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# Model-driven evaluation of exoskeletons for efficient traction battery dismantling

Max Rettenmeier*[a,b], Simon Eckstein[a,c], Christian Hackenbeck[a,d], Jonas Froehlich[a], Mark Tröster[c,e], Artur Krause[f], Mauritz Möller[b], Alexander Sauer[a,c,g]

[a]*Graduate School of Excellence advanced Manufacturing Engineering (GSaME), University of Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany*
[b]*TRUMPF Laser- und Systemtechnik SE, Johann-Maus-Straße 2, 71254 Ditzingen, Germany*
[c]*Fraunhofer-Institute for Manufacturing Engineering and Automation (IPA), Nobelstraße 12, 70569 Stuttgart, Germany*
[d]*Mercedes-Benz AG, Leibnizstr. 2, 71032 Böblingen, Germany*
[e]*Institute of Industrial Manufacturing and Management (IFF), University of Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany*
[f]*Institute for Smart Engineering and Machine Elements (ISEM), Hamburg University of Technology, Am Schwarzberg-Campus 4, 21073 Hamburg, Germany*
[g]*Institute for Energy Efficiency in Production (EEP), University of Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49 7156 303-36973; fax: +49 7156 303-0. *E-mail address:* Max.Rettenmeier@gsame.uni-stuttgart.de

## Abstract

The disassembly of traction batteries is primarily performed manually due to the difficulty of implementing automation solutions, mainly because of the large number of variants. As a result of the lack of automation, employees are frequently exposed to heavy loads and unergonomic postures, which can lead to work-related musculoskeletal disorders. This paper utilizes a modeling approach with the software “emaWorkDesigner” to evaluate the ergonomics and feasibility of exoskeletons in facilitating and improving the manual disassembly of traction batteries. The Ergonomic Assessment Work Sheet EAWS is applied as ergonomic assessment method. EAWS section criteria are analyzed to investigate the potential use of exoskeletons to support the workers. The assessment is conducted based on the example of the first disassembly step, which is the removal of the tray cover. Finally, the study concludes with recommendations and areas of future research for the traction battery disassembly in industrial applications.

*Keywords:* exoskeleton; traction battery; disassembly; ergonomics

## 1. Introduction

The further development of electric mobility will be of vital importance for the achievement of climate targets [1]. Battery-powered electric vehicles (BEVs) are a key technological derivative of electromobility [2]. These vehicles are equipped with electric vehicle traction batteries (EVBs), which provide energy for the electric powertrain system [3]. The batteries are predominantly based on lithium-ion technology, which employs rare earth elements such as lithium, nickel, cobalt or manganese, depending on the chemical composition [4]. Rare earths are only available in specific regions of the world, which poses supply chain risks and leads to uncertain and expensive procurement conditions for battery manufacturers [4]. This highlights the need for closed-loop localized supply chains that can be fed by recycled materials. Europe, in particular, has low natural resources for materials such as cobalt or lithium, hence there is a battery recycling directive that regulates and mandates the recycling of batteries [5, 6]. The first step in recycling traction batteries is dismantling or disassembly [7]. These terms will be used interchangeably in this paper. The disassembly process is essential because it separates the valuable battery

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cells or modules from the other components of an EVB. An overview of the components of a state of the art EVB is illustrated in Fig. 1 [8].

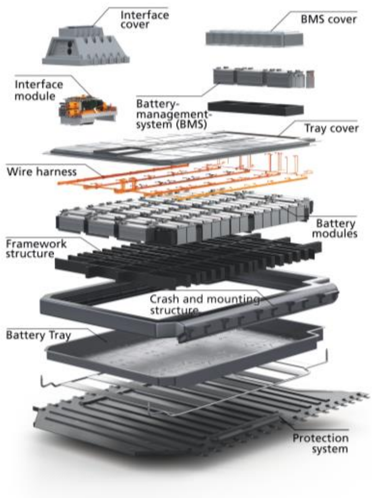


Fig. 1. Module-to-pack EVB architecture [8]

The end-of-life (EOL) stage determines when batteries are available for recycling. This stage is set by the 80% threshold of a battery's state-of-health (SOH) [9]. The SOH determines the remaining capacity of the battery [10]. Following the disassembly of the traction batteries, several separation and sorting steps are required. Further information can be found in the article of Harper et al. [7], for example.

