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Application of Ergonomic Assessment Methods on an Exoskeleton Centered Workplace

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Michael Hefferle studied mechanical engineering at the Technical University of Munich and graduated with a Master's degree in 2014. In his thesis he developed a 3D printed orthosis that helps to reduce the strains exerted on the thumb at an automotive assembly line. The assistant device was patented by BMW Group. Being employed at BMW since late 2017, Michael Hefferle is a PhD candidate at the University of Siegen. The PhD Thesis investigates the impact of exoskeletons on the ergonomic situation of a workplace as well as the development of a new ergonomic assessment method.

Abstract: Exoskeletons are becoming more and more interesting for the industry to support workers ergonomically and additionally to increase the capabilities in a production system (Perry, 2017). Today the hardest challenge is still to detect, structure, and assess all effects of an exoskeleton in a holistic approach. Especially the ergonomic assessment is one of the major challenges for the integration of exoskeletons in the industry to evaluate all relevant influences. A few laboratory use case studies are took a deeper look into the ergonomic impact. Although the results are scientific, specific and detailed, they are still not applicable in a holistic approach. Furthermore, they cannot be evaluated using the already existing assessment methods in the industry. This investigation focuses on the impact of various assessment methods that are applied at an example workplace and a sample exoskeleton in order to discuss their respective suitability. The discussed assessment methods were found best suitable and were preselected beforehand. Hence, this paper will discuss the workflow, applicability, and validity of already existing state-of-the-art ergonomic assessment methods. A review of the currently available research is presented. Requirements based on already available methods within the industry regarding the integration of exoskeletons in the production system are defined. The preselected ergonomic assessment methods are applied systematically on a fictitious workplace, typical of the automotive industry, combined with an example passive exoskeleton device. The results are discussed comprehensively to give a prospect on the potential next scientific steps.

Keywords: Exoskeleton, EAWS, KIM, RULA, REBA

1 Introduction

Figure 1 shows our chain of reasoning for the industrial motivation of provable and, more importantly, for applicable assessment methods. In the first step we discuss whether exoskeletons (as a body worn structure) have an influence on the human body (ergonomic assessment) as well as the workplace (production system) while performing a certain task. Our hypothesis is that when no effectiveness can be expected, further steps are not necessary. Concluding that exoskeletons have a relevant impact, the next step is to demonstrate this impact. If neither effectiveness nor effects can be demonstrated, new methods or another type of exoskeleton has to be chosen and the above-described loop has to be performed again. Again, it does not depend whether the effects are positive or negative, but only to know if there is an assessment method that detects any effects at all. Effects have been reported previously, in different studies, which are highlighted in paragraph 2. The focus of this investigation is to investigate the practical applicability of the above-mentioned study results for the holistic integration of exoskeletons. If the applied methods within the performed studies cannot address the applicability question, as well as the question of ergonomic benefits, there is currently no standardized way for the widespread and individual integration of exoskeletons in a production system and therefore no motivation for it. In this case, special workarounds can close the gap between methods, which are not suitable for exoskeletons, and a more comprehensive method, which still to be developed. Until a holistic method for assessing exoskeleton is developed, any workaround must be treated with caution due to its lack of completeness. All relevant industry requirements for holistic assessment methods will be defined in paragraph 3.

