the Tuve plant. Below follows a summary of relevant topics and information reported by Michael and Elin during the study.

Currently, approximately 600 workstations are assessed throughout the factory. Each evaluation involves a trained assessor observing a worker during one work cycle, recording how many times the worker enters a "red zone." The results are entered into MEC, which categorizes each workstation as red or green, where green indicates acceptable ergonomic conditions. On-site support is provided by work ambassadors and safety representatives.

Frequency is calculated by observing the worker during a single cycle time of approximately 6 minutes and multiplying the count by 10 to estimate an hourly rate. The ergonomists acknowledge this method has limitations, as short observation windows can cause assessors to miss patterns or identify trends that don't actually exist over longer time periods.

The factory has previously piloted Wergonics smart clothes, though with mixed results. Largely because the product is still in development. The most significant challenges have been sensor interference, caused either by moving out of range or by external frequency disturbances, which can require assessments to be restarted entirely. Staff find this particularly disruptive to workers. The system also tends to register an unreasonably high number of red-zone movements compared to manual assessments, likely because it struggles to distinguish when a new, distinct movement begins, something a human observer can intuitively recognize.

Despite these previous issues, the team sees genuine potential in the use of body tracking technology. The team reportedly values the reduced subjectivity body tracking could offer relative to manual assessments, and sees promise in its ability to account for individual differences in ergonomic evaluations. The ergonomists also emphasized the importance of being able to understand and verify how ergonomic results are generated. Solutions that allow assessors to visually follow the evaluation process, for example through synchronized video recordings or visualized body tracking, were considered preferable to systems that only provide summarized numerical outputs without insight into how the assessment was derived. On the practical side, the preferred setup time, including changing and calibration, is around 5 minutes. As anything longer risks adding unnecessary stress for workers. That said, there is some flexibility if a workable solution requires slightly more time. Workers themselves are generally reported to be positive about trying new ergonomic assessment tools, feeling that it leads to better outcomes for them. When questioned about what grade of accuracy to be required from the body tracking technology, the answer was that there was none, and that the important part was that it was usable within the workflow and produced reasonable results that were traceable

Michael and Elin have also had prior contact with the company Occurrence and been involved in their project in Volvo in India regarding body tracking implementation. It was through this prior collaboration that the thesis authors came in contact with Occurrence Ergo and why the system had implemented MEC methodology.
Optical marker-based body tracking has been ruled out entirely for the Tuve facility, due to concerns around investment costs, obstructed camera angles, usability, data volumes, and general practical feasibility. Markerless tracking, however, appears to be a direction several Volvo facilities are exploring in parallel. The U.S. operation has purchased licenses for Gemba Lens and is working on implementation, while a separate development effort is underway in India. In France, a markerless solution called Soter is being piloted, though it is primarily oriented toward performing more general workplace safety assessments rather than ergonomic assessments.

Additionally, the ergonomists were clear that they would prefer not to be involved in developing, coding or building a custom solution from, and that they would prefer a solution that is mostly "ready-to-use" with some tweaking and collaboration with the technology provider seen as acceptable. Their preference is for the project group to identify an existing, market-ready tool that suits the factory environment and assess how it could realistically be implemented within Swedish regulatory constraints. They also openly acknowledge that assessments currently vary depending on who conducts them, and that while the ideal would be to have a single assessor perform all evaluations for consistency, this simply isn't operationally feasible. This makes the case for a more objective and standardized assessment method all the more pressing.

C

Summary of interview with Jörgen Eklund, Professor Emeritus

Jörgen Eklund is Professor Emeritus in Applied Ergonomics at KTH Royal Institute of Technology. With an academic background in engineering, his work has focused on connecting ergonomic theory and real-world application in production environments. He has published extensively within the field and has experience from working directly with industry partners to develop and implement ergonomic solutions. In addition, Jörgen serves on the board of Wergonic, a company developing IMU-based wearable technology for ergonomic risk assessment, which gives him insight into the practical and commercial challenges of translating body tracking technology into an industrial context. Taken together, his experience from applied ergonomics in combination with the commercial dimensions of ergonomic technology, he became a relevant expert to consult in the context of this project. Below is the summary of the insights and discussion topics from the interview with Jörgen.