It is crucial to disassemble as many components as possible to reduce the effort required for subsequent process steps and achieve high purity of the recycled materials [11]. To perform the disassembly process, a high degree of flexibility is required, as there are many EVB variants [7, 12, 13]. However, this poses significant challenges for the automation of the disassembly process, which is why manual labor is still employed throughout this step [14–16]. Since manual work will still be necessary in the coming years and module-to-pack architectures will be the main architectures entering the EOL stage, this will be the focus of this paper. Thus, it is imperative to investigate methods for assisting human workers in performing exhausting disassembly tasks to ensure an ergonomic work environment. One personal measure of assisting the human worker with physically demanding tasks is the use of exoskeletons [17]. An exoskeleton is an assistive device that is worn by the operator and supports certain movements [18]. The support can be applied to many different body regions. In particular, the ergonomic importance of the shoulder for assembly tasks has been investigated in previous studies [19–21].

Therefore, this paper investigates the role of exoskeletons for the shoulder of a human operator during EOL EVB disassembly. The scope is limited to the first disassembly step, which is the removal of the tray cover, as the modeling methodology itself can be applied to several other process steps. A general overview of the disassembly process sequence for the EOL EVB can be found in numerous other studies [22–25]. The main purpose of this paper is to pave the way for this research, with a first initial evaluation for the use of exoskeletons focusing on the removal of the tray cover with a shoulder-supported exoskeleton. Further studies can then build on our methodology and model the ergonomic impact for other body regions with other exoskeletons. In addition, our approach can be used to investigate the further steps in the process after the tray cover has been removed. The results will provide implications for decision-makers in the field of production management regarding the future use of shoulder-supported exoskeletons for EOL EVB disassembly, with a particular focus on tray cover removal. The objective is to provide an initial assessment of the potential for exoskeletons to facilitate the disassembly of EOL EVB. Finally, further areas of research for future investigation are outlined.

## 2. State of the art

In the rapidly evolving field of manufacturing and disassembly, the integration of exoskeleton technology has emerged as a significant trend, addressing ergonomic challenges and enhancing efficiency [26]. Voilqué et al. [27] classify and analyze industrial exoskeleton technologies, emphasizing their role in supporting workers in manual handling tasks, thereby potentially increasing productivity and reducing the physical strain. While their work thoroughly explores ergonomic supports, the potential application of such technologies in aiding the unscrewing process in disassembly operations remains less examined, presenting an opportunity for further integration of ergonomic supports in unscrewing tasks that are often repetitive and physically demanding. Arkouli et al. [28] extend the conversation to reconfigurable manufacturing, noting the importance of exoskeletons in maintaining low physical workload for workers engaged in the assembly of large-scale parts. Their insights suggest a pivotal role for exoskeletons in enhancing worker stamina and precision, which are crucial in tasks involving intricate unscrewing processes. Jorgensen et al. [29] delve into the specifics, evaluating the impact of passive shoulder exoskeletons on muscle activation during aircraft manufacturing tasks, suggesting significant benefits in terms of reducing muscle activity. However, the adaptation of such technology specifically to assist in the unscrewing of components in complex assemblies could further alleviate muscular strain and enhance disassembly efficiency. Reyes et al. [30] offer a comprehensive review of shoulder-support exoskeletons, focusing on current applications, challenges, and future directions for overhead work tasks in industrial settings. The integration of these technologies in settings that require frequent unscrewing could transform ergonomic practices, significantly reducing overhead labor and associated risks. Mironov et al. [31] developed a robot with a control system for the automated disassembly of electronic devices, emphasizing the need for sophisticated control systems that mimic human haptic feedback in unscrewing tasks, a fundamental operation in disassembly that precedes critical steps such as battery removal. This underscores the multifaceted challenge in the disassembly sector, particularly in battery dismantling and other tasks requiring precision and significant physical effort.

