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Development of a Work System Design Method for the Application of Exoskeletons

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Abstract

Especially, if the potential of technical and organizational measures for ergonomic workplace design is limited, exoskeletons can be considered as innovative ergonomic aids to reduce the physical workload of workers. Recent scientific findings from ergonomic analyses with and without exoskeletons are indicating that strain reduction can be achieved, particularly at workplaces with lifting, holding, and carrying processes. Currently, a work system design method is under development incorporating criteria and characteristics for the design of work systems in which a human worker is supported by an exoskeleton. Based on the properties of common passive and active exoskeletons, factors influencing the human on which an exoskeleton can have a positive or negative effect (e.g. additional weight) were derived. The method will be validated by the conceptualization and setup of several work system demonstrators at Werk150, the factory of ESB Business School on campus of Reutlingen University, to prove the positive ergonomic effect on humans and the supporting process to choose the suitable exoskeleton. The developed method and demonstrators enable the user to experience the positive ergonomic effects of exoskeletal support in lifting, holding and carrying processes in logistics and production. The new work system design method will contribute to the fact that employees can pursue their professional activity longer without substantial injuries or can be used more flexibly at different work stations. Also new work concepts, strategies and scenarios are opened up to reduce the risk of occupational accidents and to promote the compatibility of work for employees. A training module is being developed and evaluated with participants from industry and master students to build up competence.

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Keywords: Exoskeletons; Selection criteria; Design of workplaces; Training module; Ergonomics;

1. Introduction

Human Augmentation was identified as a key tech trend in the Gartner Hype Cycle of Emerging Technologies [1]. Occupational exoskeletons serve as body-worn mechanical, machine or robotic support structures to reinforce, facilitate, stabilize or supplement the movements of the employee [2]. The supposed aims are either to compensate deficient physical abilities of employees with altered capacities for the reason of occupational inclusion, to reduce the workload in a given working situation to sustain workforce health or to enhance the physical abilities of employees to improve manufacturing performance [3]. To achieve those objectives, passive exoskeletons make use of elastic potential energy of spring elements, whereas active ones are using motor-driven actors for force exertion [4]. Hence, active exoskeletons can be considered as robots that are attached to the human body to assist the user's motions during load handling, repetitive tasks and body constraint postures. Since the technological readiness of active exoskeletons available for occupational deployment is still relatively low, mainly passive exoskeletons are used in test and pilot runs with the aim to establish application fields for their implementation in industrial practice. In addition, the use of an exoskeleton according to *ArbSchGs § 4* [5] is to be considered as an individual protective measure following the STOP principle (substitution, technical, organisational and personal

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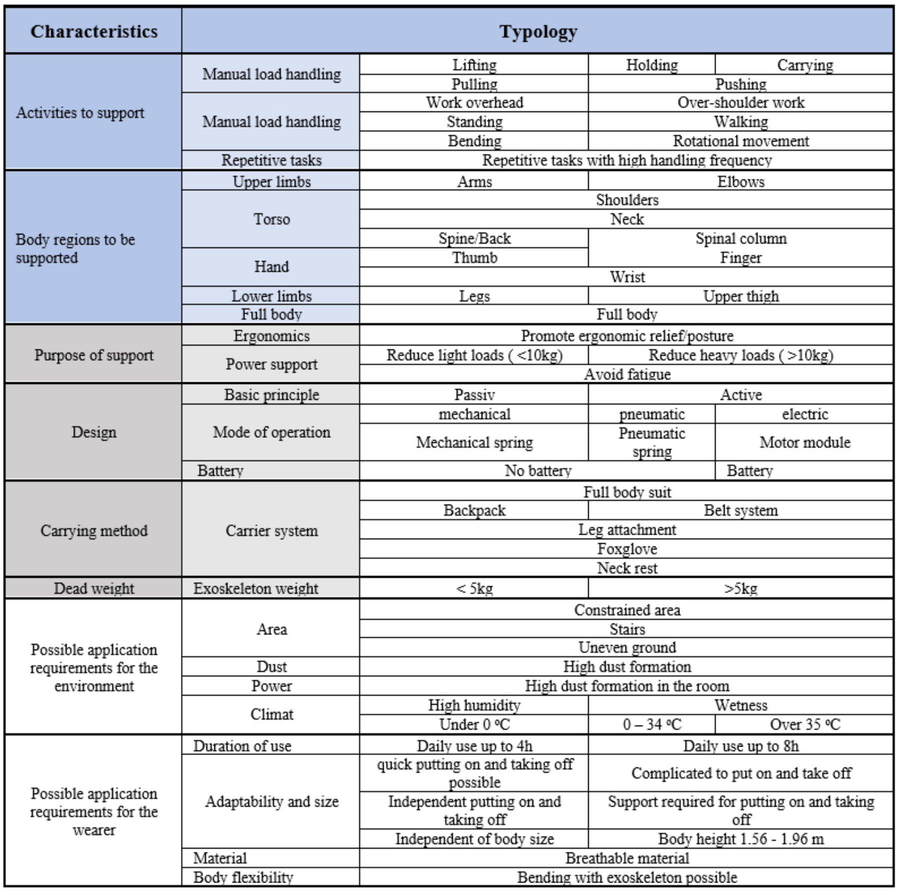
protective measures) subordinate to all other measures for hazard reduction. Exoskeletons should therefore be used as a complementary measure to all other improvement or occupational safety measures, such as ergonomic improvement of processes or workplaces. Exoskeletons are currently in test phases in factories and offer a flexible solution for use in logistics and dynamic production environments, especially for manual tasks with high physical load [2] [4] [6]. *Gartner* [1] considers exoskeletons as an innovation trigger with a maturation duration of more than ten years to reach the plateau of productivity with their successful application in industrial practice. Key challenges for the industrial implementation of exoskeletons exist, in particular, due to a lack of experience with exoskeletons among end users, a variety of commercially available systems with different promises and many aspects to consider, and a lack of regulatory frameworks due to the novelty of exoskeletons [6].

