Technical University of Munich
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Design and Development of Ergonomic Exoskeletons for Lifting and Carrying

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Abstract

Exoskeletons are promising tools in workplaces that mainly rely on manual labor with a high demand for flexibility. To be practical, exoskeletons must be integrated into the specific working environment and be well adapted to the unique needs of the workers in these environments. Research has shown that there is no "one-exoskeleton-fits-all" solution. Rather, exoskeletons have to be specifically developed and adapted to the individual contexts of use. To create suitable exoskeleton solutions for different contexts of use, development processes that focus on human needs, follow agile principles, and cover every aspect of the exoskeleton design are required. These enable the rapid design of specialized solutions that offer good usability and user experience, resulting in a better user acceptance.

A development process - based on literature research on process models, requirements, and evaluation methods - has been developed. It combines aspects of the human centered design process with agile principles. The entire exoskeleton is divided into its main components that can be independently developed, evaluated, and iterated upon, in order to parallelize and expedite the entire process. Thereafter, these components are integrated into a complete exoskeleton and evaluated through user-involving methods. The development process includes successive iterations, each focusing on specific development goals, until the exoskeleton is fully developed and enters a long-term evaluation phase.

The developed process is applied in two case studies, for two exoskeletons for lifting and carrying in industrial context. The resulting prototypes are evaluated incorporating human centered evaluation methods and both show promising results regarding usability in the respective workplaces.

Based on the insights of both case studies, the development process is revised and future development opportunities are discussed.

List of Abbreviations

cHMI	cognitive Human Machine Interface
DHM	Digital Human Model
DoF	Degrees of Freedom
EMG	Electromyography
HCD	Human Centered Design
LMM	Key Indicator Method (Leitmerkmalmethode)
NASA TLX	NASA Task Load Index
PDT	Pressure Detection Threshold
pHMI	physical Human Machine Interface
PTT	Pressure Tolerance Threshold
RoM	Room of Movement
SUS	System Usability Scale
TAM	Technology Acceptance Model
UCAD	User Centered Agile Development
UEQ	User Experience Questionnaire
UI	User Interface

Contents

1. Exoskeletons in Industrial Applications

Human workers will remain a part of production processes for decades. Despite predictions based on the last industrial revolutions and technological advances, there are still a respectable number of tasks that require a human. This is not only true for factories and logistic centers, but for workers in agriculture and construction industry. Due to globalization and increased competitiveness, companies need to stay flexible and adjust their production methods quickly to adapt to changing customer demands and volatile markets. Highly automated production lines cannot offer this, but human workers can.
Increased demands and shortages of skilled workers lead to higher workloads for the physical workers. This creates bottlenecks of those processes. The described workplaces contain straining tasks, including handling or assembling heavy loads in unnatural static postures. With the increased workload, musculoskeletal diseases are a common reason for sick leave in this field of work. According to recent statistics by the Federal Institute for Occupational Safety and Health, 23 % of sick leaves were due to musculoskeletal diseases, resulting in a 35.2 Billion € loss of gross value added in Germany (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2022). Therefore, not only companies but also insurance and trade associations are increasingly looking for ways to reduce strain on workers in the workplace.

With technological advances, body-worn physical assistance systems for occupational use - exoskeletons - became relevant around 2006 (Abdoli-Eramaki et al., 2006). With the described demand for physical assistance and the technological possibilities of building feasible body-worn robots, several research projects and manufacturers arose within a short period of time (de Looze et al., 2016; Kermavnar et al., 2021).

But their products did not seem to meet the demands of either the companies or the workers since only a few examples could assert themselves on the shop floor permanently. Recent reviews show a disconnect between the developed exoskeletons and the requirements of the workers and their tasks (Kermavnar et al., 2021; Kuber et al., 2023; Monica et al., 2021; Schnieders and Stone, 2020; Voilqué et al., 2019; Young and Ferris, 2017). With more insights into the potentials of exoskeleton technologies, it turned out that occupational exoskeletons are not a "one-size-fits-all" solution. Instead they need to be adapted to specific use cases and work conditions (Monica et al., 2021; Young and Ferris, 2017). Representative examples of this are passive overhead exoskeletons. These were designed specifically for overhead working tasks. In these specific workplaces, the exoskeletons were mostly well received and accepted (Kim et al., 2022; Ekso Bionics, 2020; Hensel and Keil, 2018; Smets, 2019). First health benefits could be proven with reduced sick leaves in a specific workplace (Smets, 2019; Ekso Bionics, 2020) and the first successful long-term field study was conducted (Kim et al., 2022). Using those exoskeletons in similar workplaces was not as successful because those workplaces are structured differently where side tasks played a more significant role. But restriction of application to specific tasks during the work day led to acceptance by a majority of the workers (de Looze et al., 2021; de Vries et al., 2022). This suggests that while the beneficial effects of exoskeletons have been demonstrated in this context, there is potential for broader application across different workplaces. Several types of exoskeletons are designed to reduce work-related musculoskeletal disorders, yet achieving usability and acceptance is crucial for their success in longer-term studies (Monica et al., 2021). Therefore exoskeletons must be designed for the user and the context of use to show their beneficial effects on workers in highly straining activities. A human-centered design processes can be used to increase acceptance of the developed systems (Monica et al., 2021; Gupta et al., 2020; Schmidtler et al., 2015).

Designing exoskeletons for specific use cases and users is challenging, as this increases the variety of exoskeletons while the number of suitable workplaces may decrease. This necessitates faster, more agile, and cost-effective development processes that effectively tailor exoskeletons to both the intended use case **and** the user. By incorporating rapid development along with user needs and contextual requirements, it is possible to efficiently generate more specialized exoskeleton solutions. Additionally, development processes do not need to start from scratch; they can adapt existing solutions for new contexts or optimize them further in a structured manner. Iterative processes enable this flexibility, allowing engagement at various stages of development. This approach results in time and cost savings in exoskeleton design and development, potentially benefiting a wider range of individuals in physically demanding workplaces.

2. Objective

This thesis aims to design and evaluate an agile, holistic exoskeleton development process that focuses on Human Centered Design (HCD).

First, essential elements for a design process must be determined and existing methods have to be analyzed for their suitability to design exoskeletons. Including ergonomic aspects as early as possible in development is essential to reduce effort and costs (Lindemann, 2016). Design methodologies, such as HCD DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019) and the Agile Manifesto (Kent et al., 2013), embrace approaches that center on understanding user needs and the context in which products or solutions will be used. These methodologies encompass both methods and mindsets for the identification and assessment of these requirements. Similar approaches are used by already existing development processes that are focused on exoskeleton design, which are first discussed in Chapter 3.3. Succesful aspects of these exoskeleton specific methods, together with essential elements derived from the aforementioned product design processes are the ground work for the new development process, that is the objective of the thesis. Relevant milestones within the development process must focus on aspects that closely interact between the human and the exoskeleton. All exoskeleton parts have to be considered, not only singular components like the kinematic structure or the physical attachments. Methods to evaluate the exoskeleton as a whole and in earlier design stages are necessary for a more streamlined development that reduces costs and effort.

Participatory user research is vital to ensure a continuous fit between the workplace, user, and the exoskeleton (Giusino et al., 2020). For the design and evaluation to succeed, design principles must be defined. These insights are derived from literature reviews, which have compiled findings from two decades of research in the field of occupational studies. These reviews shed light on the design choices that have proven successful and, notably, those that have failed in the development of exoskeletons. Afterwards, based on the design principles, design requirements can be determined by assessing the individual workplaces requiring specifically designed exoskeletons (Monica et al., 2021; Young and Ferris, 2017).

An extensive literature review will bring together general design principles for exoskeletons and a method will be presented for analyzing the workplaces to derive individual exoskeleton relevant requirements. Methods are presented, to evaluate exoskeletons in early stages of development. With the knowledge of design processes, evaluation methods, and requirements, a novel development process is proposed. The novel development process incorporates human centered design, agile principles, and focuses on the requirements for exoskeleton specific components. The aim of the process is to accelerate exoskeleton development processes while focusing the design on the needs of the users and the individual requirements of each context of use. The proposed novel development process is then applied within two case studies, each aiming to develop a new exoskeleton for specific use cases. Afterward, the development process is revised and discussed based on insights of those two case studies. One evaluation criterion is the applicability and adaptability to different contexts of use. The other is the usability and the novelty of the resulting exoskeleton.

The structure of the thesis and the process of developing the process is depicted in Figure 1.