Exoskeletons emerge as a promising solution to enhance worker safety, efficiency, and comfort while addressing the ergonomic challenges of repetitive, strenuous tasks. The ongoing development and refinement of exoskeleton

Table 1. State of the art literature review

| Article | Title | Type of paper | Relevance | Summary |
|---|---|---|---|---|
| [27] | Industrial exoskeleton technology: classification, structural analysis, and structural complexity indicator | Review / Conceptual | Exoskeletons: Yes;<br>Manufacturing: Yes;<br>Disassembly: No;<br>Battery Dismantling: No;<br>Unscrewing: No;<br>Ergonomic Perspective: Yes | Provides a classification and analysis of industrial exoskeletons, introducing a structural complexity indicator. |
| [28] | AI-enhanced cooperating robots for reconfigurable manufacturing of large parts | Review / Conceptual | Exoskeletons: Yes;<br>Manufacturing: Yes;<br>Disassembly: No;<br>Battery Dismantling: No;<br>Unscrewing: No;<br>Ergonomic Perspective: No | Examines the synergy between robotic systems, human workers, and ICT tools in manufacturing, highlighting the use of exoskeletons. |
| [29] | Influence of different passive shoulder exoskeletons on shoulder and torso muscle activation during simulated horizontal and vertical aircraft squeeze riveting tasks | Empirical | Exoskeletons: Yes;<br>Manufacturing: Yes;<br>Disassembly: Yes;<br>Battery Dismantling: No;<br>Unscrewing: No;<br>Ergonomic Perspective: Yes | Evaluates passive shoulder exoskeletons in reducing muscle strain during aircraft manufacturing tasks. |
| [30] | Shoulder-support exoskeletons for overhead work: current state, challenges, and future directions | Review / Conceptual | Exoskeletons: Yes;<br>Manufacturing: Yes;<br>Disassembly: Yes;<br>Battery Dismantling: No;<br>Unscrewing: No;<br>Ergonomic Perspective: Yes | Reviews the development, applications, and challenges of shoulder-support exoskeletons for overhead work. |
| [31] | Haptics of screwing and unscrewing for its application in smart factories for disassembly | Empirical | Exoskeletons: No;<br>Manufacturing: Yes;<br>Disassembly: Yes;<br>Battery Dismantling: No;<br>Unscrewing: Yes;<br>Ergonomic Perspective: No | Focuses on developing control systems for automated disassembly, particularly the unscrewing process. |

technology, alongside advances in robotics, signal a paradigm shift towards more sustainable, human-centric manufacturing and disassembly processes.

## 3. Methodology

The disassembled element is an EVB demonstrator, designed in accordance with the state of the art EVB architectures (see Fig. 1). The dismantling of the tray cover was achieved by unscrewing the screws with an automatic screwdriver and carrying the tray cover to a logistics steel box. Two workers (50th percentile, male, age group 40) are employed in this process, as other studies have already investigated, and as the tray cover is difficult to handle for a single person due to its size [32, 33]. For the disassembling process and subsequent ergonomics modeling, the software ema Work Designer (version 2.3.1.1) was used as an ergonomic planning tool for manufacturing environments. The disassembly setting consists of a manual station, as generally described in several other articles [22, 34, 35]. The manual setup was selected for two reasons. Firstly, it reflects the state of the art in EOL EVB disassembly. Secondly, since this study aims to provide a transitional support for manual operations until the process will be automated in future, effective methods for enhancing manual work are required. Each worker's closed-loop disassembly working cycle is evaluated separately and their EAWS score is scaled to an 8-hour work shift based on their cycle score, break times, and extra points. A visualization of the modeling setup in ema Work Designer is presented in Fig. 2.