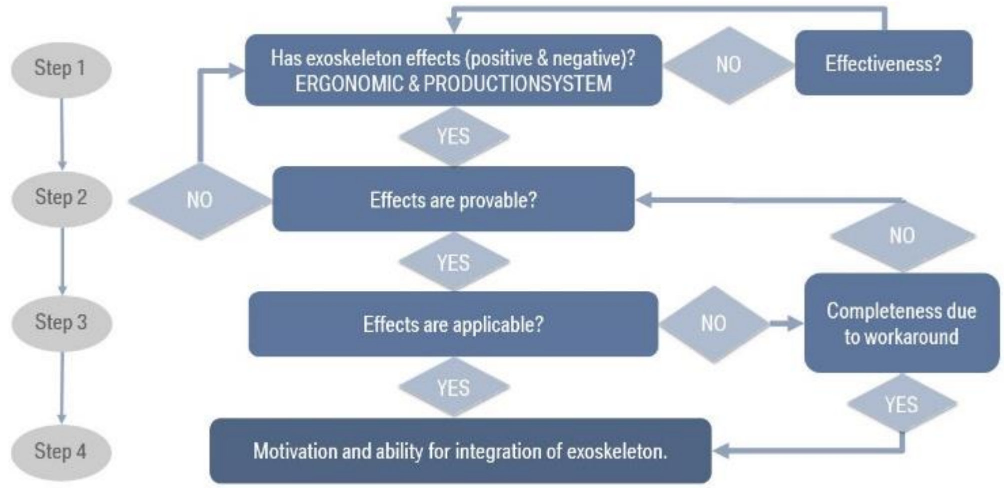

Figure 1: Chain of reasoning to employ exoskeletons.

2 Review of ergonomic exoskeleton studies

Looking at the literature one can find numerous articles regarding the effects of an exoskeleton device on particular muscle groups using electromyography (EMG) while performing certain tasks. However, the majority of these articles focuses on the impact on the muscle groups which are intended to be supported by the assistant devices (de Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016). In general, this leads to the conclusion that the specific exoskeleton is beneficial regarding the scope of the study. The potential negative aspects, for example the biomechanical load shift to other joints or muscle groups and further trade-offs are rarely investigated, even though previous studies showed that the use of exoskeletons can cause significant postural changes – especially during overhead work – or result into kinematic strains (Sylla, Bonnet, Colledani, & Fraisse, 2014; Ulrey & Fathallah, 2013a, 2013b; Weston, Alizadeh, Knapik, Wang, & Marras, 2018). Additionally, a few investigations have been carried out that estimate the effects of the integration of an exoskeleton device on the ergonomic risk assessment of a workplace (Spada, Ghibaudo, Gilotta, Gastaldi, & Cavatorta, 2017). This might be an obstacle for the large-scale implementation of exoskeletons in industrial production systems and it supports our assumption that the currently existing methods are somewhat limited regarding the introduction of exoskeletons. Butler et al. conducted a field study with an exoskeleton device to support overhead work used on a welding and paint workplace. They reported a decreased pain in the shoulder region besides increased productivity and quality as positive side effect (Butler, 2016). Gillette and Stephenson proved by using EMG (tested on the assembly line while performing an overhead task with an exoskeleton by 6 worker) that a reduction of muscle activity is measurable up to 27 % in the upper arm and the shoulder as well as 19 % in the upper back (Gilette & Stephenson, 2017). Rashedi proved reduced muscle activity and discomfort up to 56 % by using EMG and a subjective evaluation questionnaire (RPD - rate of perceived discomfort). The study results are only comparable to a certain extend since the study settings were different and especially because the exoskeleton device used was not a usual anthropomorphic device (Rashedi, Kim, Nussbaum, & Agnew, 2014). Rashedi et al. measure an increased discomfort due to the weight of the device which can be improved by a better fit. There is also a hint that the tested device leads to a different working posture (more straight). More test subjects and a specialized analysis are needed to validate this. Exoskeleton impacts on movements and postures are investigated in (Sylla, Bonnet, Venture, Armande, & Fraisse, 2014). The result is a detected interaction between human and machine that leads to different (energetically advantageous) movements due to this special setting.

3 Assessment requirements and selected methods based on industry needs

As discussed in paragraph 2 there is no direct connection between study results and a comprehensive and holistic assessment method for exoskeletons in an industrial environment. Existing studies focus almost exclusively on the varying influences on specific parts of the human body but do not aim to present the results in a simplified "assessment-score" suitable for industrial demands, i.e. figures and colors (traffic lights) that show the impact on the individual workplace assessment. Furthermore, these studies are highly complex, requiring vast amounts of money and time to produce new results. Being so complex, the results are often too specific to apply them for further use cases, i.e. other exoskeletons at a different workplace. Meeting the industry's demand for applying methods in a fast and simple way to assess varying conditions - especially with exoskeletons - contradicts the complexity of the human body and the resulting influences. However, there is a need to present all the influences in a unique and clear way. There is a critical discrepancy between the need for sufficient accuracy as well as responsibility and the evaluation of complex work systems without great effort. Based on these contradictory requirements, there are many scientific and standardized assessment methods designed to handle this challenge. Some large companies have even developed their own systems to assess their workplaces, although most of these are still based on these standard methods.