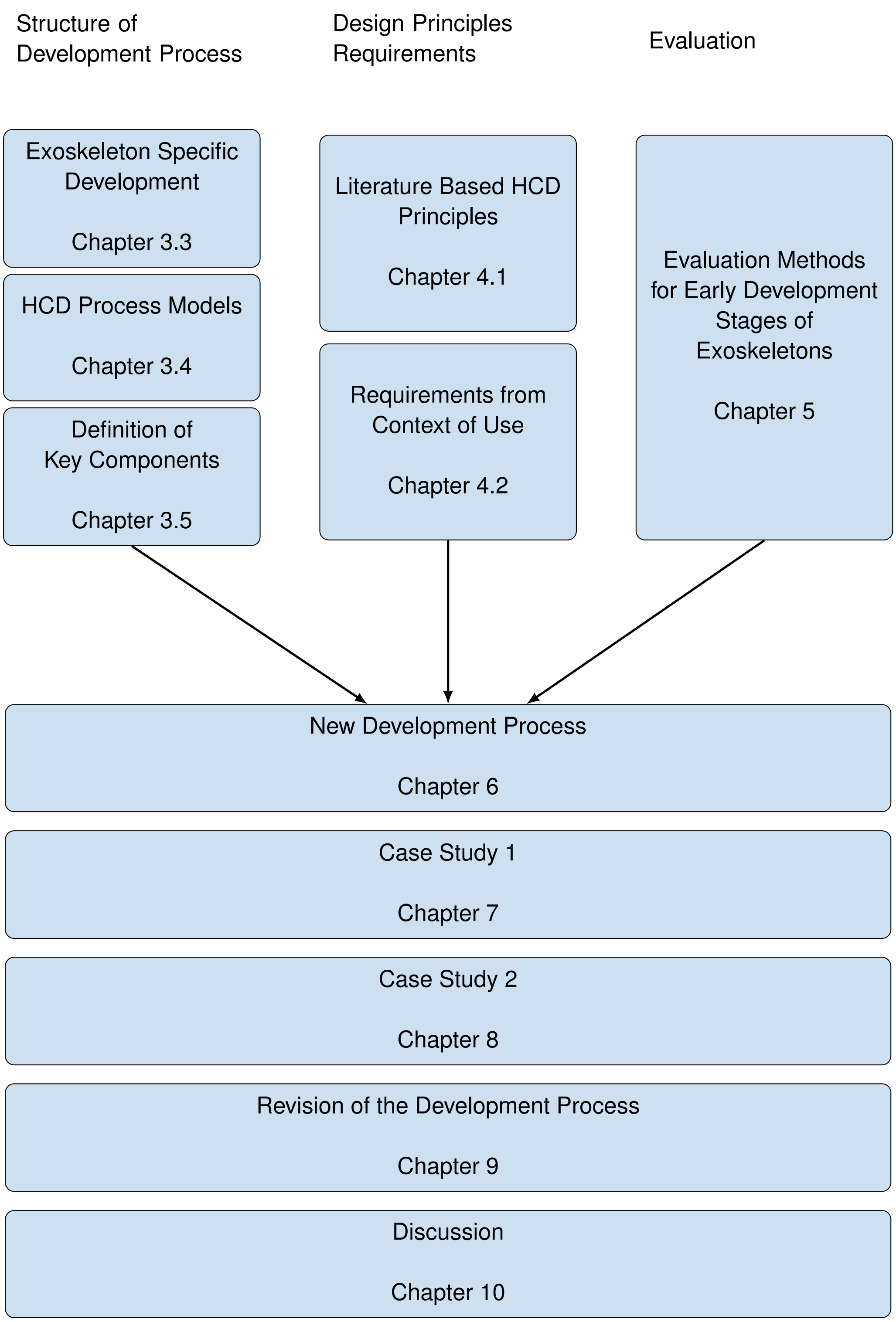

Figure 1 Structure of the thesis: The thesis begins by establishing fundamental structures and terminology of exoskeletons in Chapters 3.1 and 3.2 (not depicted). Next, it introduces a basic structure for the development process, identifies methods for defining requirements based on literature and workplace analysis, and explores evaluation methods for early development stages. These three components are integrated into a novel development process, which is then tested and evaluated through two case studies. Insights gained from these studies are used to refine and discuss the proposed process in the conclusion.

3. Development of Exoskeletons for Occupational Use

The first step this thesis aims to design a development process, that enables the agile design of occupational exoskeletons in a HCD way. In the second step this process is used to develop the first usable prototypes of ergonomic exoskeletons for two specific occupational applications. A deeper understanding of the technology is necessary to tailor an optimal and adaptive development process, especially for early development stages. In the following chapters, the essential aspects of the technology of exoskeletons will be explained including relevant design processes and the methods utilized.

3.1. Exoskeletons - An Emerging Technology with a Volatile Market: Overview and Classification

Wearable robots are used for augmentation, assistance, or substitution of human motor functions and this perfectly describes the diversity of the exoskeleton technology. Depending on the purpose of the exoskeleton, very different contexts of use, especially users with very different needs, must be considered in the system design. Exoskeletons are an emerging technology. Even though first ideas of enhancing the human body with machines first came up in the 1960's (Mosher, 1968), only the development of lighter and more efficient materials and electronics made the technology feasible in the 2000s. Military and rehabilitation applications were the first to employ this technology to augment or substitute human motor functions. A heavy, bulky robot was not as much of an issue in those areas. In the occupational area, the focus for exoskeletons is assisting healthy humans to reduce strain and fatigue and prevent long-term damage caused by physically heavy work. Due to the high requirements for robots to be used on healthy humans within industrial areas in terms of weight, usability, and safety, the first exoskeleton usable in the field emerged in 2012 with the suitX in North America and 2013 with the laevo exoskeleton in Europe. Therefore, the technology is very young and much needs to be learned. This is reflected in many prototypes emerging either in research or on the market then disappearing (Harbauer and Bengler, 2022). This trend can also be seen in publications around the topic of exoskeletons. The speed of new technologies and related publications poses a challenge to stay up to date (Figure 2) (Young and Ferris, 2017).

As discussed in the introduction (Chapter 1), success in this volatile market cannot be achieved by extensive analysis of distinct exoskeletons, but rather by comparative evaluations. For this, the commonalities between the available exoskeletons must be defined. Contrary to the general belief at the beginning of the exoskeleton hype, they are not a "one exoskeleton fits all applications" technology. They are a specialized tool to support workers in specific environments for specific tasks. Some basic design principles can be commonly used across different applications, but most requirements will have to be developed and fitted to the unique context of use. As Young and Ferris (2017) states: states: "commercial success of robotic lower limb exoskeletons is most likely to occur in smaller niche markets".

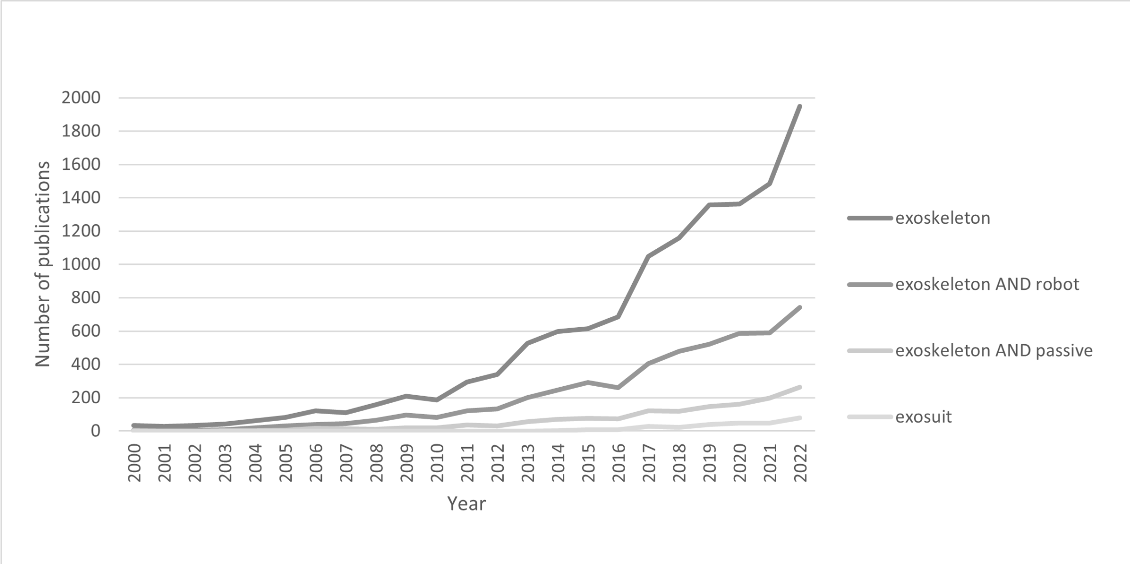

Figure 2 Publications in Scopus with the keywords "exoskeletons", "exoskeleton robot", "exoskeleton passive", and "exosuit" excluding keywords from the fields of chemistry and biology

In literature exoskeletons are usually classified into different subgroups (DGUV, 2020), each with their specific advantages in different applications: Field of application, assisted body region, type of actuation, kinematic structure, basic materials. To gain a deeper understanding of the exoskeleton technology in general, these are now briefly described.

Field of application

As previously mentioned, exoskeletons can be defined by their intended field of use. There is the military field, where they are deployed for **augmenting** soldiers in terms of higher power and endurance in the field. In the medical field exoskeletons are either used as rehabilitation tools so patients can learn lost body functions again or to even **replace** lost body functions for people with permanent disabilities. The third field defines the industrial or occupational exoskeletons, which are used as a physical **assistance** system to support humans during heavy physical work. The occupational exoskeletons are only intended to reduce fatigue and prevent long-term damage due to straining manual labor. They are not meant to augment people in workplaces to a degree higher than their natural power.

Assisted body region

The most significant difference among exoskeletons is the type of limb the exoskeleton supports and the number of joints the exoskeleton supports. The most common exoskeletons on the market for occupational contexts of use only support one limb with one movement. This results in designs with relatively low complexity such as the exoskeletons that support the hip flexion, like the laevo, the Hunic, or the CrayX. Other examples are exoskeletons that support the arms during overhead work, like the Skel-Ex, the paexo, and the ExoIQ. If the exoskeleton supports more than one limb or motion of a limb, it increases the complexity drastically (Gupta et al., 2020; Toxiri et al., 2018). Descriptive examples are the different types of leg exoskeletons and their degrees of freedom (DoF). Commonly supported joints are ankle, knee, hip, back, shoulder, elbow, wrist, finger/thumb, and neck (Voilqué et al., 2019; Schnieders and Stone, 2020; de La Tejera et al., 2021).

Type of actuation

Another commonly used differentiation between exoskeletons is their general type of actuation. The "passive" type uses recuperation methods like springs, gas struts, or elastic bands. They are mostly elastic components and have advantages in being simpler, rather lightweight, and more reliable due to using fewer components (Zhang et al., 2021). The function principle is that they store compression or extension energy when the limb moves in one direction and supports the motion in the opposite direction. This principle works by bigger muscle groups that are used to tension the passive actuation elements, and the energy is used to support smaller muscle groups (Argubi-Wollesen, 2021). Due to the limited assistance they can give and the fact that they require work by the user to function, they are more suitable for light or moderate assistance and little dynamic movements, such as light load handling or holding postures (Toxiri et al., 2018). Examples of passive Exoskeletons are the laevo, the nonee, and the paexo. Active exoskeletons use any actuation that needs an external power source, e.g., DC motors or pneumatic actuators. So the user does not need to exert extra energy before being able to be supported by the exoskeleton. However, those exoskeleton types are usually heavier since the actuation module itself is heavier and a battery needs to be included for mobile use. There are also hybrid exoskeletons that combine active and passive joints.

Kinematic structure

There are two ways exoskeletons are designed to support certain body parts. Either they try to replicate the kinematics of the human limbs they are supporting or they replicate the needed trajectories with different kinematic chains. These are also called anthropomorphic or non-anthropomorphic exoskeletons, respectively (Viteckova et al., 2018; Liang et al., 2022). A self-evident example is the arm exoskeleton from the "Robo Mate" project (Huysamen et al., 2018a). This exoskeleton supports the user's arm by a serial structure of two parallelograms, that connect between the back and the wrist. The kinematic chain of the human arm is not followed but rather avoided by the structure going around it on the transversal plane. The type of kinematic structure is also the main difference between the paexo exoskeleton and the earlier Skel-Ex version or the Comau exoskeleton. While the Skel-Ex and the Comau try to replicate the shoulder belt with its t-shaped structure, the paexo skips the complicated lateral movements of the shoulder (Kapandji and Rehart, 2016) with its v-shaped structure. This makes it possible to follow the same trajectories as the upper arms but greatly reduces its complexity and weight.

Basic materials

Another considerable difference between exoskeletons is the material of the basic structure. Some exoskeletons primarily rely on a rigid frame where the actuation is mounted. Examples are the laevo, the paexo, the CrayX, the Nonee, or the ExoIQ. Other forms are so-called soft exoskeletons, sometimes called "exosuits." Those contain mainly soft or textile elements and only a few rigid features. Examples are the Ironhand and the Hunic exoskeletons. They also use soft kinds of actuation systems, like tendon-driven actuation, elastomeric actuators, pneumatic artificial muscles, or shape memory alloys (SMA) (Masia et al., 2018, Xiloyannis et al., 2022).