Fig. 2. Manual disassembly station visualization in ema Work Designer

Following the process modeling, an ergonomic evaluation was automatically generated with the Ergonomic Assessment Work Sheet v1.3.6 (EAWS) based on [36]. This was performed through the digital human model in the ema Work Designer software [37]. The tasks which are to be operated during the process are automatically tracked in the ema Work Designer software and evaluated in suitable sections. Thereafter, the EAWS risk score composition of the modeled process tasks is investigated and analyzed to identify hazardous work situations. The EAWS evaluation is structured according to a point-based system, which is divided into three ranges [36]:

- 0-25 points: low risk
- >25-50 points: possible risk
- >50 points: high risk

Regarding applied forces, a force of 30N was assumed for the arm force within the unscrewing task. Given the possibility that screws in EOL EVB may be rusted, an automatic screwdriver with medium strength (5-7Nm) was selected as a suitable tool for use in ema Work Designer. The corresponding vibrations were also assumed to be of a medium level. Appendix A presents further relevant modeling characteristics and assumptions.

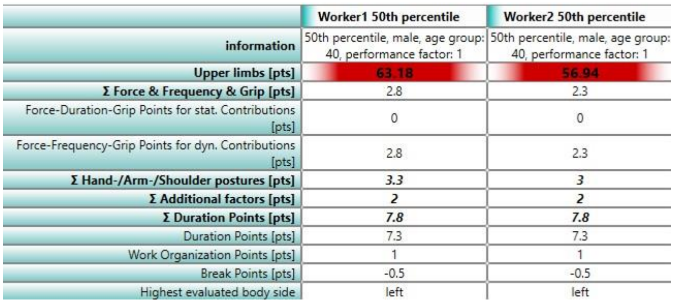
Table 2. Evaluation matrix for the potential use of exoskeletons in the field of EOL EVB disassembly

| Study | Body region | Type of exoskeleton | EOL EVB disassembly process step |
|---|---|---|---|
| Our study | Upper limb | Upper limb | Tray cover removal |
| Future studies | Other body regions, see for example [38–40] | Other exoskeletons, see for example [41–44] | Subsequent disassembly steps, see for example [22–25] |

In addition to the specific modeling of the ergonomic impact of removing the EOL EVB tray cover, a general framework is also presented. The matrix presented in Table 2 aims to provide a framework for exoskeleton evaluations in the area of disassembly.

## 4. Results

The modeling results will be concentrated on the upper limb area, as this is the primary focus of this paper. Fig. 1 illustrates that the overall ergonomic evaluation based on the EAWS methodology for the upper limb is classified within the red area. This indicates that there is a significant ergonomic risk posed to the workers who operate it. A more detailed examination of the results in Fig. 3 reveals that the hand, arm, and shoulder postures, as well as the duration of the task, contribute to the high score. The score of two points for additional factors was assumed due to the use of vibrating tools, which are employed for more than one-third of the time. In Fig. 3, the highest evaluated body side is the left side, which is defined as the available secondary hand used to repetitively grasp and place the bolts.



| | Worker1 50th percentile | Worker2 50th percentile |
|---|---|---|
| information | 50th percentile, male, age group: 40, performance factor: 1 | 50th percentile, male, age group: 40, performance factor: 1 |
| **Upper limbs [pts]** | 63.18 | 56.94 |
| **Σ Force & Frequency & Grip [pts]** | 2.8 | 2.3 |
| Force-Duration-Grip Points for stat. Contributions [pts] | 0 | 0 |
| Force-Frequency-Grip Points for dyn. Contributions [pts] | 2.8 | 2.3 |
| **Σ Hand-/Arm-/Shoulder postures [pts]** | ***3.3*** | ***3*** |
| **Σ Additional factors [pts]** | ***2*** | ***2*** |
| **Σ Duration Points [pts]** | ***7.8*** | ***7.8*** |
| Duration Points [pts] | 7.3 | 7.3 |
| Work Organization Points [pts] | 1 | 1 |
| Break Points [pts] | -0.5 | -0.5 |
| Highest evaluated body side | left | left |