2. Developed method for designing work systems with exoskeletons

The method, which is currently being validated, is intended to create conditions for the targeted integration of the exoskeleton in the work system. For this purpose, specific research and application questions have been posed and partly already answered. An interface analysis documents the influence of the exoskeleton on the work system design. It can be linked to all elements of a work system. The work task and the work process influence the selection of the exoskeleton. According to the selected exoskeleton, changed conditions are placed on the further design. The working environment, workplace and work equipment can thus be aligned with the use of the exoskeleton and the wearer.

2.1. Selection criteria for exoskeletons

Due to diverse designs and technical differences of exoskeletons, the identification of the appropriate one is complex. To support the selection, a morphology was developed based on the comprehensive characteristics of different exoskeletons. Data sheets of various exoskeletons were used to develop the morphology. For the literature research, exoskeletons for use in the industrial sector from 21 manufacturers were included according to a market overview by *Fraunhofer Austria* [7]. In addition data sheets of exokeletons have been included into the research and analysed regarding word frequencies using the tool MAXQDA, a software for computer-assisted qualitative data and text analysis, to build up a morphology to support the exoskeleton selection (see Fig. 1).



Characteristics	**Typology**			
Activities to support	Manual load handling	Lifting	Holding	Carrying
		Pulling	Pushing	
	Manual load handling	Work overhead	Over-shoulder work	
		Standing	Walking	
		Bending	Rotational movement	
	Repetitive tasks	Repetitive tasks with high handling frequency		
Body regions to be supported	Upper limbs	Arms	Elbows	
	Torso	Shoulders		
		Neck		
		Spine/Back	Spinal column	
	Hand	Thumb	Finger	
		Wrist		
	Lower limbs	Legs	Upper thigh	
	Full body	Full body		
Purpose of support	Ergonomics	Promote ergonomic relief/posture		
	Power support	Reduce light loads (<10kg)	Reduce heavy loads (>10kg)	
		Avoid fatigue		
Design	Basic principle	Passiv	Active	
	Mode of operation	mechanical	pneumatic	electric
		Mechanical spring	Pneumatic spring	Motor module
	Battery	No battery		Battery
Carrying method	Carrier system	Full body suit		
		Backpack	Belt system	
		Leg attachment		
		Foxglove		
		Neck rest		
Dead weight	Exoskeleton weight	< 5kg	>5kg	
Possible application requirements for the environment	Area	Constrained area		
		Stairs		
		Uneven ground		
	Dust	High dust formation		
	Power	High dust formation in the room		
	Climat	High humidity	Wetness	
		Under 0 ºC	0 – 34 ºC	Over 35 ºC
Possible application requirements for the wearer	Duration of use	Daily use up to 4h	Daily use up to 8h	
	Adaptability and size	quick putting on and taking off possible	Complicated to put on and take off	
		Independent putting on and taking off	Support required for putting on and taking off	
		Independent of body size	Body height 1.56 - 1.96 m	
	Material	Breathable material		
	Body flexibility	Bending with exoskeleton possible		

Fig.1 Morphology for exoskeleton selection

The guide designed is based on morphology and consists of three sections. In the first section, the load type of physical work and the loaded body region are delimited, followed by the second section of defining the support purpose of the exoskeleton. The user is shown whether a passive or active system would be advantageous. In the third part, unchangeable environmental conditions are included, supplemented by optional criteria. The three intermediate results of the guide lead to a target formulation for the procurement of the exoskeleton to set the base for a situation-specific selection of an exoskeleton for the future work system.