This overview shows that there are already many categories of exoskeletons, each advantageous for a specific context of use. For example, research showed for some exoskeletons, that passive actuation is best received and has the most benefit when supporting static postures (Kermavnar et al., 2021). Due to their soft structures, exosuits, unlike rigid frames, cannot lead forces away from the human body through an alternate path. Instead, they are lighter and thinner, thus suitable for contexts of use where the supported forces are not that high and a light, slim design is essential. Considering those advantages and disadvantages, those categories can help choose the appropriate exoskeleton design for the desired contexts of use. Within those categories, there are still many ways of designing the exoskeletons. How to go about those will be defined in the following chapters.

3.2. Terminology of Development Processes

In the further progress, the terms "context of use", "development step", and "stage of development" are defined as follows.

Context of Use The context of use describes the combination of users, goals, tasks, resources, and environment (DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019)).

Development Step The development step are the steps within an iteration, that are carried out incrementally.

Stage of Development The stage of development refers to the progressive maturation of the exoskeleton design, attained through each successive iteration within the entire development process.

3.3. Exoskeleton-Specific Development Processes

Exoskeletons are a very interdisciplinary and new technology. In research projects a lot has been learned about what designs are successful in the industrial environment especially with healthy human workers. Information about what failed in that context of use was also gathered. There are already approaches in the literature from bringing those insights together in defining development processes or guidelines for exoskeleton design. The methods of how they retrieve their design requirements and what methods are used to evaluate the design requirements are distinct. The structure of the processes varies as well, especially in the number of development steps that are recommended.

Most identified processes focus on kinematics development Drees et al., 2021; Martínez and Avilés, 2020; Heidari et al., 2018; Tröster et al., 2020; Otten et al., 2016). While some focus on physical attachments between the human and the exoskeleton, the physical Human Machine Interface (pHMI) (see Section 3.5) (Linnenberg et al., 2018; Meyer, 2019; Sposito et al., 2019).

The defined steps within the processes and guidelines vary from three steps (Drees et al., 2021; Tröster et al., 2020) to up to 13 steps (Martínez and Avilés, 2020). Some implement iterations (Otten et al., 2016; Otten, 2023; Meyer, 2019; Drees et al., 2021; Heidari et al., 2018) or focus on parallel testing and development (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018). Every process includes development steps, with some specifically addressing user involvement and definition of HCD requirements (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018; Linnenberg et al., 2018; Meyer, 2019).

Others include definite methods for evaluation of the developed solutions (Otten et al., 2016; Otten, 2023; Tröster et al., 2020; Martínez and Avilés, 2020; Klabunde and Weidner, 2018; Meyer, 2019; Sposito et al., 2019). The core of Meyer (2019) is revolving around optimizing the existing pHMI through active user involvement and evaluation. Otten (2023) divides the development process in the three essential steps of "Identify support needs", "Implement support needs" and "Evaluate support" focusing on the development of the morphological structure, actuation and control. Used methods in the exoskeleton-specific development processes for defining requirements are workplace analysis (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018) or lab testing utilizing motion capture (Drees et al., 2021; Klabunde and Weidner, 2018; Heidari et al., 2018). For the individualization of pHMI, 3D-scans are used (Linnenberg et al., 2018).

In literature more focus is on the evaluation of exoskeletons. Therefore, it plays a major role in most development processes. Most often biomechanical simulation is utilized in the evaluation of concepts or early prototypes (Otten et al., 2016; Otten, 2023; Tröster et al., 2020; Martínez and Avilés, 2020). The simulation is used to ensure biomechanical compatibility or estimate the reduction of physical strain by the exoskeleton to compare different designs. Further laboratory testing is included in Otten et al. (2016) and Otten (2023), again using motion capture to ensure biomechanical compatibility. Field testing (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018) or testing with future users (Otten et al., 2016; Otten, 2023; Meyer, 2019) are methods implemented to gain insight especially on subjective parameters. In that vein Sposito et al. (2019) gives an overview of metrics that can be used to evaluate pHMI objective and subjective Objective tools are the circumferential and single-point pressure magnitude, distribution, duration, direction and time to put on and off the attachment. Subjective measures that can be collected with individualized or standardized questionnaires are perceived pain, Pressure Detection Threshold (PDT) and Pressure Tolerance Threshold (PTT), perceived comfort, mental load, physical load and ease of use. Sposito et al. (2019) explore examples of pressure measurement in terms of sensors, measurement methods, and implications by human physiology, like stopping capillary flow with too high of pressure. As subjective measures, the System Usability Scale (SUS) (Brooke, 1996), the NASA Task Load Index (NASA TLX) for mental load (Hart and Staveland, 1988), and the Visual Analog Scales (CLINE et al., 1992) for PDT and PTT are mentioned. The SUS (Brooke, 1996), pain rating scales like the Borg CR10 (Borg, 1998) and body maps, are commonly used in other evaluation procedures (Meyer, 2019, Huysamen et al., 2018a, Huysamen et al., 2018b). Otten (2023) uses the Borg CR10 scale to evaluate perceived exertion.

The described development models either focus on only one component of the exoskeleton, like the kinematics (Klabunde and Weidner, 2018; Otten et al., 2016; Otten et al., 2016; Heidari et al., 2018; Tröster et al., 2020; Martínez and Avilés, 2020; Drees et al., 2021) or the pHMI (Linnenberg et al., 2018; Meyer, 2019; Sposito et al., 2019). Others do not specify methods for deriving HCD requirements (Otten et al., 2016) or evaluation methods (Drees et al., 2021, Klabunde and Weidner, 2018, Linnenberg et al., 2018). While all the presented processes describe solutions for designing the physical interaction between the exoskeleton and the users, they are missing specific solutions for the designing the cognitive interaction between human and machine, like the user interface or sensors detecting human intent. In Otten (2023) intention recognition is part of the development of the control system, whereas Bengler et al. (2023) defined this as a separate step in the development process.

Combining all of those aspects of a development process, Bengler et al. (2023) developed a holistic design framework that could potentially develop every kind of exoskeleton efficiently. It uses methods that were described in the aforementioned design approaches, like biomechanical simulation of motions and lab-testing for evaluation of biomechanical compatibility. Unfortunately, the framework by Bengler et al. (2023) uses the principle of design catalogs with an iterative evaluation cycle that focuses on Digital Human Model (DHM). They state that a lot of fundamental research is missing to implement a framework like that. On the one hand, fundamental research is necessary to fill the design catalogs with kinematics for every possible joint, motion, and their combinations. On the other hand, it is essential to develop DHM further so they represent the interaction between human bodies and exoskeletons sufficiently and are usable for engineers who are not experts in the field of DHM. The design process describes the exoskeleton development in incremental steps, first kinematics, then actuation independent of type, and then implementation of user interaction principles and, if necessary, control and software. Each step is evaluated with DHM and, if possible, user studies with prototypes to ensure bio-mechanical compatibility and optimal force transmission throughout development.

The presented development processes and methods show potential and positive results in improving exoskeleton design when applying them. They include HCD aspects, like thorough analysis of user needs and context of use, or evaluation methods focusing on the effects of exoskeletons on users and their perception of it. But there is not one that covers the whole product and all these aspects of HCD in detail. Bengler et al. (2023) presents a promising process, but it needs fundamental research to be applicable in how it is presented. However the described process can also be followed with available models and tools.
In the following chapters, essential steps of design processes are described, to build upon those and include the presented elements for exoskeleton development from this chapter, including the holistic approach of Bengler et al. (2023).

3.4. Process Models for Human Centered Product Development

In the development processes described in Section 3.3 the focus is on human centered aspects. Meyer (2019) specifically used the HCD process (DIN EN ISO 9241-210) in the development of their process. Also, Gupta et al. (2020), Fosch-Villaronga and Özcan (2020), and Monica et al. (2021) propose a specific HCD approach for the design of exoskeletons. The HCD is an essential part of exoskeleton design since the human is in a literal sense the center of the machine. Therefore, there will be a closer look into the HCD process of the DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019). The basic steps are shown in 3 and explained in more detail. The focus lies on the methods proposed for defining requirements and the evaluation of those.

The HCD process proposes four essential steps that are iterated until the desired outcome is achieved (DIN Deutsches Institut für Normung e.V., 2019). It is defined as "the design is based on a comprehensive understanding of the users, tasks and working environments, the users are involved during design and development, refinement and adaptation of design solutions is continuously driven based on user-centered evaluation, the process provides for iterations, the design considers the overall user experience,

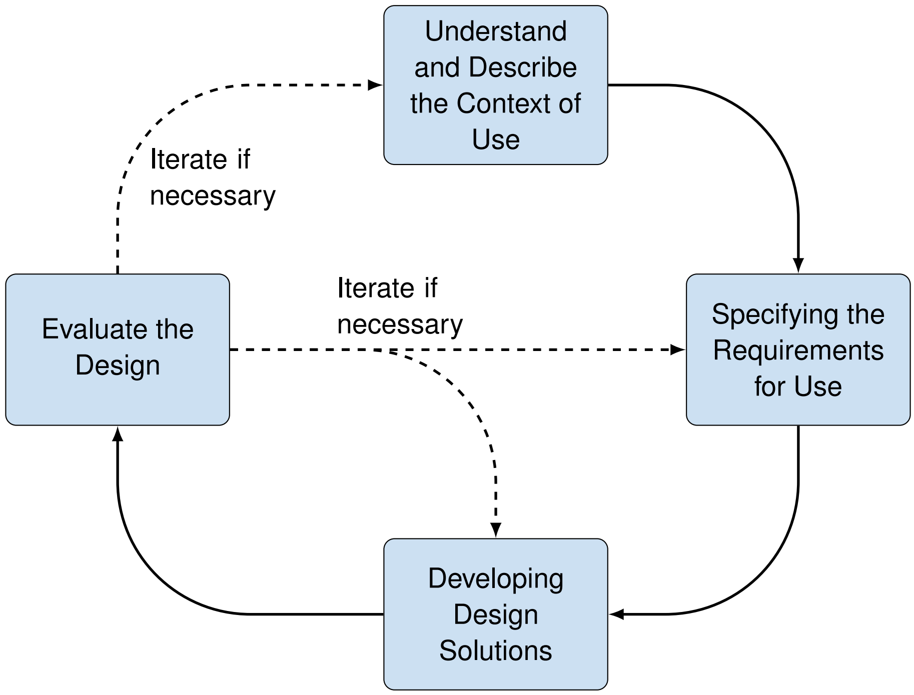

Figure 3 The HCD process according to DIN EN ISO 9241-210

and the design team combines cross-disciplinary skills and viewpoints" (DIN Deutsches Institut für Normung e.V., 2019). First of all, the process needs to be thoroughly planned. Adequate methods, relevant players, and resources need to be allocated. Milestones and time frames need to be set. The four steps according to the DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019) are:

1. **Understand and describe the context of use** The user and how they will interact with the product must be identified here. Essential characteristics of each have to be specified, like the user demography. It is crucial to address the entirety of the user group (like the 5th to 95th percentile in anthropometrics). Next is the definition of the goals and tasks regarding the product, the context of use, including the physical environment, and social and cultural aspects. When defining the tasks, especially factors that might influence the usability or might present risks to the user, the successful completion of the task itself or the surroundings is necessary. Additional duration and frequency of those tasks, as well as side tasks, that might be necessary for the product use. But the tasks should not only be described in relation to the product, but in general.
2. **Specifying the requirements for use** The requirements must be based on the previously chosen context of use and user needs. Also, general requirements from standards, norms, guidelines, and relevant ergonomic fundamental principles must be included. Measurable criteria for usability requirements and goals have to be defined, including criteria that measure efficiency and user satisfaction. Additional requirements regarding the organizational structures involving the user have to be derived, since they effect the user and and the context of use. All those requirements need to be free from contradictions, measurable, and verified with relevant stakeholders. Since the HCD process is iterative, it must be updated regularly during the ongoing development project based on new insights from the other steps.