His work with Wergonic began in 2015 at KTH in collaboration with industrial partners including Scania, Volvo Cars, and Volvo Group. Early optical motion capture systems were found to provide high accuracy but were difficult to implement in real production environments due to occlusion, long calibration times, and complex setup procedures. In line production, operators cannot be away from their stations for extended periods, which made such systems impractical. He also mentioned systems such as Xsens to be too costly and time-consuming to calibrate for everyday industrial use.

Consequently, the focus shifted toward IMU-based solutions integrated into wearable garments, which led to the creation of the Wergonic system. The system is designed to be fast, user-friendly, and suitable for ergonomic risk assessments using established methods such as RULA, REBA, and RAMP. The overall aim of Wergonic is to enable quick and accurate ergonomic evaluations directly at the workstation.

Jörgen mentioned that accuracy depends heavily on correct calibration and proper sensor attachment, and during optimal conditions, an accuracy of about 3–5 degrees can be achieved. Furthermore, the primary source of error is often not the IMU sensor itself, but instead how the sensor is positioned on the body. The highest accuracy is obtained when sensors are mounted directly on the skin, followed by tight-fitting garments, and lower accuracy when attached to work clothing. Magnetic interference and Bluetooth connectivity was also reported to possibly affect system stability, although newer system versions have improved robustness.

When further discussing accuracy, Jörgen mentioned that the impact of small measurement errors depends on the purpose of the assessment. In some tasks, an error of a few degrees has minimal influence, but in certain situations it may affect the final risk classification. Despite these limitations, IMU-based body tracking systems were reported to be more reliable than manual observational assessments, which are subject to variability and lower precision.

For body tracking to be successfully implemented in production environments, a strong emphasis on usability and workflow integration is required. Calibration must for example be fast and simple, as time constraints in line production are strict. Furthermore, a pilot implementation in a limited area is a good approach, since it allows users to gain experience while providing insight if system functions correctly in practice. Lastly, ergonomists should be involved during the implementation process to conduct analyses beyond simplified risk outputs, and the system should enable data storage to support before-and-after comparisons and continuous improvement efforts.

In conclusion, the importance lies not in whether a system offers the highest possible technical accuracy, but whether it is accurate enough for its purpose, cost-effective, and practically feasible in a production context. Body tracking technology should therefore be viewed as a decision-support tool that substantially increases the objectivity and efficiency of ergonomic assessments.

D

Summary of interview with Liyun Yang, Assistant Professor Karolinska Institutet

Liyun Yang is an Associate Professor at Karolinska Institutet with experience in the development and application of body tracking technologies for ergonomic assessment. Her doctoral research focused on the development of a mobile application for ergonomic analysis, giving her direct technical insight into the challenges and opportunities associated with digitalizing ergonomic evaluation methods. She has also collaborated with both academic and industrial partners, with a publication record in applied ergonomics. This makes her a relevant expert to consult in the context of this project. Below is the summary of the insights and discussion topics from the interview with Liyun.

The interviewee has lots of experience from research and development projects assessing different body tracking systems, particularly in production settings. Overall, body tracking technologies are considered promising and increasingly user-friendly, with generally positive feedback from operators. She mentioned that current systems can measure body angles with an expected accuracy of approximately 5–10 degrees, provided that sensors are properly positioned and calibrated. While this level of accuracy is sufficient for ergonomic risk assessments and often more reliable than visual observation alone, body tracking systems cannot independently perform ergonomic evaluations. Human expertise remains necessary to interpret data and assess risk.

Significant technical limitations remain however, particularly regarding rotational measurements in magnetically disturbed industrial environments. Calibration quality was mentioned to strongly influence measurement accuracy, and there is a trade-off between calibration speed and precision. Implementation challenges, on the other hand, were reported as not purely technical. Successful deployment requires strong leadership support, early involvement of operators and stakeholders, clear communication regarding privacy concerns, and visible demonstration of benefits. Without integration into existing workflows, ergonomic risk assessments risk becoming time-consuming without leading to change.

In conclusion, body tracking technology should be viewed as a supportive decision-making tool rather than a replacement for professional ergonomics. With proper implementation and stakeholder engagement, it has potential to increase the efficiency, objectivity, and reliability of ergonomic evaluations in industrial settings.