2.2. Designing work systems with exoskeletons

Work system design is also referred to as work design and is concerned with technical, organisational and social measures to adapt a work system [8]. In this research area, work system design is referred to as the planning and design of all elements of a work system. Work system design should combine the goals of humanity and economic efficiency [9]. The method developed is intended to create conditions for the regulated integration of the exoskeleton in the work system, e.g. the work system is designed and implemented taking into account the use of an exoskeleton that creates changed conditions. An interface analysis documents the influence of the exoskeleton on the work system and thus forms the basis for the design. The interfaces provide information about the arrangement and sequence of the individual elements in the work design process. The working environment, the workplace and the work equipment could thus be aligned with the exoskeleton and the wearer. Afterwards, the conception of the "exoskeleton-integrated methodology for comprehensive work design" takes place with the inclusion of design features, environmental features, procedural sequence as well as accompanying necessary information. Fig. 2 summarizes the changes caused by an exoskeleton and the requirements for the design principles.

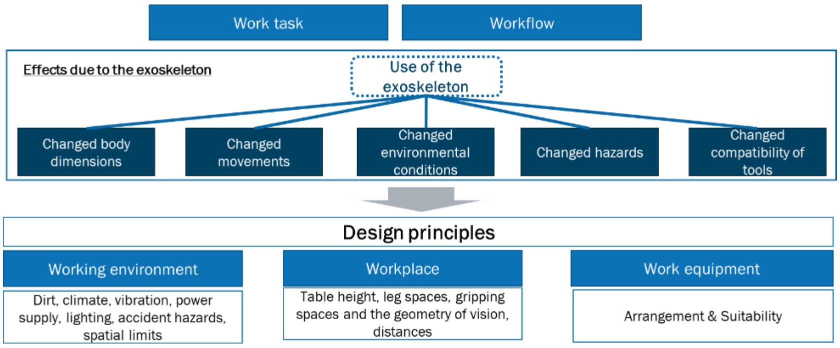


Fig. 2. Overview changes due to an exoskeleton and requirements for design principles

The individual elements of the work system and other design areas are assigned to the higher-level process segments. The arrangement of the individual elements is based on the interfaces of the exoskeleton and the work system. Fig. 3 shows an overview of the developed method.

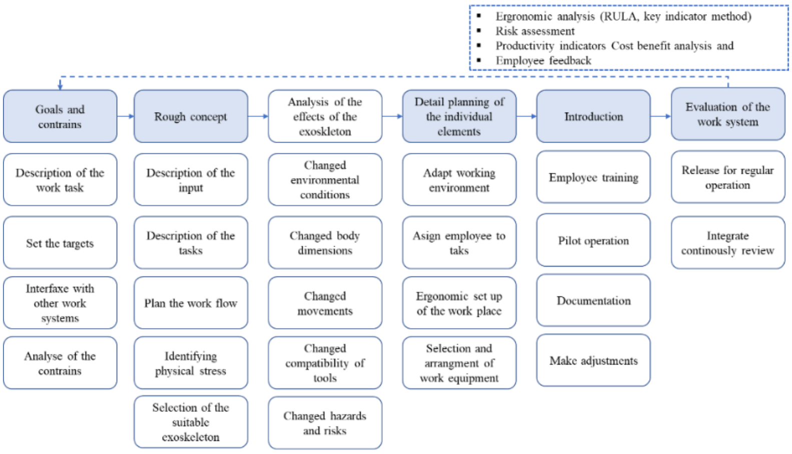


Fig. 3. Process segments of work system design with exoskeleton

The result is a guideline for companies that identifies the connection of the work task with the work system to be designed and provides support for the selection of a suitable exoskeleton.

3. Validation experiments and demonstrators

The validation comprises a digital and physical demonstrator as well as several experiments which have been developed, implemented and executed in the learning factory Werk150 at ESB Business School (Reutlingen University).