Fig. 3. Modeling results for the upper limb area

In particular, the high scores for hand, arm, and shoulder postures are analyzed in detail, as a previous study has demonstrated that exoskeletons can be beneficial in supporting these areas, particularly for movements with arm flexion angles greater than 80° [45]. Fig. 4 illustrates an analysis of the flexion angles for the left and right arms for worker 1. The results for workers 1 and 2 are comparable, as they mainly perform the same tasks (see also Fig. 3). Moreover, it is evident that the aforementioned threshold of 80° has been exceeded on multiple

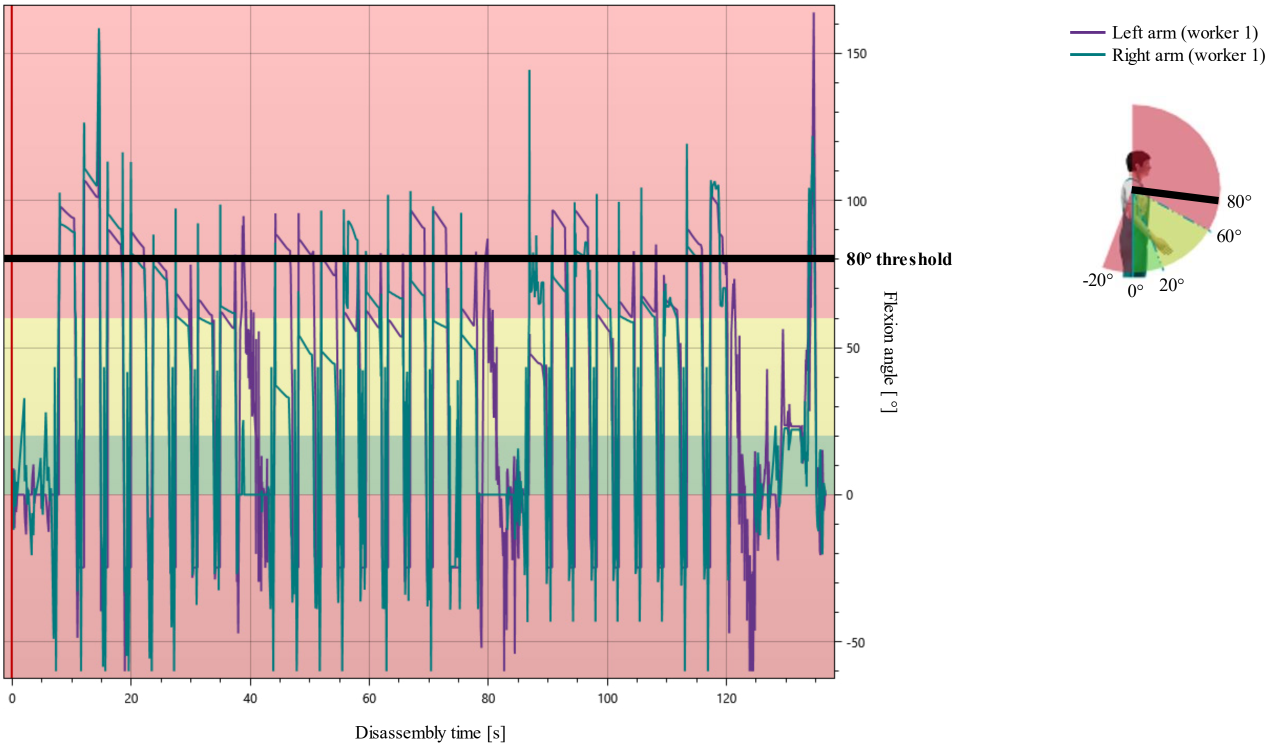


Fig. 4. Modeling results for arm flexion during tray cover removal

occasions. This indicates that an upper limb exoskeleton, as proposed by Caragnano et al. [45], can indeed support the disassembly of an EOL EVB tray cover.