E

Summary of interview with Lars Hanson

Lars Hanson has extensive experience in ergonomics, digitalization, and automation. He has previous experience from being a professor in intergraded product development, program owner of factory for tommorow at Volvo group and from Scania. His current responsibilities is related to introducing new techniques for ergonomic assessment and industrial development. He has also been involved in the development and application of the Wergonic system in a long-term supporting role, giving him practical insight into the possibilities and limitations of wearable body tracking technologies in production environments. This makes him a relevant expert to consult in the context of this project. Below is the summary of the insights and discussion topics from the interview with Lars.

The interviewee emphasized that the choice of body tracking technology involves a trade-off between measurement accuracy and practical usability in production. Marker-based optical systems were described as highly accurate in laboratory environments, but difficult to apply in production environments because of extensive setup requirements and limited flexibility. IMU-based wearable sensors were instead reported as more realistic for industrial use, even if their measurement accuracy tends to be lower. More advanced IMU systems such as Xsens were considered less attractive from a cost perspective. Markerless systems, were mentioned as promising in open and unobstructed environments, but limited by occlusion and correct postural reconstruction in production environments. A promising direction was therefore described as combining camera-based tracking with wearable sensors to improve robustness.

Several implementation challenges were reported, particularly in relation to production conditions and methodological clarity. Production environments were described as time-pressured, leaving limited room for calibration procedures or complicated setup. However, the interviewee emphasized that the main challenge is not only technical. Data governance was also highlighted as an important factor, describing that sensitive production data should be kept internal rather than external. GDPR and the handling of personal movement data were also mentioned as important considerations. Worker acceptance was considered achievable regarding sensor-based systems in production environments since wearing equipment is already common.

In conclusion, body tracking technologies were viewed as promising for supporting ergonomic assessment, but their practical value depends on how well they can be integrated into production conditions and existing ergonomic methods.

F

Summary of interview with Health and Safety Ambassadors and Environmental Technician

The Health and Safety Ambassadors and Environmental Technician at Volvo Trucks Tuve represent a valuable stakeholder group in the context of this study. These people bring first-hand experience from both sides of the ergonomic assessment process. The interviewees represented a broad range of production-related roles and experiences from Volvo Trucks, including assembly work, team leadership, material handling, rehabilitation science, and environmental coordination. With extensive experience as shop-floor workers who have previously performed the tasks being evaluated, to now being involved in carrying out ergonomic assessments and driving safety improvements. This dual perspective gives them an understanding of the practical realities of production work alongside an awareness of the organizational and procedural requirements. This makes the group relevant to consult in the context of this project. Below is the summary of the insights and discussion topics from the interview with this personnel.

The group had some prior hands-on experience with body tracking technology, especially sensor-based solutions in the form of Wergonic. Their general attitude toward body tracking technology was positive, and they saw potential in being able to generate numerical data from ergonomic assessments. The participants mentioned that the biggest issue with their use of Wergonic was the loss of sensor-connectivity during evaluations. It was mentioned that this hinders them using it complicates the evaluations more than today's system.

A recurring issue with the current manual method was that subjectivity affects the ergonomic evaluations, and that video-based assessments frequently miss parts of the body due to obstructed sight. The feeling was that well-placed cameras, or body-worn sensors, could reduce this subjectivity and make assessments more objective. Markerless systems were something the group expressed curiosity about testing. However, camera placement was flagged as a challenge, particularly at cramped and crowded workstations.

The group also expressed that transparency about how the data is used would be essential since there was awareness that technology has historically been associated with monitoring worker speed, and that this perception could linger and hinder implementation if not addressed correctly. Another aspect that was noted was that workers often perform unnecessary movements such as waving or drinking water which would be captured by body-tracking systems, but does not reflect the actual task. There were differing views on whether such movements should be included or filtered out, but having the freedom to filter these movements out were generally seen as positive.

The group felt body-tracking technology could earn acceptance if introduced thoughtfully. They were also clear that worker-experience needs to be built into any implementation process. They also valued human expertise and that the human contextualization during evaluation and that body-tracking technology should not be used to bypass that part of the process. Participants further emphasized the importance of being able to follow and verify how the system arrives at its ergonomic conclusions. Solutions that provide visual feedback, such as synchronized video recordings or visible body tracking overlays, were therefore considered more trustworthy than systems that only generate summarized numerical outputs without showing how the assessment was derived.