3.1. Experiments within the digital work system

The digital workstation demonstrator exemplifies the work with heavy loads focusing on the processes of lifting, holding and carrying. For the demonstrator stone plates with a weighing of 20 kg are picked from a pallet and placed on a height-adjustable worktable (see Fig. 4). Afterwards, these plates are placed on a conveyor belt. Thus, a (generic) process chain of lifting, holding and carrying operations has been modelled, which is of relevance for numerous industries (industrial assembly, construction, etc.) and illustrates the potentials and limitations of exoskeletons to support manual handling processes of heavy goods. The experiments have been carried out using the following human models representing different body type categories: Cat 1: 97 kg body weight, 185 cm body height; Cat 2: 79 kg body weight, 175 cm body height; Cat 3: 60 kg body weight, 164 cm body height. The human model is analysed in different positions, like bent over to pick up or lift the load, in an upright position to put down or hold/carry the load and to put down the load. The analyses were performed with 4 cycle runs per minute.

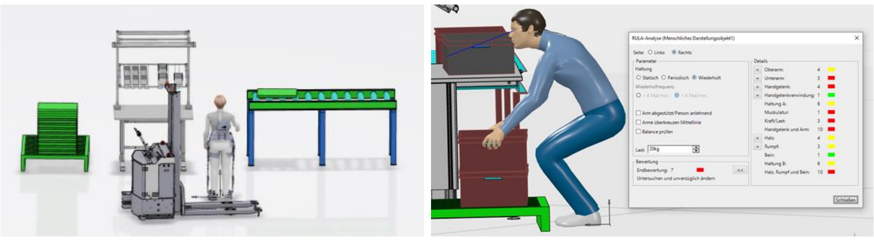
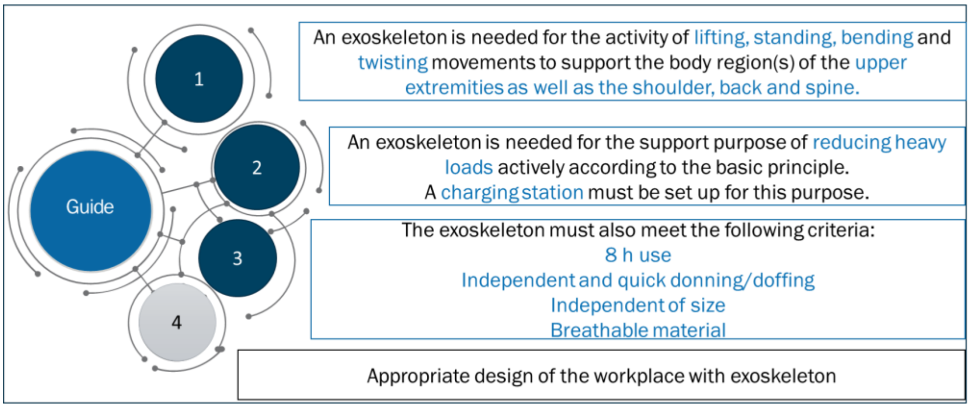


Fig. 4. Experiments using the digital work system

The ergonomic analysis using the Rapid Upper Limb Assessment (RULA) was carried out based on the developed industry-independent application scenario described above, which considered an employee with and without an exoskeleton. The results of the RULA analysis of the digital work system resulted in a recommendation to change the work system or the postures and work processes of the human model for the work without exoskeleton as an ergonomic overstraining of numerous body regions due to the heavy load to be handled has been determined. The values analysed include the upper arm, forearm, wrist, neck, trunk, leg, musculature and strength.

3.2. Physical demonstrator and experiments using the developed method

By means of various experiments with a physical demonstrator, the practical suitability of the holistic approach was examined. The experiments were conducted with professionals but also with participants of training and further education events. Based on the guidelines for the selection of exoskeletons (see Fig. 5) and the "exoskeleton-integrated methodology for comprehensive work design", the design and set-up of a demonstrator (see Fig. 6) as well as the ergonomic analyses for lifting, holding and carrying processes with heavy loads (>10 kg) were carried out in the ESB Business School's Werk150.



An exoskeleton is needed for the activity of lifting, standing, bending and twisting movements to support the body region(s) of the upper extremities as well as the shoulder, back and spine.

An exoskeleton is needed for the support purpose of reducing heavy loads actively according to the basic principle.
A charging station must be set up for this purpose.