Hence, the next step is to evaluate the impact of exoskeletons on different workplace assessments with the current existing methods, also mentioned in (Spada et al., 2017). Our research turned up 36 different scientific assessment methods, each based on one of the following: forms for monitoring tasks, questionnaires, norms and threshold tables. All of them try to assess the ergonomic situation by focusing on known biomechanical and ergonomic factors, which include body postures, time and loads. The 36 found methods were screened and categorized. Characteristics were, for example, based on a short description with relevant advantages and disadvantages, the scientific background and underlying standards, availability (publically accessible), objectivity, field of application/activity, considered body region, data acquisition method, and required input. All these parameters were based on the above-mentioned industry requirements.

The 36 methods were selected through a score-system, that selects and prioritizes the method with the highest amount of factors that the exoskeleton would have an impact on (i.e. force- and exhaustion analysis, execution conditions, forced posture, heat, discomfort, etc.), as well as the industrial applicability. After the score-filter was applied with both conditions (exoskeleton impact and industry requirements), only 5 out of 36 methods remained (see Table 1). For the sake of performing a holistic approach, negative aspects are included as well. The five methods selected are common industrial tools used to assess the ergonomic workplace situation. In addition, they consider factors relevant to the main benefits and impacts of exoskeletons (positive: weight reduction for upper limbs, brace the arms, negative: additional weight on body, other factors). The content and handling with these forms is described through an application in paragraph 5.

Table 1: Selected assessment methods.

Highlighted methods	Considered exoskeleton impacts			
	positive		negative	
	Weight reduction for upper limbs	Brace/lean the arms	Additional weight on body	Other factors (discomfort, hygiene)
EAWS (total body)				x
EAWS (upper limbs)	x	x		x
KIM MA	x			x
REBA		x		
RULA	x	x	x	

4 Explanation of workplace and device

To demonstrate the possible impact on the ergonomic assessment while using an exoskeleton device during a manual assembly task, the integration of the device was simulated at an example workplace. Table 2 shows the technical specifications of the sample workplace and the exoskeleton. Figure 2 depicts the workplace, the task, and the supportive nature of the exoskeleton as a rough draft**.** Although the provided information on the characteristics are imaginary for the sole purpose of demonstrating the method, the presented values are similar to an automotive assembly line. This applies for the exoskeleton device as well. The selected workplace and task are both typically found at an automotive assembly line, where the underbody

Figure 2 Workplace conditions for overhead work.

of a car has to be sealed off against moisture, splash water, and mud. This can be achieved by mounting underfloor trims or by applying plugs. The car body is lifted up, so that the workers can access the underfloor to perform their tasks while standing below the frame. While performing the sample task the worker stands below the car body in an upright posture and mounts the pre-clamped underfloor trim by using a cordless screwdriver. The worker holds the screwdriver in one hand and uses the remaining hand to pick up and position each screw correctly. While screwing in the twenty screws he uses the second hand to support himself against the underbody. Both arms are abducted, with an angle of roughly 90° degrees between the chest and the upper arm and between the upper and the lower arm. The worker performs five seconds of overhead work for each screw. This is considered as a static work posture. Hence, it takes the worker around 100 seconds in total. Correct positioning below the car body, raising and lowering the arms, as well as picking up the material takes about 60 seconds after which the worker completes the assumed cycle (20 screws x 5 s/screw + 60 s = 160 s).