3. Developing design solutions This step is the most elaborate one since it contains the following sub-activities:

- Defining the user tasks, how the user interacts with the system, and the user interface to meet the defined requirements
- Deriving detailed design solutions
- Modifying the design solutions according to user evaluation and feedback
- Implementing the design solutions

When designing solutions, they should conform to the fundamental principles of ISO 9241-110:2020 (DIN Deutsches Institut für Normung e.V., 2020): Task adequacy, self-descriptiveness, conformity to user expectations, conduciveness to learning, controllability, error tolerance, and customizability. Even though the HCD is centered around hardware development, it is also suitable to software development. Software must also address the user needs and enable hardware to fulfill the defined requirements.

4. Evaluate the design They should be evaluated to assess if the design solutions fulfill the requirements. Even in the early stages, this offers a better understanding of user needs, but real-world use of that solution is complex. Nevertheless, user-centered evaluation is a necessary element of HCD. The direct evaluation with users is not always feasible or effective, but there are other methods like task modeling or simulation. The value of early and frequent user-centered evaluation according to the DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019) is to:

- "a) Gather new information about user needs;
- b) provide feedback on the strengths and weaknesses of the design solution from the user perspective (to improve the design);
- c) assess whether user requirements have been achieved (this may include evaluating conformance to international, national, local, company, or regulatory standards);
- d) collect baseline data or make comparisons between design alternatives."

Therefore, user-centered evaluation includes feedback to improve the product in the early stages and to evaluate whether requirements have been met. Consequently, it needs to be planned accordingly which methods should be used, at what stage, and how they need to be used to result in meaningful results for the respective state of development. The most commonly used approaches to user-centered evaluation are testing with users, inspection based evaluation, and long-term observation. Testing with users can be done with different kinds of product descriptions including sketches, models, scenarios, or prototypes. With the latter, it is essential that they can interact with the prototype. A special kind of prototype testing is the field evaluation, but there has to be an emphasis that the product is not ready yet. Inspection-based evaluation utilizes guidelines, like usability or accessibility requirements. It can complement user testing and eliminate major problems in advance, making the process more effective. Ideally, it is conducted with experts from the field by placing them in the role of the user working with the solution. Tools like checklists, guidelines, or best practices can support this. That expert evaluation effectiveness depends on the evaluator's skills, experience, and knowledge. Hence, choosing the right participants to represent the user group and guiding them with the proper guidelines and standards during the evaluation is essential. The effect of the individual constitution of the participants needs to be assessed, since aspects like mood, fatigue, or nervousness have an impact on how they perceive the presented prototype. Even though an inspection based evaluation is faster and covers a broader range of users, it may not uncover the same issues as user involved testing. It shows the more apparent discrepancies between the user needs and the solution but not the details arising in more complex day-to-day scenarios. The more significant the difference between the expert and the real users, the less reliable the evaluation may be. So, when necessary, experts from the application domain should be involved. The long-term observation is always a field observation with users and a prototype over an extended period of time, usually six months or a year. During this time, user feedback is collected using various methods. This evaluation usually occurs in the last stages of development and gives insights into the solution's performance and whether the needs and requirements have been met. It even evaluates if the requirements and needs have been identified and formulated correctly. Especially long-term effects, like physical health or mental load topics, are only measurable after extended usage periods. The implemented measurement tools fulfill the three aspects of a good measurement method: Validity, Reliability, and Objectivity. This means it measures as intended, delivers consistent values in repeated measurements, and allows low bias and personal interpretation.

The four steps are iterated until a solution is generated that fulfills the user requirements. Now that the basic principles and methods of the HCD are understood, there are aspects of other development processes that can be adapted and used to enrich the process. Especially due to the focus on defining requirements and planning, the model risks slow development with too few or too late iterations. It does not emphasize techniques for generating novel ideas for designing solutions, as is the case in other process models, like the "Double Diamond" model (Katja Tschimmel, 2012, p.9). The Double Diamond model revolves around the same principles as the HCD: understanding, defining, designing, and evaluating. However, the HCD emphasizes iterations, while the double diamond emphasizes exploring new ideas and selecting fitting solutions. Rather than opposing each other, those two models can be used to enrich each other. For example, in the stage of HCD where design ideas are developed, the spirit of the double diamond to explore and open the solution space can be implemented.

Those two models carry the risk of being relatively slow since they portray a holistic approach to the whole product. Much time is needed for planning and documentation. Another approach is agile development. Those processes focus on efficient development using an iterative and incremental process instead of a plan-driven one (Petersen and Wohlin, 2010). By splitting the process into subsystems, it is possible to generate output earlier and, therefore, test and evaluate more frequently. Stemming from software development, the agile way of development supports the rapid exploration of new solutions, continuous error fixing, and frequent feedback loops (Constantine, 2001). The Agile Manifesto of 2001 defines 12 principles (Kent et al., 2013):

1. "Our highest priority is to satisfy the customer through early and continuous delivery of valuable software."
2. "Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage."

3. "Deliver working software frequently, from a couple of weeks to a couple of months, with a preference for the shorter timescale."
4. "Business people and developers must work together daily throughout the project."
5. "Build projects around motivated individuals. Give them the environment and support they need, and trust them to get the job done."
6. "The most efficient and effective method of conveying information to and within a development team is face-to-face conversation."
7. "Working software is the primary measure of progress. Agile processes promote sustainable development."
8. "The sponsors, developers, and users should be able to maintain a constant pace indefinitely."
9. "Continuous attention to technical excellence and good design enhances agility."
10. "Simplicity - the art of maximizing the amount of work not done is essential."
11. "The best architectures, requirements, and designs emerge from self-organizing teams."
12. "At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly."

As these core principles show, agile development not only addresses the user-centered design but also team organization and communication. Examples for the most commonly known agile frameworks are "Scrum," "extreme programming (XP)," and "Kanban". These agile principles come from software development, but are also applicable in hardware development. Due to their focus on quick deliveries and efficient development, they have the risk of not correctly framing the problem and forgetting the context of use, thus losing the focus on the user (Begnum, 2021). Combining agile frameworks and HCD processes into User Centered Agile Development (UCAD) has the potential to embrace user-centered aspects while having quick deliveries and efficient communication within the development team, as well as with the users. However, existing UCAD models do not emphasize the iterative exploration of user needs and the evaluation of those (Begnum, 2021). The HCD mindset, the agile mindset, and the usage of methods from both promise to efficiently develop solutions tailored to user needs and utilize frequent evaluations to ensure those needs are met.

All these presented methods are very general and give a guideline on how individual development processes can be designed and the whole project should be organized. They offer several methods for each stage, and different approaches are recommended depending on the model's goals.

Since this thesis focuses on the HCD of exoskeletons, the main focus will be methods to gain insights into user needs and evaluate them as quickly as possible in the agile spirit. "While direct user involvement takes time and effort, relying on indirect user contact runs the risk of creating a product no one needs" (Begnum, 2021). The definition of requirements in the HCD process says not only should they involve the user and the context of use, but how they should be defined is rather vague. Other process models in engineering, like the V-Model according to VDI 2206 (VDI Verein Deutscher Ingenieure, 2021), have

standardized methods for determining requirements. They state, that requirements need to be verifiable, independent, and, if possible, quantifiable (Lindemann, 2016). This helps in evaluating the requirements and assessing the fulfillment thereof. This results in more time needed in the first iteration for identification, definition, and quantification of requirements but results in easier and faster evaluation steps, thus potentially enabling more and quicker iterations in the following process. This implies that in a development process, besides accurately identifying user needs, there must be a defined process or method for converting them into requirements that are measurable, independent, and verifiable.
In the choice of the evaluation methods, there is a differentiation between what method should be used in which stage of development. It is unclear when the next stage will be achieved and when the next iteration of the human-centered development process needs to be initiated. This poses a challenge, especially in complex systems and new technologies like exoskeletons.The HCD process outlined in DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019) serves as a valuable guideline, but the direct application to exoskeletons is challenging due to general nature of product development process models. There is a gap in design processes or guidelines for exoskeletons (Shore et al., 2018). As described in Bengler et al. (2023), many different components are involved that need to be evaluated individually but also in combination. Also, their development process doesn't start at the same time. So, the development of an exoskeleton cannot be described as a whole and needs to consider all the singular components. Further, some interact with humans more directly than others, like the pHMI, so some might require more and faster evaluation cycles than other components. Therefore, another type of user involvement might be necessary for each component. Begnum (2021) summarizes the different ranges of user contact as "user-focused," "user involved," "co-design," and "participatory."

The analysis of the process models revealed that specific components are essential in a human-centered development process:

- Methods for identifying and describing user needs and the context of use (DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019)
- A process to translate those into measurable, independent, and verifiable requirements (VDI 2206 (VDI Verein Deutscher Ingenieure, 2021))
- Methods to generate new design solutions ("Double Diamond", Katja Tschimmel, 2012, p.9)
- Short development steps and means for quick delivery to the users (Agile Manifesto (Kent et al., 2013))
- Methods for evaluating the design and the satisfaction of user needs (DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019)

3.5. Definition of Key Components for User-Centered Exoskeleton Design

Exoskeletons interact with the human user in multiple instances. They are highly interdisciplinary in their development, and the user must be considered in different subsystems in various ways. Therefore the key components are defined within this chapter, which the development process will also be based upon. Similarly, as in Bengler et al. (2023), splitting up the whole exoskeleton project into smaller key components which can build onto each other enables more frequent user centered evaluations and offers the possibility of parallel development. Based on the principles of Pons (2008), there can be a differentiation between physical and cognitive human machine interaction and the corresponding interfaces. Based on these, the pHMI and the cognitive Human Machine Interface (cHMI) are defined.

pHMI are the interfaces between humans and machines, where only forces are transferred. These are usually defined by mechanisms that create a form or force closure on the human body. Examples are braces, cuffs, straps, or belts.

cHMI are interfaces where information is actively transferred between humans and machines. This includes sensors of the machine detecting biosignals, but also the machine communicating to the user, implementing different ways of communication, like visual, acoustic, or tactile signals.