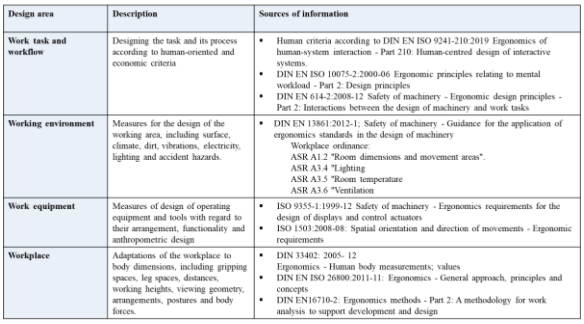
The exoskeleton must also meet the following criteria:
8 h use
Independent and quick donning/doffing
Independent of size
Breathable material

Appropriate design of the workplace with exoskeleton

Fig. 5. Guide for the selection of an exoskeleton with examples

Two different exoskeleton system have been used for the practical experiments. A passive system, Paexo Back of the manufacturer Ottobock SE & Co. KGaA, and an active system, Cray X with carbon fibre frame of the manufacturer German Bionic Systems GmbH. The used loads for the demonstrator are euro containers (dimensions 600 mm x 400 mm) filled with concrete plates, which are lifted from a pallet by the employee and placed on the adjacent worktable. The loaded container is then transferred from the worktable to a roller conveyor. The pick-up height of the container from the pallet can be varied by using an electric forklift. Likewise, the work table used is electrically height-adjustable, so that the deposition height on the table can also be varied for the experiments.

The work system with exoskeleton was then designed for this work task and built in the Werk150 at Reutlingen University. For the design, additional guidelines and supporting information were applied for the process segments (also see Fig. 6) to enable realistic experiments and tests.



Design area	Description	Sources of information
Work task and workflow	Designing the task and its process according to human-oriented and economic criteria	▪ Human criteria according to DIN EN ISO 9241-210:2019 Ergonomics of human-system interaction - Part 210: Human-centred design of interactive systems. ▪ DIN EN ISO 10075-2:2000-06 Ergonomic principles relating to mental workload - Part 2: Design principles ▪ DIN EN 614-2:2008-12 Safety of machinery - Ergonomic design principles - Part 2: Interactions between the design of machinery and work tasks
Working environment	Measures for the design of the working area, including surface, climate, dirt, vibrations, electricity, lighting and accident hazards.	▪ DIN EN 13861:2012-1; Safety of machinery - Guidance for the application of ergonomics standards in the design of machinery Workplace ordinance: ASR A1.2 "Room dimensions and movement areas". ASR A3.4 "Lighting ASR A3.5 "Room temperature ASR A3.6 "Ventilation
Work equipment	Measures of design of operating equipment and tools with regard to their arrangement, functionality and anthropometric design	▪ ISO 9355-1:1999-12 Safety of machinery - Ergonomics requirements for the design of displays and control actuators ▪ ISO 1503:2008-08: Spatial orientation and direction of movements - Ergonomic requirements
Workplace	Adaptations of the workplace to body dimensions, including gripping spaces, leg spaces, distances, working heights, viewing geometry, arrangements, postures and body forces.	▪ DIN 33402: 2005- 12 Ergonomics - Human body measurements; values ▪ DIN EN ISO 26800:2011-11: Ergonomics - General approach, principles and concepts ▪ DIN EN16710-2: Ergonomics methods - Part 2: A methodology for work analysis to support development and design

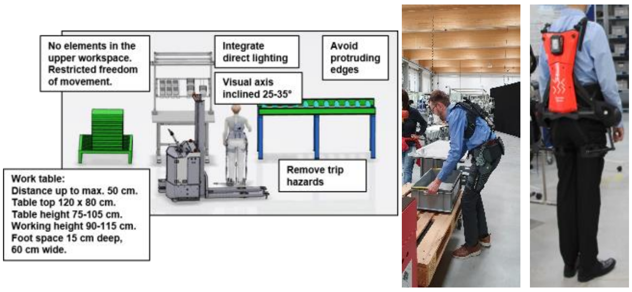


Fig: 6: Works system with proposed design principles and exoskeletons and respective information

In preparation for carrying out the tests and experiments in the Werk150, a test protocol and plan for usability tests were developed, taking into account ISO 9241 (ergonomics of human-system interaction), among other things. The comparative tests with and without the exoskeleton using the physical demonstrator at Werk150 showed that the application of the exoskeleton avoids an ergonomic overload of the back muscles when lifting and putting down the load (20 kg), which occurs without the exoskeleton. When carrying a load of 20 kg, there is also a reduction in the strain on the back muscles, although the limit value is not exceeded even without an exoskeleton.