Table 2: Characteristics of the sample workplace and exoskeleton for overhead work

Characteristics of the overhead sample workplace:	
duration of shift	9 h
brake times	1.5 h (4x15 min, 1x30 min)
time performing overhead work	3 h 40 min
length of cycle / screws	160 s / 20
time per screw (static work)	5 s
weight of screw driver	1.55 kg
weight of underfloor trim	1.45 kg
body posture angles	Between upper arm and chest: 90° Between forearm and chest: 90°
Characteristics of the overhead exoskeleton device:	
supported weight / force	2.4 kg / ~ 24 N
total weight of exoskeleton	2.0 kg
miscellaneous	Reduced convenience Reduced range of motion

The sample exoskeleton used for this investigation is a passive device that supports the upper limb region. Specifically designed to reduce strains and stresses during prolonged overhead work (normally per definition work where the arms are raised to a level at or above the shoulders); the main frame of these devices is typically worn like a backpack and is fixed to the body with belts or straps. The bottom side of each upper arm lies on a pad which is connected to the main frame (see Figure 3). The presented device is an exemplary passive exoskeleton for overhead work. In this context passive means that no external power is needed to support the device – only passive elements for example springs are combined with an intelligent mechanism (Bowden cable or lever based) which creates the supporting force. The supporting force is assumed equal to the weight of the working tools, which is generally known as a ZeroG compensation approach. Many exoskeleton manufacturers recommend this simplified approach as the devices' supporting forces can often be adjusted accordingly in reality. The degree of support is adjusted to compensate for the weight of the lifted arms, which is the cause for the relief of strain. In the presented example, the device provides supports of approximately 24 Newton during the described static work task.

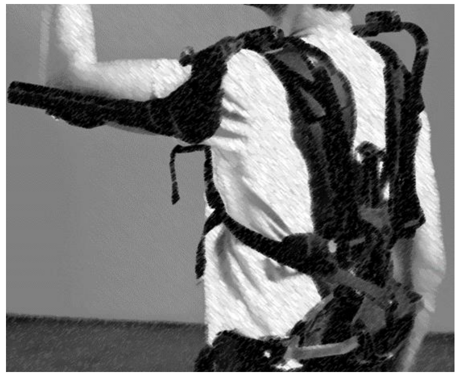

Figure 3: Sample exoskeleton device.

5 Application of assessment procedure

Based on the selection and filter process described in section 3 there are few methods which are most suitable to assess main exoskeleton impacts (positive and negative) by considering industry requirements. These methods are explained, applied, and discussed in this section. It is important to note that all methods are applied in the same way. The assessment-user answers questions from a guided and structured questionnaire regarding the workplace conditions, forces, and postures. The results are added, multiplied, or are determined through non-linear tables and add up to a number/score, which leads to a final recommendation for action. Significant differences are the area of focus, the assessment method it is based on, threshold levels and specific exoskeleton input parameters that are considered (see Table 1). In (Jones & Kumar, 2010; Roman-Liu, 2014) a few easy-to-use-methods are compared. In the next sections, the different methods are applied on workplace with and without Exoskeleton. Only criteria which are influenced by the exemplary exoskeleton are presented. Irrelevant parameter that are not influenced by the device are not displayed.

5.1 EAWS – Ergonomic Assessment Worksheet

The EAWS (IAD and AMI, 2012) method has two different types – assessment for the whole body and a separate assessment for upper extremity. The procedure for data collection is completely independent but follows the same approach. The whole body analysis include the subsections: posture, forces, loads, and extra. This method was applied twice: with and without exoskeletons for the sample workplace (see also chapter 4).

The difference in the ergonomic workplace assessment at the sample workplace is shown in Table 3. Performing an EAWS assessment four relevant criterions were identified. The result of the total EAWS score changed, which indicates a degradation caused by the increase in discomfort in criterion 0e). The highest impact was detected in section 20) in the EAWS sheet for the upper extremity assessment as it can be expected for an upper limb exoskeleton. While by the whole body assessment the score without exoskeleton is better (based on only negative influences considered), but always deep red, the upper extremity assessment shows a relevant positive impact.

Table 3: Relevant parameters for the EAWS assessment.