G

Summary of interview with the Union and Safety Representatives

To gain insight into the perspectives of shop-floor workers and understand the position of worker representation at Volvo Trucks Tuve, an interview was conducted with the union and safety representatives at the plant. With many years at Volvo and lots of experience from working in production environments, the interviewees bring understanding of how changes to working practices are perceived and received at the shop-floor level. Their perspective was therefore valuable in the context of this project. Below is the summary of the insights and discussion topics from the interview with the Union and Safety Representatives.

Concerns that body tracking technology could be used for unintended purposes, such as time studies or production balancing was raised. It was emphasized that such technology must not be used for workstation balancing or performance monitoring. Safeguarding personal integrity is considered essential, and participation in any form of testing must be voluntary. Under no circumstances should operators feel compelled to take part in assessments.

Data management was also reported as a priority. Recorded material and collected data must be approved if it had to leave the internal network, and strict compliance with GDPR requirements must be ensured. It was explained that current practice during ergonomic assessments involved attempting to avoid capturing identifiable facial features when filming. Furthermore, these recordings are stored temporarily on internal computers and are deleted after evaluations, and any future system must maintain or strengthen these safeguards.

The introduction of additional equipment, such as smart garments or body-mounted sensors on or beneath work clothing, was perceived as potentially burdensome. Production environments impose strict safety requirements, and it is not permitted to wear items that could become entangled in machinery, interfere with production processes, or compromise protective clothing. Therefore, any technological solution must be compatible with existing safety regulations and should not introduce new physical risks or discomfort.

For successful implementation, worker feedback and input was described as essential. Moreover, involving workers and other affected personnel in the implementation process is considered important to reduce concerns or resistance since it provides an opportunity for questions to be raised and addressed. Furthermore, implementation should not occur abruptly. Instead, employees should be given the opportunity to observe pilot testing on site and to gain a practical understanding of how the technology functions and how it will be used. Clearly presenting the purpose of the technology and by demonstrating sample outputs may contribute to increased transparency and reduced resistance.

From a functional perspective, it was considered beneficial if the technology could help with reducing the manual counting of movements within risk zones. However, it was emphasized that human judgment and analysis must remain central to the assessment process. The system should not operate as a fully autonomous decision-making tool that generates outputs without human interpretation. Transparency in how data is processed and presented would therefore be essential. Ideally, the system would allow the assessment to be reviewed collaboratively, supporting the ergonomics assessor in verifying how many times a risk zone has been reached without requiring repeated manual review of recorded material.

It was also reported as advantageous if the technology could segment or structure work tasks into identifiable phases, rather than providing only a final aggregated result. The system should highlight specific time periods or specific body regions, since this would aid in-depth analysis to better understand the underlying causes of exposure. In summary, the ability to visually follow evaluations and/or filter and extract relevant data is considered highly valuable.

Finally, it was considered advantageous if the application of the technology could be expanded beyond assembly operators to other occupational groups within the factory, such as forklift drivers or personnel performing different types of tasks. Flexibility and adaptability were therefore regarded as important characteristics of any prospective solution.

H

Summary of interview with Volvo Employees responsible for Gemba lens in France

Three Volvo Group employees involved with the Gemba Lens system were interviewed across two separate sessions. The first interviewee has been involved with Gemba Lens since it started in late 2023. The second interviewee worked as an apprentice to the first and was involved in the day-to-day use and evaluation of the tool. The third interviewee works with workplace organisation and builds competence in safety, ergonomics, and quality, with a particular focus on supporting ergonomic analysis. All three have hands-on experience with the system from its early stages through to its current pilot use.

Gemba Lens is an internal initiative developed together with the startup DataTimeSpace. The tool was built to digitalize the 3M analysis, with the goal of making it faster and more systematic. The first interviewee described the project started in response to the time it took to record operators and then manually review the footage, and that a digital tool could cut the required time drastically.

The system runs on mobile devices equipped with LiDAR. The user first scans the environment where the assessment will take place. This scan does not need to be repeated for each subsequent recording at the same location. All data is stored on a Volvo server.