Pons (2008) differentiated those mostly from the human side of those interactions. At the level of the machine, several key components can be defined that take part in most of the human machine interaction.

Similarly Gull et al. (2020) defined design challenges for upper limb exoskeletons in the areas of "kinematic compatibility," "workspace limitations," "Discomfort and Misalignment," "Human-Robot Interaction," and "Sensing and Estimation." (Fosch-Villaronga and Özcan, 2020) defines, "an exoskeleton needs to integrate the mobility requirements from the end users (human gait analysis, conditions, and characteristics) into the mechanical design, control system, and the user interface".

Based on the presented state of the art and the work of Gull et al. (2020), Pons (2008), key components between the human and the machine are being defined. Those factors are defined by the highest interaction between the human and the machine, and design choices need to be focused on achieving a HCD. The design of the exoskeleton has the most impact on the human components and directly influences the acceptance by the user. Conversely, those are the components where the human can best influence the machine. They are presented in Figure 4.

For designing the **pHMI** well, the user is not supposed to sense any chafing, pressure, heat, or any other type of discomfort. On the one hand, this influences the design of the **pHMI** itself so that pressure is distributed evenly, nothing puncturing or chafing the skin, humidity, and heat are not trapped between the body and the cuffs and the materials conform to DIN EN ISO 22523 (DIN Deutsches Institut für Normung e.V., 2007). On the other hand, for the user to not experience excessive pressure, shear forces, or, in the worst case, being forced into unnatural motions and postures, the **dynamics** of the exoskeleton needs to be highly compatible with human biomechanics. By this definition, **dynamics** is not only concerned with the mechanics of the exoskeleton, but also with the behavior of the system during actuation. This goes further into the actuation design, designing the exoskeleton behavior so that the trajectories comply with human motions. This aspect includes not only the **kinematic design** but also kinetics, which includes what forces are acting between the human and exoskeleton. These forces are determined by the used actuation, therefore the kinetics are referred to as **actuation** in the following. In passive exoskeletons,the assisting forces depend only on the actuation design, but in active exoskeletons the corresponding **control** strategies are equally influential. To achieve this, the machine has to detect the state of the human itself and its environment at any given time and interpret it correctly. Thus, the exoskeleton needs **sensors** for detecting and collecting any required data on top of the inherent machine parameters like the power consumption of the actuators. **Sensors** can also be used to detect human motion intentions, thus making the operation of the exoskeleton easier for the user. Therefore, they are an essential part of the cHMI, too. The primary influence on the cHMI is the **User Interface (UI)** as a whole.

Another factor influencing the user's attitude towards the system is its appearance and overall system behavior, as described in the Technology Acceptance Model (TAM) 3 (Venkatesh and Bala, 2008, see Section 4.1). That aspect is not central to the functionality of the machine itself. It applies mainly to aesthetics, functional integration, and interaction design in greater detail, making it essential in design stages where the whole exoskeleton is conceptualized and evaluated. For simplification, these aspects are summarized as **general design** and have a high number of relations to the other subsystems mentioned above. Compared to the other factors, that component only influences the human and has no direct effect on the technical functionality of the machine. It instead describes how the features are implemented altogether. It also is more difficult to define within concrete requirements. Since it surrounds all the other interaction modalities, it has a higher level that encloses them and makes them fit together.

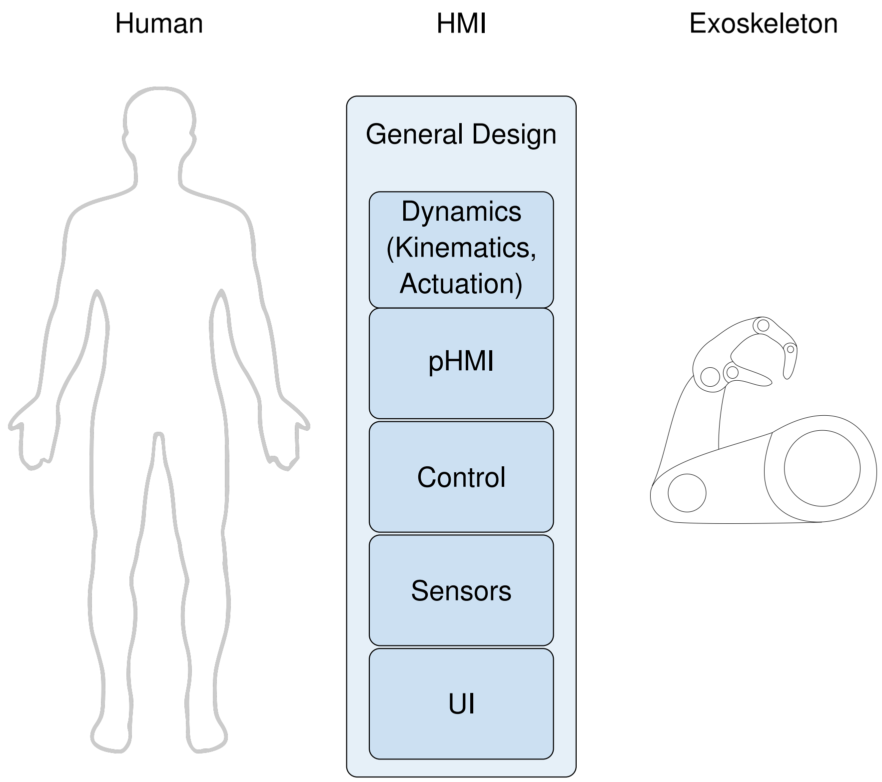

Figure 4 The six essential exoskeleton key components defining the interaction between human and machine

The hypothesis for the following requirement synthesis and exoskeleton development is: If the exoskeleton development focuses on an agile, HCD on the six components **dynamics, pHMI, control, sensors, UI, and general design**, it will result in a useful and well acceptable system.

The first step in building an exoskeleton is the mechanical structure with the actuation, active or passive, meaning the **kinematics**, the **pHMI**, and the overall concept of how the exoskeleton should be used. That involves the **UI** and the case of active exoskeletons, the **sensors** for intention recognition. In the following, the focus will be on these four aspects.

First, following the HCD process, extensive research for gathering enough data on the context of use and the users will be conducted, thus defining the requirements for the design process. Those requirements will be involved in two case studies for developing two different exoskeletons for different contexts of use. As given by the HCD process, the developments will follow an iterative process to ensure the fulfillment of the requirements in the early stages. To keep it agile, frequent and small evaluation cycles for the components are included. The solution space will be reopened for each cycle, and the tools for evaluation will be adapted to the needed data to begin the next cycle.

4. Requirements for Exoskeletons in Specific Contexts of Use

As the human-centered design process requires, the first crucial step is understanding the context of use and the user. Based on this is the next step specifying design principles for the use of the product to be developed. These need to be individual assessments for every context of use as described in Section 3.1. Based on literature, norms, and insights from exoskeleton evaluations, a basic set of design principles can be defined, which need to be specified and quantified for each individual context of use. The aim of this chapter is defining those design principles in Section 4.1 and presenting a method to translate these into requirements for individual contexts of use in Section 4.2.

4.1. Human Centered Design Principles for Exoskeletons from Literature

In an extensive literature review, 64 relevant publications addressing design principles of exoskeletons or fundamental guidelines for body-worn systems were identified. The full list, categorized by *key components*, can be found in the Appendix B. Many of these publications highlight common issues or reference the same fundamental design principles, based on ergonomic and machine design principles and norms. They are also derived from evaluations of existing exoskeletons, which will be discussed later. In this chapter, there will be a summary of all relevant exoskeleton-specific design principles from fundamental research, norms, and exoskeleton evaluations. They will be grouped into the *key components* presented in Section 3.5.

For the literature review, publications were required that discuss technical designs of exoskeletons, their optimization potential, or already define requirements for exoskeletons. These are mainly present in reviews of the current state of the art of exoskeletons, including structural analysis of different types of exoskeletons (Liang et al., 2022). Other appropriate literature focuses on the acceptance of exoskeletons and relates it to specific technical designs (Shore et al., 2022) or focuses on specific *key components*, such as control strategies (Li et al., 2017) or pHRI design (Sposito et al., 2020, Massardi et al., 2022). In the Scopus database, 59 sources falling under these categories were identified. Then they were analyzed for statements giving specific requirements or design guidelines for one or more of the *key components*. All statements were collected for each component and then grouped into themes that addressed similar issues or concepts. For example, statements related to problems in adapting exoskeletons to individual body types and statements calling for anthropometric adaptability were grouped into the same theme. Where statements addressed multiple *key components*, they were copied to each component and analyzed individually in relation to that *key component*. For the clustered statements, a unique term for a design principle, including a definition, was derived for each theme. In addition, literature providing general ergonomic principles and guidelines, such as user interface design, was added to the list when exoskeleton-specific publications did not go into enough detail to derive design requirements. The most relevant *key component* in this scenario is the *User Interface (UI)*. In this case, principles were derived from the international standard for ergonomic requirements for the design of displays and control actuators (ISO, 1999a) and the standards for ergonomic aspects of driver information and assistance systems DIN Deutsches Institut für Normung e.V., 2017. The final list represents the resulting design principles in Annex B, which are explained below.

It is important to note that these design principles focus on exoskeletons that assist healthy users during straining physical tasks. The analyzed literature also includes many references for medical exoskeletons, rehabilitation, or assistive devices for patients with body impairments. Especially in terms of user needs, the design principles for healthy workers overlap to a high degree with patients using medical exoskeletons. Therefore, literature about medical exoskeletons will be included in aspects not exclusive to the medical context of use, like the *UI* and *pHMI*.

Occupational exoskeletons are built to assist the human wearer during straining physical activities. The forces applied by those straining tasks are harmful due to overloading the body parts either with peak or long-term repetitive moderate forces. The goal of these exoskeletons is benefiting the workers short term by reducing fatigue and long term by lowering health risks that occur due to overly straining tasks. The measurable effect of the exoskeleton on the human body to achieve these goals can be reduced metabolic costs, muscle activity, or joint interaction forces.

ISO 13482:2014 (DIN Deutsches Institut für Normung e.V., 2014) defines technical design principles regarding physical safety measures. However, it is very general and does not specify the implications of special robots, like exoskeletons. Further, it does not include protective measures and design guidelines for other aspects of human-machine interaction (Fosch-Villaronga and Özcan, 2020) and does not explicitly describe HCD design principles (Shore et al., 2018). The regulations of the European Union 2016/425 define regulatory measures that need to be fulfilled to put new personal protective equipment and specify basic health and safety requirements (European Union, 2016). Both norms and regulations must be fulfilled for the safe workplace integration of exoskeletons, but they only provide minimal guidance on designing a safe and efficient exoskeleton. Therefore, they are included into the design principle of 'safety'.