EAWS	Without exoskeleton	With exoskeleton
0e) other physical stress: degradation based on exoskeleton discomfort	**0**	**5**
Whole body: Overall result (with weighted factors)	**61** Deep red: high risk - design measures are necessary.	**66** Deep red: high risk - design measures are necessary.

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20a) upper extremity - static and dynamic griffin conditions: improved based on lower forces	**8.5**	**5.125**
20b) shoulder strain: improved due to support	**9**	**3**
20c) other factors: degradation based on friction and discomfort	**2**	**3**
<u>Upper extremity:</u> Overall result (with weighted factors)	**78** Deep red: high risk - design measures are necessary.	**44.5** Yellow: potential risk – rethink design measures.

5.2 KIM - Key Indicator Method

The Key Indicator Method (BAUA, 2012) is also used with and without an exoskeleton (see Table 4). This method has three steps. In step 1 the time determination is considered, step 2 contains the determination and the evaluation of conditions (posture and type of movement). In the last step, 3, a mathematical expression concludes the result scores from step 1 and 2. The traffic light result without the exoskeleton is deep red and therefore improvements are necessary. However, it should be considered that an improvement of exoskeleton was detected at all. This method fails to consider the origin of the supporting source of the exoskeleton. The change from “bad condition = 3 points” for hand-/arm positions to “good condition = 0 points” with exoskeleton in step 2 “hand- and arm posture and movements” is a questionable assumption and still open for discussion. It is notable that these differences from both assessments are multiplied with a work time dependent factor.

Table 4: Relevant parameters for the KIM assessment.

KIM - Key Indicator Method	Without exoskeleton	With exoskeleton
Step 2: hand- / arm position and movements: improved due to support	**3**	**0**
Step 2: execution conditions: degradation based on exoskeleton discomfort	**0**	**1**
Step 3: Over all result limit value from yellow to red is 50	**72.5** deep red: high strain, probable body overstrain: design measures are necessary.	**67.5** red: high strain, task is possible under normal conditions: Design measures are to examine.

5.3 REBA – Rapid Entire Body Assessment

The REBA (Hedge, Hignett, & McAtamney, 2000) assessment (see Table 5) is a short and simple method. The method includes assessment based on different body regions, forces and postures in 13 steps. Step 1 to step 6 is called group A and assesses the neck, trunk, and leg region. Group B focuses on the arm and wrist assessment in step 7 to step 13. In each step a number/score is calculated, which are added separately in each group (A and B). Both group results are the input parameter for a third table to identify the overall result.

REBA has only one input parameter which is affected by the given combination of the exoskeleton and the workplace and has impact on the supported arm structure assessment. A reduction of risk through the integration of exoskeleton is therefore demonstrated.

Table 5: Relevant parameters for the REBA assessment.

REBA – Rapid Entire Body Assessment	Without exoskeleton	With exoskeleton
Step 7: locate upper arm Position: improved based on support	**4**	**3**
Table C: over all result	**4** Medium risk. Further investigate. Change soon.	**3** Low risk. Change may be needed.

5.4 RULA – Rapid Upper Limp Assessment

The RULA (Mark Middlesworth) method is split in three sections with eleven steps. Section 1 analyses the arm- and wrist postures by adding points regarding the selected situation. In section 2 the neck, upper body, and leg posture is analyzed, but without influences of the exoskeleton. In section 3 the results from section 1 and section 2 are combined into a holistic result. Positive changes are observed due to the support from the armrest (section 1) and the assumption of force compensation (section 2), as mentioned above by EAWS-method. The result (7 points with and 6 points without the exoskeleton) is based on a table, which uses the input parameters, calculated in sections 1 and 2. The RULA method can also be used in a virtual assessment environment, for example through a simulation, described in (Constantinescu, Mureșan, Gînța, & Todorovic, 2014).

Table 6: Relevant parameters for the RULA assessment.