On the ergonomic side of Gemba Lens, the functionalities were more limited. The system captures some body postures and some joint angles as part of the Muri analysis, and it can export data to Excel showing how often an operator enters certain postures and the number of risk zone entries. It cannot, however, export ergonomic risk scores or outputs that would feed directly into a dedicated ergonomic evaluation. The lead interviewee was clear that the tool was designed around the production process, not around ergonomics. He also stressed what he called the "Muda trap", that organisations tend to jump straight to eliminating waste when the correct order is to address Muri first, then Mura, and only then Muda.

The technical foundation for more ergonomic functionality does exist. Future versions are expected to count occurrences of risk positions and time spent in those positions, and this work is already underway. The other two interviewees confirmed that the development team plans to release a basic ergonomic output for general users, with more advanced features aimed at experts, but ergonomics remains on the roadmap rather than being a current priority. The accuracy of the system has not been formally quantified, which was acknowledged as difficult to do. Experimental comparisons with manual evaluations have been carried out, and while absolute accuracy is uncertain, the measurements appear to be internally consistent over time.

Several practical challenges came up across both interviews. Multiple people in the production environment can cause the system to swap between tracked individuals, disrupting the recording. GDPR compliance and union discussions were flagged as recurring concerns, as was the need for open dialogue with workers being recorded. More broadly, gaining acceptance for digital solutions over established manual methods can be difficult, regardless of the specific tool. The accuracy of the measured joint angles was also pointed to as a known limitation still being worked on.

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Detailed System–Expert Comparison Tables Used for MAD Calculations

Table I.1: Comparison between the investigated systems and ergonomics expert evaluation for Production Video 1

	Angle 1		Angle 2			Angle 1		Angle 2	
	1:09 min	Deviation	1:10 min	Deviation		1:09 min	Deviation	1:10 min	Deviation
Ergonomic Expert					ErgoPlus				
Wrist	5	-	7	-	Wrist	-	-	-	-
Shoulder	16	-	12	-	Shoulder	13	3	3	9
Trunk	6	-	6	-	Trunk	7	1	7	1
Neck	9	-	6	-	Neck	11	2	17	11
Yellow zone	9	-	12	-	Yellow zone	-	-	-	-
Red zone	9	-	10	-	Red zone	-	-	-	-
Occurrence Ergo					SoterAI				
Wrist	-	-	-	-	Wrist	26	21	18	11
Shoulder	15	1	12	0	Shoulder	26	10	6	6
Trunk	35	29	23	17	Trunk	32	26	11	5
Neck	20	11	18	12	Neck	20	11	18	12
Yellow zone	12	3	10	2	Yellow zone	10	1	3	9
Red zone	8	1	7	3	Red zone	10	1	3	7
TuMeke									
Wrist	32	27	48	41					
Shoulder	11	5	9	3					
Trunk	8	2	6	0					
Neck	8	1	8	2					
Yellow zone	-	-	-	-					
Red zone	-	-	-	-					

Table I.2: Comparison between the investigated systems and ergonomics expert evaluation for Production Video 2

	Angle 1		Angle 2			Angle 1		Angle 2	
	1:16 min	Deviation	1:11 min	Deviation		1:16 min	Deviation	1:11 min	Deviation
Ergonomic Expert					**ErgoPlus**				
Wrist	6	-	3	-	Wrist	-	-	-	-
Shoulder	24	-	18	-	Shoulder	19	5	8	10
Trunk	2	-	6	-	Trunk	7	5	11	5
Neck	12	-	6	-	Neck	25	13	18	12
Yellow zone	9	-	12	-	Yellow zone	-	-	-	-
Red zone	16	-	11	-	Red zone	-	-	-	-
Occurrence Ergo					**SoterAI**				
Wrist	-	-	-	-	Wrist	8	2	13	10
Shoulder	23	1	17	1	Shoulder	5	19	10	8
Trunk	21	19	15	9	Trunk	10	8	12	6
Neck	20	8	25	19	Neck	6	6	17	11
Yellow zone	11	2	8	4	Yellow zone	18	9	17	5
Red zone	24	8	20	9	Red zone	23	7	20	9
TuMeke									
Wrist	38	32	37	34					
Shoulder	29	5	17	1					
Trunk	7	5	4	2					
Neck	15	3	7	1					
Yellow zone	-	-	-	-					
Red zone	-	-	-	-					

Table I.3: Comparison between the investigated systems and ergonomics expert evaluation for Production Video 3