Based on the ergonomic analyses, user tests with industry participants and students wearing the active and passive exoskeleton have been conducted at Werk150. The participants were asked via an online questionnaire directly after testing the exoskeletons at the demonstrator about the support or discomfort they felt from the exoskeleton on various parts of the body, about usability aspects according to DIN EN ISO 9241-11 when putting on and taking off the exoskeleton as well during the process execution at the demonstrator. In addition, necessary optimisations of the workstations, recommendations for action for the configuration and further development of the exoskeleton were determined. The surveys showed that participants felt significant relief in the lower back, thighs, and buttocks, especially with the active exoskeleton (CrayX). Discomfort was felt by a few test subjects in the thighs and upper back, which could be partially reduced by adjusting the exoskeleton's harness system. The convenience of putting on and taking off the exoskeletons as well as the usability of the exoskeletons when performing the task has been rated as rather high by most the participants. The experiments also showed that only very few adjustments were necessary for the workplace due to the applied "exoskeleton-integrated methodology for comprehensive work design". These few were due to the differences in body sizes being too much.

4. Training module „Exoskelett for learning factories"

The participants were so enthusiastic about the experiments and the experience at Werk150 that the idea was created to design a new exoskeleton module (see Fig. 7) for the existing training and further education programme in the context of work system design using innovative technologies at Werk150 and to carry it out in the future in the learning factory. This ensures that participants come into contact with this technology at a very early stage, gain experience and thus positively shape their attitude for future use in the industrial environment. After the development work for "exoskeleton-integrated methodology for comprehensive work design", the necessary competences were defined and specific enablers required to define, understand and implement an exoskeleton were identified. The results were structured into a learning module on the base of three building blocks. These will be offered in form of face-to-face and virtual lectures, demonstrators, group work and hands-on work in Werk150. According to Learning Goal Taxonomy by *Anderson and Krathwohl* [10] whereby "create" produces the highest effectiveness in competence development, cardboard engineering was selected as the basic method for the module. Cardboard engineering is a method for physically simulating planned work systems using low-cost building materials. The workplace is constructed from cardboard boxes, pipe systems and other readily available materials to replicate the planned system. The designed workplaces can be tested and optimised through cardboard engineering before they are actually built. The designers can quickly test different design scenarios for their suitability at low cost [11].

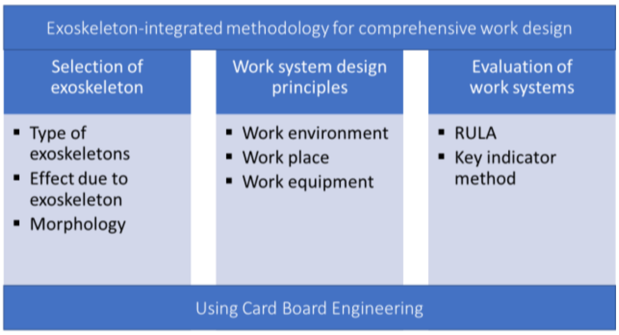


Fig. 7 Training module exoskeleton

The learning module "Exoskeleton" has already been deployed several times in 2021 with a passive (Paexo Back) and an active (CrayX) exoskeleton system in both training and further education and led to high approval and a very positive evaluation from all participants.

5. Conclusion

With the development of the exoskeleton work system design method, a new field of research has been explored and results in an approach, with categories and a guideline for the selection of an exoskeleton. As an emerging technology, exoskeletons are bringing still up numerous open questions, which need to be addressed from different perspectives. One research question is whether exoskeletons should be given their own country-specific class, as they are currently subject to the machinery guidelines and are considered wearable robots in Germany, but have their own new characteristics, so this remain to be discussed. Furthermore, another question arises, which can probably only be answered by the medical profession, if employees with performance impairments will also be allowed to wear passive and active exoskeletons.

The future of exoskeletons points towards Industrie 5.0, in which the working person will continue to play a major role in the factories and connected systems. Exoskeletons should be improved in terms of anthropometry to come as close as possible to human movements. For the use of exoskeletons in industry, long-term studies must be carried out to obtain certainty about the effects on health. As long as a possible injury to the wearer can be caused by the exoskeleton, preventive use will not be possible. To reduce the hurdles for the use of exoskeletons, further exoskeleton systems from other manufacturers must be integrated into training, research and validation environments as the Werk150 and additional demonstrators must be designed and built.

Acknowledgements

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