As described in 3.5, the key component *general design* integrates all the other aspects of the exoskeleton. This results in dependencies with the other five key components. Therefore the design principles defined for the *general design* translate into the other *key components*. The achievement of these design principles within the individual components have a major influence of the achievement of the design principles of the overall *general design*. This is also represented within the analyzed literature. Most evaluations of exoskeletons in literature evaluate the system as a whole (e.g.: Hensel and Keil, 2019; de Looze et al., 2021; Huysamen et al., 2018a; Huysamen et al., 2018b; Kopp et al., 2022; de Vries et al., 2022). Only few focus on single key components, like the *pHMI* (Massardi et al., 2022; Schiele, 2009; Sposito et al., 2019; Kermavnar et al., 2018; Kermavnar et al., 2020; Huysamen et al., 2018a; Huysamen et al., 2018b). A representative example is the design principles for the *general design* exoskeleton to be lightweight. This relates to the *dynamics*, that also have to be light weight, resulting in lightweight materials, that have to be used, as well as using actuation with a good power to weight ratio. Based on these descried dependencies between the *general design* and the other key components, the design principles for the *general design* will be described in detail. Afterward these will be broken down into the other five key components and complemented with literature focusing on these specific key components.

The identified sources (Appendix B) give general design recommendations and the majority focus on kinematics and actuation since most attention was paid to the biomechanical effects of exoskeletons (Crea et al., 2021). These relate primarily to the aspect *dynamics*.
Fundamental literature that is useful to identify requirements for the design of physical assistance systems can be found in the fields of biomechanics or physiotherapy and ergonomic product design, like Kapandji and Rehart (2016), Zeagler (2017), Klepser and Morlock (2020), von Salis-Soglio (2015).

Another focus of the reviews was the *control* algorithms for active exoskeletons, most of them in the area of walking support. Only a few give a general review (Masia et al., 2018), and one was identified that focuses on lower back support exoskeletons (Toxiri et al., 2019). It must be mentioned that sometimes general design recommendations are given in one source but do not go more deeply into the respective control strategies or hierarchies. In other sources, the authors focus more deeply on the control principles of exoskeletons and that are specifically designed for the desired context of use, like gait assistance (Tucker et al., 2015; Yan et al., 2015).
In the context of control, *sensors* are discussed as means of detecting input data for humans in the loop or to assist as needed control strategies and also to ensure the safety of the human exoskeleton user.

Few references focus especially on the *pHMI* of the exoskeleton and its high relation to discomfort. In most sources, the *pHMI* is discussed as part of the kinematic chain that influences comfort or means to effectively transfer forces between human and machine.
General knowledge about pressure sensitivity of human skin in different areas can be acquired from medicine, e.g., from pressure algometry (Fischer, 1987) or studies related to perceived pain or discomfort thresholds, like Huysamen et al. (2018a), Huysamen et al. (2018b) used them.

The least focus in literature is on the *user interface*. How information between human and machine can be exchanged in the most effective, efficient, and safe way is only researched in a few projects. The human-machine information exchange is often mentioned in a side note to make the exoskeleton safe and easy to use.
Fundamental research and norms already define how to design a user-friendly UI adapted to the context of use in, for example, DIN EN ISO 6385 (ISO, 2016) and DIN EN ISO 9355-1 (ISO, 1999a).

In the following the condensed design principles for exoskeletons will be described. The respective sources are found in the resulting lists of design principles found in the Appendix C, Appendix D, Appendix E, Appendix F, Appendix G, and Appendix H. In the list, the design principles are presented, with methods and literature to survey the data for the requirements. Further tools to evaluate those requirements are presented, either if they are directly measurable, or with an standardized or an individualized questionnaire. Methods on how to implement these tools are described in chapter 5. The lists show dependencies between the design principles, allowing for the independent definition of the resulting requirements.

First the design principles for the *general design* are synthesized, and the resulting list is presented in the Appendix C.
Based on the design principles for the *general design*, the principles for *dynamics*, *pHMI*, *control*, *sensors*, and the *user interface* are derived and supplemented with design principles found in literature. For better readability, within the following chapters and the further case studies, the derived design principle is referenced to the ID-Nr. of the lists presented in the Appendix D for *dynamics*, Appendix E for *pHMI*, Appendix F for *control*, Appendix G for *sensors*, and the Appendix H for *user interface*.

4.1.1. General Design Principles

Most importantly, exoskeletons must be accepted by their users. TAM (Figure 5) define influence factors that design principles can be built upon, with the TAM (Davis, 1985) and its evolutions (Venkatesh et al., 2003) being the most relevant for exoskeleton design (Shore et al., 2022; Shore et al., 2018). The users' perceived ease of use and usefulness are the most important factors that define the attitude toward using the exoskeleton. The perception of usability and ease of use are influenced by design factors as well as factors that may lie outside of the technical design, like age, gender, social influence, and experience. A study by Elprama et al. (2020) showed that the perceived ease of use has the highest impact on the intention to use an exoskeleton.

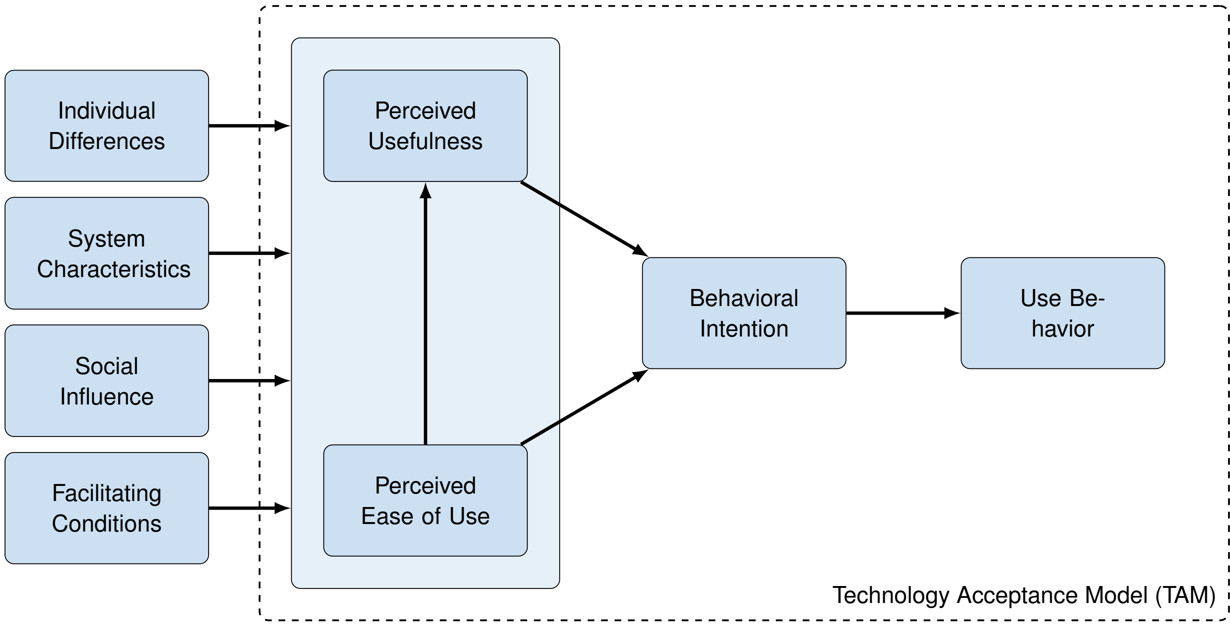

Figure 5 Basic principles of technology acceptance (Venkatesh and Bala, 2008)

Moyon et al. (2019) defined an exoskeleton-specific acceptance model and focused on practical acceptance in terms of usability with affective, cognitive, utility, and physical aspects. In the context of occupational exoskeletons, they defined the influence factors on acceptance as follows: Safe for people, comfort, release of global strain, morphological adaptability, efficient for quality standards, low susceptibility to errors, assist task, flexible with other tasks, minimum disturbance of processes, robust, ease of use, ease of learning/ memorizing, light cognitive workload, minimum changes in perception and positive connotation (Moyon et al., 2019). Based on the TAM and the acceptance model by Moyon et al. (2019), *general design* principles are defined. Based on these, design principles for the key components are deducted in the following chapters. The resulting list of general design principles is presented in the Appendix C. For better readability, the resulting list is only listed in the appendix for an overview, to be referenced later in the case studies. Within the following chapters, the derived design principle is referenced to the ID-Nr. of the list in the Appendix C.

Usability (G.1)

According to ISO 9241-11, usability is defined as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (DIN Deutsches Institut für Normung e.V., 2018). In the context of occupational use, this not only relates to the defined scenario in which the exoskeleton is used. High usability needs also be achieved in the side tasks, meaning not to hinder tasks where assistance is not required. Further, the whole process of using the exoskeleton, including putting it on and taking it off, must be effective and efficient and result in high user satisfaction. During the assisted task, it must help as much as required and follow the natural motions. As a result, this design principle is essential for all the human machine interaction aspects of the exoskeleton, the *dynamic* of the exoskeleton, as well as *control*, *pHMI*, and an *UI* adaptive to the context of use. The right choice of sensors is essential for the control to work effectively.

User Experience (G.2)

Usability (G.1) is a central part of the user experience according to ISO 9241-210. The concept of user experience also includes the interaction with the product before and after the task it is designed for. So, it includes aspects of the complexity of learning to use it, a pleasurable experience of using it that extends the principle of getting the task done and having a satisfactory feeling after having used the product. This includes aspects of storage, cleaning, and maintenance of the system. (DIN Deutsches Institut für Normung e.V., 2019)

Ease of use (G.3)

The design principle for ease of use for the exoskeleton is highly requested but not only as it relates to good usability (G.1) for the exoskeleton in the defined context of use for the assisted activity. It is necessary for every aspect where direct input and user participation is required. The *pHMI* has to be easy to use, and information exchange with the *UI* must be easy to use and understand, including an easy set-up.

Aesthetic appeal (G.4)

Social aspects are a high influence factor in technology acceptance and are an often mentioned user need, e.g., wishing to wear the system underneath clothes. However, it is only partially achievable with the technical design. Influence is the kinematic design in terms of bulkiness, unnatural shapes, and hindrance in natural motion, as well as the overall optical design, making it aesthetically pleasing to the user.