	Angle 1		Angle 2			Angle 1		Angle 2	
	0:43 min	Deviation	0:46 min	Deviation		0:43 min	Deviation	0:46 min	Deviation
Ergonomic Expert					**ErgoPlus**				
Wrist	8	-	9	-	Wrist	-	-	-	-
Shoulder	9	-	6	-	Shoulder	11	2	4	2
Trunk	4	-	6	-	Trunk	7	3	10	4
Neck	10	-	12	-	Neck	14	4	18	0
Yellow zone	10	-	12	-	Yellow zone	-	-	-	-
Red zone	5	-	5	-	Red zone	-	-	-	-
Occurrence Ergo					**SoterAI**				
Wrist	-	-	-	-	Wrist	8	0	6	3
Shoulder	8	1	7	1	Shoulder	5	4	3	3
Trunk	12	8	24	18	Trunk	10	6	10	4
Neck	18	8	21	9	Neck	6	4	4	8
Yellow zone	15	5	11	1	Yellow zone	5	5	3	9
Red zone	8	3	5	0	Red zone	10	5	2	3
TuMeke									
Wrist	27	19	34	25					
Shoulder	10	1	6	0					
Trunk	7	3	7	4					
Neck	8	2	4	8					
Yellow zone	-	-	-	-					
Red zone	-	-	-	-					

Table I.4: Comparison between the investigated systems and ergonomics expert evaluation for Production Video 4

	Angle 1		Angle 2			Angle 1		Angle 2	
	1:40 min	**Deviation**	**1:59 min**	**Deviation**		**1:40 min**	**Deviation**	**1:59 min**	**Deviation**
Ergonomic Expert					**ErgoPlus**				
Wrist	7	-	11	-	Wrist	-	-	-	-
Shoulder	15	-	24	-	Shoulder	17	2	14	10
Trunk	3	-	10	-	Trunk	9	6	11	1
Neck	15	-	10	-	Neck	15	0	23	13
Yellow zone	20	-	12	-	Yellow zone	-	-	-	-
Red zone	17	-	23	-	Red zone	-	-	-	-
Occurrence Ergo					**SoterAI**				
Wrist	-	-	-	-	Wrist	30	23	26	15
Shoulder	20	5	26	2	Shoulder	25	10	28	4
Trunk	25	22	43	34	Trunk	15	12	23	13
Neck	48	28	35	25	Neck	16	1	20	10
Yellow zone	28	8	23	11	Yellow zone	28	8	22	10
Red zone	16	1	20	3	Red zone	34	17	10	13
TuMeke									
Wrist	29	22	50	39					
Shoulder	17	2	21	3					
Trunk	14	11	9	1					
Neck	10	5	8	2					
Yellow zone	-	-	-	-					
Red zone	-	-	-	-					

Table I.5: Comparison between the investigated systems and ergonomics expert evaluation for Production Video 5

	Angle 1		Angle 2			Angle 1		Angle 2	
	1:14 min	**Deviation**	**1:17 min**	**Deviation**		**1:14 min**	**Deviation**	**1:17 min**	**Deviation**
Ergonomic Expert					**ErgoPlus**				
Wrist	6	-	4	-	Wrist	-	-	-	-
Shoulder	20	-	24	-	Shoulder	20	0	18	6
Trunk	0	-	4	-	Trunk	11	11	12	8
Neck	18	-	16	-	Neck	16	2	15	1
Yellow zone	2	-	2	-	Yellow zone	-	-	-	-
Red zone	19	-	24	-	Red zone	-	-	-	-
Occurrence Ergo					**SoterAI**				
Wrist	-	-	-	-	Wrist	25	19	23	19
Shoulder	13	7	16	8	Shoulder	22	2	10	14
Trunk	22	18	11	7	Trunk	9	9	12	8
Neck	23	7	28	12	Neck	12	6	6	10
Yellow zone	5	3	4	2	Yellow zone	7	5	15	13
Red zone	11	13	15	9	Red zone	13	6	31	7
TuMeke									
Wrist	25	19	31	27					
Shoulder	24	4	22	2					
Trunk	10	10	5	1					
Neck	10	8	7	9					
Yellow zone	-	-	-	-					
Red zone	-	-	-	-					

Table I.6: Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 1. The workstation was designed primarily to affect the shoulders and includes repetitive arm movements.