## 5. Discussion

The results presented in Section 4 demonstrate that upper limb exoskeletons can facilitate an enhanced ergonomic situation for workers during the disassembly of the tray cover from EOL EVB. Nevertheless, our investigation only covers a part of the overall framework presented in Table 2. In order to reach a full evaluation of the potential of exoskeletons for the disassembly of traction batteries, further studies must investigate other body regions, different exoskeletons and further EOL EVB disassembly process steps. Once this picture is completed, a final evaluation will be possible. However, our investigations provide initial indications for decision-makers in the battery disassembly industry that exoskeletons warrant further examination to facilitate the transition between non-supported manual work and automated disassembly in the future. It should be noted that the so-called TOP principle is generally applied for ergonomic optimization processes [45–47]. The TOP principle states that technical solutions (T) and organizational optimizations (O) have to be investigated before personal measures (P) are taken into account [48]. In the context of this study, it was assumed that the implementation of technical and organizational measures would be more challenging than the use of exoskeletons, which are intended as a transitional solution until the processes are sufficiently automated. Furthermore, exoskeletons can be implemented rapidly without necessitating changes to the working environment or the addition of other technical solutions. It is still recommended in advance of the final deployment of exoskeletons to conduct a detailed biomechanical assessment, for instance through a musculoskeletal modeling approach. This is necessary since the effects of exoskeletons on the human body embody a complex and direct mechanical interaction.

The process modeling and result evaluation are subject to different limitations. The modeled workstation is simplified and may differ in a real disassembly environment. This also affects the modeling, as the height and geometry of the table and the battery significantly influence the angles at which the workers operate. However, as previously stated, we assumed that the other parts of the TOP principle are not applicable to this specific case.

Within the software, only standing and kneeling are possible, so no slight flexion of the knees is permitted. Moreover, it should be noted that the visualization in Fig. 4 displays unrealistic values for the three peaks (red circled) for the arm flexion angles. However, these values are immediate occurring artefacts in the generated motion patterns and therefore too short to contribute to the ergonomic score. This limitation has been considered acceptable.

## 6. Conclusion

This study provides initial insights into the feasibility of exoskeletons as a tool for enhancing the ergonomic situation for operators engaged in the disassembly of EOL EVB. To achieve this, the study considers a representative step, namely the tray cover removal, and analyses its performance in conjunction with an exoskeleton designed to assist the upper limb. The implications presented in the study are intended to provide initial guidance to production managers in the field of EOL EVB disassembly, who may then be better equipped to assess the potential benefits that exoskeletons could have in their operational environment. This study also presents an overall framework matrix, which indicates the necessity for future research to evaluate the potential use of exoskeletons for the disassembly of EOL EVB. Further studies should demonstrate the beneficial use of exoskeletons for other body regions, different exoskeletons, and additional process steps.

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## Appendix A. Simulation parameters (S) and task characteristics for the two workers (W1 and W2)

| ID | Setting/ Task | Characteristics and assumptions | EAWS-Section |
|---|---|---|---|
| S | Cycle time | 195.84 s | - |
| S | Cycles per shift | 135 | - |
| S | Simulation time | 135.84 s | - |
| S | Break time per cycle | 60 s | - |
| S | Shift time | 480 min | |
| S | Gross shift time | 440 min | |
| W1/ W2 | Breaks (≥ 8 min) | 2 | - |
| W1 | Scan QR-code | Hold scanner:<br>- power grip, 0.2 kg right hand | Postures |
| W1/ W2 | Unscrew screws | Hold electric screwdriver:<br>- power grip, 1.5 kg right hand<br>Use electric screwdriver:<br>- Vibrations<br>- 5-7 Nm torque<br>- 30 N arm/body force<br>- secondary hand support | Action forces & Upper limbs |
| W1/ W2 | Pick and place 6-8 M6 screws per grip | Reposition screws:<br>- strong pinch grip < 0.5 kg left hand<br>Hold screwdriver:<br>- power grip, 1.5 kg right hand | Postures & Upper limbs |
| W1/ W2 | Remove tray cover | Reposition tray cover:<br>- 50% power grip, 4.95 kg both hands | Manual load handling |

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