Weight (G.5)

The most mentioned and criticized design principle is the weight. Being a body-worn technology, weight has a major influence on the system's acceptance. High weight of exoskeletons are proven to increase metabolic costs, thus negatively impacting the exoskeleton's effectiveness since the system's goal is to reduce strain on the human body. Asbeck et al. (2014) reports an increase of metabolic costs of 1-2 %/kg for load at the torso and up to 8 %/kg for load at the foot. A higher weight on the limbs increases the inertia of the system which, in turn, impacts the natural motion of the user and affects the system's performance negatively, as well as control complexity. The parts that influence the weight the most are the kinematic structure, the actuation, and for active exoskeletons, the electronic components and the energy source. An important factor is if the exoskeleton has a connection to the environment where loads can be transferred away from the body. Otherwise, the load is redistributed within the body in addition to the system's weight, especially with exoskeletons that help lift and carry loads. According to the rules of the German Statutory Accident Insurance (Deutsche gesetzliche Unfallversicherung, DGUV), similar personal protection equipment should weigh below 5 kg if intended for long-term use (Deutsche Gesetzliche Unfallversicherung e.V., 2021).

Size (G.6)

Apart from the weight, the size of the exoskeleton is mentioned as a limiting factor in acceptance and usability. A bulky system reduces the aesthetic appeal and the ability to move in tight spaces, making it more cumbersome for daily activities. The latter is especially important in the occupational context, where users must work in confined spaces or move around with machines and other people in the same space. The size is influenced mainly by the mechanical structure, the size of actuation units, and batteries. Functional integration is one way to reduce the overall size. Zeagler (2017) developed a body map that shows where and up to which size wearables are accepted by users on their bodies.

Use Time (G.7)

The size of the batteries depends on the power consumption of the actuators and the electric components. Therefore, the use time of the exoskeleton in the context of use needs to be defined and correctly identified so batteries can be kept as small as possible. At the same time, the system must work reliably for the whole shift. The battery size can even be smaller with adequate quick change or fast charge strategies.

Transportable and storable (G.8)

When the system is turned off or not on the body, it needs to be transportable and storable to be easily transported to the location of operation or stored at the end of the workday.

Set Up (G.9)

In this context, another critical influence factor on acceptance by users that is reported is a quick and easy setup. This includes the *pHMI* mechanisms to be easy and fast and the arms to be operable with one hand. Also, the means to adapt the exoskeleton to the user's body must be low complexity and adjustable without another person's help. For active exoskeletons, the booting up and calibration routines must be as short as possible for the sensors and the control. The setup times must be as quick as possible and suitable for the context of use.

Safe State (G.10)

In case of an empty battery or another system failure, the exoskeleton must automatically go into a safe mode. This includes not suddenly dropping any load or the user having to handle the whole weight. It also means the user can still move or free themselves quickly from the device. This results in the actuation having to be back-drivable and the structure to have a safe configuration to which it automatically returns.

Emergency Exit (G.11)

In case of an emergency, the exoskeleton needs to be able to be stripped off the body as fast as possible. This does not necessarily involve an emergency caused by the exoskeleton but rather evacuation scenarios or a medical emergency of the user that requires first responders to remove the system. The time for the user to take off a body-worn system must be as short as possible. The maximum allowable values for removing the exoskeleton in an emergency situation differ based on workplace regulations.

Support rate (G.12)

Quantitative performance factors must be specified to measure effectiveness in the desired context of use. These could be lifting a load within a specific frequency, constant support of a cyclic motion like walking, or static support in a specific posture. These need to be defined, and the amount of assistance the exoskeleton needs to provide. In some cases, 100 % assistance is not required or wanted by the user, or might even be harmful due to the potential muscle loss of the user. Those factors are quantifiable, for example, with the increase or reduction of the time the main or side tasks need (Kopp et al., 2022; Hensel and Keil, 2019).

Discomfort (G.13)

In most evaluations, discomfort is one of the most commonly mentioned reasons why the user does not accept an exoskeleton. Different reasons are described for the *pHMI* and the kinematic structure. Reportedly, they stem from misalignments between the exoskeleton and human joints, resulting in parasitic forces, shearing, or even injuries at the *pHMI*. Further thermal discomfort or high pressure at the *pHMIs* are described, which need to be avoided by the design of the *pHMI*s.

Mobility and Independence (G.14)

Users expressed the desire to move independently and experience self-liberty despite wearing the device. This involves the users moving freely with the device without being hindered in their usual motions. This also addresses the safety aspect, that users may need to be able to do involuntary movements to, e.g., keep their balance when tripping.

Low Noise Emission (G.15)

The exoskeleton's closeness to the human body makes the noise emission of the system a vital factor for acceptance but also for safety. The noise needs to be within the regulations for workplace use, but it also should not prevent the user from hearing necessary acoustic signals from machines or coworkers.

Vibrations (G.16)

In the same vein as the noise emissions, vibrations on the body must be as low as possible, at minimum below safety workplace regulations (DIN Deutsches Institut für Normung e.V., 2001, DIN Deutsches Institut für Normung e.V., 2015)

Safety (G.17)

The exoskeleton needs to be inherently safe, as specified in several norms and guidelines that focus on the safety of machines like the EU machine directive (European Union, 2023) and personal assistance robots EN ISO 13482 (DIN Deutsches Institut für Normung e.V., 2014). Monica et al. (2021) did a comparative review of existing international standards that are in any form relevant for occupational exoskeleton design.

Compatibility with side tasks and tools (G.18)

The usability (G.1) of the system should be good not only for the primary supported tasks but also for side tasks. The system does not support these side tasks but it is still worn during these. These may involve using tools, so the exoskeleton must not hinder access to or operation of those tools. To ensure the design of the exoskeleton meets user needs, secondary tasks and tool interactions must also be taken into account(Fosch-Villaronga and Özcan, 2020; Monica et al., 2021).

4.1.2. Key Component "Dynamics"

More specific design principles can be derived from the general design principles in Section 4.1.1 for the exoskeleton's *dynamics*. Those will be described briefly in this subsection, and the overview table will be presented in Section D.

As described in Section 3.5, the *dynamics* can be separated into the kinematics, *dynamics (kinematics)*, relating to the motion of the rigid bodies of the mechanical structure, and the forces acting on the them by the passive or active actuation, *dynamics (actuation)*.

Dynamics (Kinematics)

The biggest focus in research is the kinematic compatibility (D.2) of the exoskeleton kinematics with the human biomechanics since macro- and micro-misalignments lead to discomfort, increased metabolic costs, or even injuries. This is achieved via anthropometric adaptation mechanisms (D.1) for the 5th to 95th percentile and misalignment compensation (D.2) for the elongation of body dimensions during motion via self-aligning mechanisms, compliant structure or compliant joints. Misalignments also reduce the room of movement or the Degrees of Freedom (DoF) (D.3) in which the human can move. A full DoF is necessary, so in addition to the DoF that needs to be assisted, all DoF must be represented in the exoskeleton structure (D.3). This is possible via passive DoF and compliant actuation (D.8) that must be defined according to the context of use. Similarly, there has to be a lightweight mechanical structure (D.4), with low inertia (D.5) and low complexity (D.6) to achieve a good weight perception of the system. Therefore, for the placement and the build-up on the body, the humans' body awareness (D.7) and the perception of the placement of wearables on the body must be considered.

Dynamics (Actuation)

The second important aspect of good dynamics is an appropriate actuation within the kinematic structure. The actuation has to generate appropriate assistive forces (D.9) while having a good power to weight ratio (D.10). Just as with the mechanical structure, it needs to add to the compliance (D.8) of the whole system, have a compact size (D.11), low noise emission (D.12), low vibration (G.16), and low inertia and stiffness (D.13). In active systems, the motors need to have high control bandwidth (D.14), accurate torque delivery (D.15), robust against disturbance (D.16), transparency (D.18), repeatability (D.15), and have low energy consumption (D.17). Especially for the safe state (Section 4.1.1), the motors need to be back-driveable (D.18) so that the user can still move even when the motors are not powered. There are a few context of uses where it might be necessary that the joints of the exoskeleton be locked or only slowly released to ensure the user's safety, for example, when a heavy load is lifted. This can be implemented with a safe state in the control or mechanical elements like magnetic brakes or clutches.

The resulting list of *dynamics* design principles is presented in Appendix D.

4.1.3. Key Component "pHMI"

The role of the *pHMI* fixtures is to transfer assistive forces (P.1) between the human and the exoskeleton effectively and efficiently. The *pHMI* is the interface between the kinematic structure and the human body, and the transferred forces depend on how the actuators are controlled. They have to fit the human at the designated spot and therefore not only account for the anthropometric length (P.2) and circumference (P.3) of that body part, but also account for the changing volume (P.4) of muscles, as well as skin stretching due to elongation (P.5). They contribute to the kinematic compatibility with either passive DoF or biocompatible materials, resulting in a compliant design (P.6). Effects of poorly designed physical interfaces are pressure peaks or shear forces (P.12) that are contributing to experienced discomfort (P.11) or pain by the user. Due to the large surface areas of the skin the attachment covers, thermal comfort (P.7), and hygiene (P.8) are essential factors. They may come in direct contact with sweat and are exposed to potential environmental factors. Therefore, it needs to have a long war durability. The *pHMI* needs to be put on easily and quickly (P.9), at the arms even with only one hand (P.10) and without the help of others. From a safety aspect, they need to be removable quickly, even when the exoskeleton is in operation, to prevent hazards during set up and use times.

The resulting list of *pHMI* design principles is presented in Appendix E.

4.1.4. Key Component "Control"

The control algorithm of active exoskeletons depends on the context of use, the *UI*, and the used *sensors*. This is the basis for the "Assist-As-Needed" control strategy that an exoskeleton should follow. The context of use defines the appropriate assistance, the needed accuracy in following trajectories (C.1), and potential disturbances, which the algorithm needs to adapt in unstable situations (C.2). The context of use defines different modes of the exoskeleton, where different trajectories need to be followed. For example, a mode where the exoskeleton follows the user's motion without adding any force and one where it actively supports a specific movement pattern with force. The control needs to be able to detect and switch smoothly between modes (C.3). Especially in nonstructured environments, there is a high risk of unforeseen adverse events where a late detection might cause risk to the user. Therefore, with the data of the *sensors*, the control needs to have real time performance (C.1), a decent fault tolerance (C.4) against unforeseen or involuntary movements, and low latency (C.1) in detecting the desired trajectories, which also calls for preferring more simplicity (C.5) in the used algorithms. There will potentially be a trade-off between the system's accuracy and responsiveness. The control also needs to complement the *dynamic* of the whole system as well as the kinematic structure. Therefore, the control needs to promote low inertia (C.6) and the velocities and accelerations of natural motion (C.1) to increase acceptance by the users. The control must account for non-linearity by the compression of soft tissue (C.7) to minimize interaction forces and offer friction and inertia compensation (C.8). Another critical factor is the *UI* that defines the interaction between the user and the exoskeleton. The control needs to implement individual settings and patterns from the user and send feedback signals (C.9) to the user. A hierarchical structure (C.10) within the *control* is recommended in literature, where, for example, the low-level controller controls the torque, the mid-level controls the dynamic performance, e.g., with backlash compensation, and the high-level Assist-As-Needed strategy, that estimates the motion, the necessary amount of torque and generates a reference signal with the input by sensors and user inputs (Chen et al., 2020; Masia et al., 2018; Toxiri et al., 2018; Dinh et al., 2017). Depending on the context of use, distributed control (C.11) can enhance flexibility and scalability of the exoskeleton, where the strategy can be adapted without the central controller, which might increase responsiveness and adaptation to unforeseen events (Plaza et al., 2021).