Ergonomic Expert			ErgoPlus			Occurrence Ergo		
	0:46 min	Deviation		0:46 min	Deviation		0:46 min	Devation
Wrist	12	-	Wrist	-	-	Wrist	-	-
Shoulder	19	-	Shoulder	7	12	Shoulder	13	6
Trunk	0	-	Trunk	3	3	Trunk	8	8
Neck	5	-	Neck	11	6	Neck	1	4
Yellow zone	17	-	Yellow zone	-	-	Yellow zone	12	5
Red zone	0	-	Red zone	-	-	Red zone	0	0
SoterAI			**TuMeke**					
	0:46 min	Devation		0:46 min	Devation			
Wrist	24	12	Wrist	14	2			
Shoulder	10	9	Shoulder	6	13			
Trunk	0	0	Trunk	3	3			
Neck	4	1	Neck	6	1			
Yellow zone	8	9	Yellow zone	-	-			
Red zone	5	5	Red zone	-	-			

Table I.7: Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 2. The workstation was designed to involve a combination of different tasks to target the upper-body.

Ergonomic Expert			ErgoPlus			Occurrence Ergo		
	1:00 min	Deviation		1:00 min	Deviation		1:00 min	Devation
Wrist	7	-	Wrist	-	-	Wrist	-	-
Shoulder	8	-	Shoulder	9	1	Shoulder	10	2
Trunk	0	-	Trunk	5	5	Trunk	5	5
Neck	7	-	Neck	6	7	Neck	1	3
Yellow zone	9	-	Yellow zone	-	-	Yellow zone	7	2
Red zone	7	-	Red zone	-	-	Red zone	9	2
SoterAI			**TuMeke**					
	1:00 min	Devation		1:00 min	Devation			
Wrist	20	13	Wrist	18	11			
Shoulder	24	14	Shoulder	10	2			
Trunk	9	9	Trunk	5	5			
Neck	9	7	Neck	6	1			
Yellow zone	8	2	Yellow zone	-	-			
Red zone	18	11	Red zone	-	-			

Table I.8: Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 3. The workstation involved lifting and carrying and was designed primarily to affect the trunk and shoulders.

Ergonomic Expert			ErgoPlus			Occurrence Ergo		
	1:03 min	Deviation		1:03 min	Deviation		1:03 min	Devation
Wrist	13	-	Wrist	-	-	Wrist	-	-
Shoulder	26	-	Shoulder	19	7	Shoulder	16	10
Trunk	7	-	Trunk	10	3	Trunk	22	15
Neck	7	-	Neck	16	9	Neck	8	8
Yellow zone	11	-	Yellow zone	-	-	Yellow zone	16	5
Red zone	22	-	Red zone	-	-	Red zone	13	9
SoterAI			TuMeke					
	1:03 min	Devation		1:03 min	Devation			
Wrist	16	3	Wrist	21	8			
Shoulder	14	12	Shoulder	23	3			
Trunk	18	11	Trunk	12	2			
Neck	11	4	Neck	14	2			
Yellow zone	15	4	Yellow zone	-	-			
Red zone	14	8	Red zone	-	-			

Table I.9: Comparison between the investigated systems and ergonomics expert evaluation for Simulated Production Video 4. The workstation was designed to involve repetitive arm and wrist movements.

Ergonomic Expert			ErgoPlus			Occurrence Ergo		
	0:46 min	Deviation		0:46 min	Deviation		0:46 min	Devation
Wrist	12	-	Wrist	-	-	Wrist	-	-
Shoulder	19	-	Shoulder	7	12	Shoulder	13	6
Trunk	0	-	Trunk	3	3	Trunk	8	8
Neck	5	-	Neck	11	6	Neck	1	4
Yellow zone	17	-	Yellow zone	-	-	Yellow zone	12	5
Red zone	0	-	Red zone	-	-	Red zone	0	0
SoterAI			TuMeke					
	0:46 min	Devation		0:46 min	Devation			
Wrist	24	12	Wrist	14	2			
Shoulder	10	9	Shoulder	6	13			
Trunk	0	0	Trunk	3	3			
Neck	4	1	Neck	6	1			
Yellow zone	22	5	Yellow zone	-	-			
Red zone	8	8	Red zone	-	-			

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