RULA – Rapid Upper Limp Assessment	Without exoskeleton	With exoskeleton
Section 1 – step 1a) Arm- and hand position: improved due to support	**3**	**2**
Section 3 – step 11) Force / load: improvement based on compensating forces (ZeroG approach)	**2**	**0**
Section 3 – step 11) Force / load: degradation based on exoskeleton weight	**0**	**2**
Table C: over all result	6 (B: x-axis) 6 (A: y-axis) → **7**: very high risk, implement change now	3 (B: x-axis) 8 (A: y-axis) → **6**: medium risk, further investigation, change soon

Table 4 shows the effect of the exoskeleton for the sample workplace assessment. A transformation (one point right, two points up: red to orange) resulting from the virtual implementation of the device can be demonstrated.

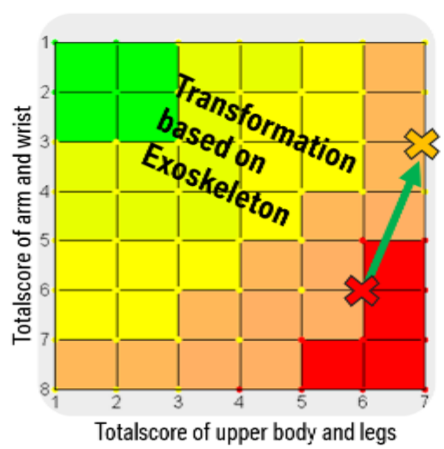

Figure 4: RULA result-transformation based on exoskeleton.

6 Discussion, conclusion and future work

Table 6 summarizes all assessment results with and without exoskeleton on sample workplace in a conceptional way. Each examined method demonstrates a positive change in the various scoring methods used when an exoskeleton device is artificially introduced. In most cases a positive change in the traffic lights can also be reported (most from red to yellow).
In this investigation, we focused on emulating the use of a device at an example workplace. Possible influences and impacts resulting from simplified exoskeleton-technology by applying different state-of-the-art ergonomic assessment methods are

demonstrated. The validity and reliability of the results are yet to be discussed. Simplifying assumptions (ZeroG, side effects, etc.) and conditions have to be elaborated in more detail, but were used here to help to give a quick overview of different impacts and resulting effects, which may motivate a more extensive investigation. Furthermore, the stress-strain-concept must be considered as well: exoskeletons do not change the strain (which is still assessed with the methods investigated here), but exoskeletons do change the individuals' perceived stress level, which should be recognized urgently by apply these methods as disaffected tool.

Looze et al. (de Looze et al., 2016) report that eighteen of the forty reviewed papers have been published after 2009. The high interest for exoskeletons for industrial applications in recent times supports the theory that there will be an increasing demand for new ergonomic workplace assessment methods, or modifications of the currently existing ones. Without a valid assessment approach, which considers advantages and disadvantages of exoskeletons equally, there is no objective basis to help determine whether an exoskeletal device should be integrated into a production system or not. Although some studies report potential disadvantages of exoskeletons, it can be assumed that the advantages could outweigh the drawbacks (de Looze et al., 2016). From our point of view, it is therefore even more important that modifications for common and newly developed ergonomic risk assessment methods be determined to encourage the integration of exoskeletons accordingly, so that employers have a greater incentive for implementing them.

Currently each combination of a workplace and an exoskeleton needs to be analyzed individually to determine an exoskeleton's impact on the workplace assessment (Theurel, Desbrosses, Roux, & Savescu, 2018). This approach is time-consuming, impractical, and therefore highly cost intensive in an industrial environment. In accordance with the results of Weston et al. (Weston et al., 2018), we suggest a holistic systems approach that could be the basis for the development of a new and generic ergonomic risk assessment method which may be the solution for the above mentioned predicament.

Table 6: Results for different assessments sheets.

Name of Method	Without exoskeleton	With exoskeleton
EAWS (total body)	61: High risk - design measures are necessary.	66: High risk - design measures are necessary.
EAWS (upper limbs)	78: High risk - design measures are necessary	44.5: Potential risk – rethink design measures.
KIM MA	72.5: very high strain: design measures are necessary.	67.5: High strain: design mearures are to examine.
REBA	4: Medium risk. Further investigate. Change soon.	3: Low risk. Change may be needed.
RULA	7: Very high risk, implement change now	6: Medium risk, further investigation, change soon

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