The resulting list of *control* design principles is presented in Appendix F.

4.1.5. Key Component "Sensors"

Sensors have three essential roles in the overall *control* of the exoskeleton: they deliver essential information about the state of the exoskeleton (S.1), state of the user (S.2), and the influence of the environment (S.3). The collected data and the sensors used must be adequate for the context of use (S.4). For example, even though surface Electromyography (EMG) shows good results in detecting users intent (S.2) by detecting muscle activation via the electric potential in the surface muscles, they are not well usable in an occupational context. They have poor usability for inexperienced people (S.4) in occupational workplaces, have high inter- and intrasubject variation (S.5), and are not robust against environmental (S.6) disturbances. The sensors used must be valid, reliable, and objective (S.7), especially when detecting interaction forces or biosignals. For example, with sensors for detecting interaction forces, the influence of shear forces and friction needs to be accounted for. Another example of biosignals is measuring muscle stiffness via force sensors, since not only the muscle stiffness but also the volume change of the muscle affects the force readings. Sensor fusion is proposed to get a more robust estimation of the user's intent. The sensors themselves need to be robust against not only the environment but also against work task-related wear and tear and also guarantee long wearability (S.8) despite the influence of sweat, hygiene-related cleaning, and frequent putting on and taking off by diverse users. This also adds to the measured data having to be with low data noise (S.7) and being stable overtime (S.7). The acceptance might be reduced if the sensors are too complex to attach, too big, or have to be calibrated too often. Therefore, it needs to have a low obtrusiveness (S.8), which positively impacts the *general design* principle for the exoskeleton to be not bulky and easy to use.

The resulting list of *sensors* design principles is presented in Appendix G.

4.1.6. Key Component "UI"

In active and passive exoskeletons, the UI needs to be designed in a way that has a high usability (U.1) in itself. The function of input options and the output signals need to be compliant (U.2), meaning it needs to be clear what their effect is by themselves without the reaction of the exoskeleton and correspond to the user's expectation. There is not much research on the interaction concepts of exoskeletons. Still, by the *general design* principles, the placement of the panels and operation elements should not hinder natural motion (U.3) and be slim (U.3) and lightweight (U.4). The input and output modalities are user and task dependent (U.5), and additionally, there needs to be a monitor interface (U.6) for developers and maintenance. The output messages need to be unambiguous (U.7) and especially noticeable during the task (U.8), which is a challenge in noisy workplaces where the worker is focusing on the task at hand. Haptic and multi-modal feedback is a potential solution. The use of the interfaces and the signals should not add mental load or distract (U.9) from safety-critical tasks. Otherwise the design of the UI should follow the standards from the DIN EN ISO 9355, meaning they have to be reachable (U.10), visible (U.11), respect accommodation size (U.12) of text and symbols for all ages, prevent misuse (U.13), grouped according to function and frequency of use (U.14), and control actuators need to be suitable for the body part (U.15) for which they are intended.

The resulting list of *UI* design principles is presented in Appendix H.

4.1.7. Summary of Design Principles

As described in 3.4, the specific design principles and the resulting design principles and values depend on the selected context of use and the targeted user group. However, the design principles in the last segments give a guideline where only concrete specifications need to be filled in. The resulting lists are presented in the Appendix C - H. Exoskeletons, especially active ones, also need to conform to safety regulations for industrial machines and body-worn robot regulations, as they are defined in the DIN EN ISO 13482, "Robots and robotic devices - Safety requirements for personal care robots" (ISO, 2014), DIN EN ISO 12100:2011 "Safety of machinery - General principles for design - Risk assessment and risk reduction" (ISO, 2010), or the low voltage directive 2014/35/EU (European Union, 2014; Monica et al., 2021). At the time of this thesis, there are efforts to standardize exoskeletons in national and international norms, as presented in Lowe et al. (2019). The next step is identifying the correct motions and tasks an exoskeleton needs to support. A method to identify potentials of exoskeleton development in existing workplaces is described in the next Section 4.2.

4.2. Defining Requirements from the Design Principles for a new Context of Use

Based on the design principles presented in Section 4.1, for each context of use, specific requirements can be deduced. In this chapter a method to do so is presented. The definition of requirements needs to be done for each workplace individually. Even though the main task might be the same, e.g., lifting heavy goods, the side tasks play an essential role in the design choices needed during the development. The influence of side tasks is described in the literature, and it is concluded that exoskeletons need to be assigned to one specific task to be useful (Monica et al., 2021; Young and Ferris, 2017). If the system hinders side tasks, it represents one of the main reasons an exoskeleton is not accepted (Hensel and Keil, 2019) and is described as useful but "somewhat cumbersome" (Huysamen et al., 2018b). Identifying exoskeletons' requirements means considering all daily routines of the user. Essential needs in the work environment include accessible storage, predefined setup times before the start of a shift and after breaks, as well as sanitation and hygiene procedures for shift changes and user transitions (Crea et al., 2021). The key is identifying straining motions or postures and deriving essential characteristics of the exoskeleton, as described in Section 3.1. For example, supporting static postures calls for a passive exoskeleton (Rimmele et al., 2023) while an active one better supports high dynamic motions. Further, it has to be identified what the effective proportion of time the assistance is needed is, the walking distances, and the limbs where the most strain is acting on (Ralfs et al., 2022; Dahmen and Constantinescu, 2020). It is also essential to involve all stakeholders when analyzing the context of use (Crea et al., 2021). This means involving the workers, the shift or production manager, and the upper management since every level has other insights into the daily routines, how they might change over days, or even reports from previous (failed) experiences with similar systems. All these stakeholders give valuable input for design requirements regarding the work processes, the influence of the work tasks and the environment on a potential exoskeleton, tools that need to be usable with the system, and specific societal factors within the workforce. As a side note, it is important to figure out how workers actually do the tasks at hand and not only how it is described in the process description since they often have tricks or shortcuts to make their work easier, even if it is not company standard. It is assumed that if the exoskeleton hinders those shortcuts, the system's acceptance will decrease significantly. Information about the available set-up times outside of breaks, periodic training possibilities, requirements for self or serviced maintenance, and possibilities for storage close to the workplace and hygiene requirements will come from the middle or upper management.

Lastly, safety protocols for evacuation of the workplace and first aid procedures need to be discussed to know if the exoskeleton could hinder fleeing from the workplace and, therefore, needs to be removable quickly. Also, in non-exoskeleton related medical emergencies of the user, the first aid personnel can remove the system quickly.

Based on literature and basic ergonomic assessment sheets, like the Key Indicator Method (Leitmerkmalmethode) (LMM) (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2019) and the ergonomic assessment worksheet EAWS (Schaub et al., 2013), a process for identifying and logging these factors during workplace assessment was developed. Based on those factors, a matching process between the identified factors and essential design characteristics from Section 3.1 was designed. The method was developed within the project "Guidelines for Implementation of Exoskeletons in Occupational Workplaces" (Guidelines für den Einsatz von Exoskeletten an gewerblichen Arbeitsplätzen Experiences, "LEXO-FA"), that was commissioned by the Bavarian metal and electrical employers' associations' subsidiary "Kompetenzzentum Mittelstand GmbH" (Harbauer and Bengler, 2022). Within this project, there was also a field testing of three exoskeletons in the analyzed workplaces. The experiences will be described briefly in the last section.

4.2.1. Methodology for Acquiring Requirements from Workplaces

Based on existing ergonomic assessment tools, a checklist was designed. The checklist protocols detail the nature and times of the main and side tasks, forces acting on the body, and identifying critical postures. Further, the environment in the workplace is sketched, and tools or machines that need to be used are identified. In more detail, the collected data contains:

- Forces acting on the body (e.g., loads to be carried, equipment to be operated)
- Body postures (e.g., standing upright, kneeling, stooping, sitting)
- Time proportions of the acting forces as well as the body postures
- Dimensions of the working area (e.g., passage widths, dimensions of open spaces)
- Environmental conditions (e.g., protective equipment to be worn, weather conditions, cycle times, tools)
- Secondary activities (e.g., PC operation, manual notes, changing the drilling attachment)

The main task is predefined based on the LMM, which is similarly found in other literature like in Monica et al. (2021) or in the ISO 11228 (ISO, 2021; ISO, 2007a; ISO, 2007b). Those are:

- manual lifting, holding, and carrying of loads
- manual pushing and pulling of loads
- manual handling operations
- whole-body forces
- awkward body postures
- body movement/locomotion

The checklist is designed so that every single motion can be described, including used tools. Afterwards, it helps summarizing postures, defining the main and side tasks, and identify confined spaces in the workplace. A translated version of the checklist is found in the Appendix A.

Based on the collected data, the potential for developing fitting exoskeletons can be assessed. The potential for the use of an exoskeleton is given if it is a non-stationary workplace and similar tasks and repetitive movements are performed throughout the workday or at least over a longer period of time. Additional prerequisite for an exoskeleton is a workplace where the application of the STOP principle [1] does not show the desired effects and the work environment is compatible with a potential exoskeleton. As described before, an exoskeleton must be designed for a specific task to be useful. One main task has to be selected - one which puts the most potentially harmful forces on the human body and takes up most of the time. In the case of a worker working on several workstations or places, using the exoskeleton on

[1] The STOP principle defines the hierarchy in which companies should reduce the worker's exposure to dangers: 1.: Substitution measures, 2.: Technical measures, 3.: Organizational measures, 4.: Personal measures

only one of the places needs to be considered (workplace-rotation). To enable this time-boxed use and quick transitions between workplaces, appropriate design decisions must be made. Therefore, it should not disrupt tasks at other workstations, requiring a stronger focus on the exoskeleton's dynamics. If it is only used at one of the stations within the workplace rotation, it should be designed for quick and easy setup to avoid disrupting the workers processes.

The collected data can determine which kind of task needs to be assisted and which motions or postures the exoskeleton needs to support. This also defines the limbs that the kinematic has to follow and gives a first solution space for the type of actuation and what materials are suitable for the occurring forces. Therefore, a category of exoskeleton as described in Section 3.1 can be set. During the project, a decision-making matrix for choosing potential market-ready exoskeletons was developed (Harbauer and Bengler, 2022). Similarly, this can also be used in this context to find the fitting category of exoskeleton to develop for the addressed context of use (Table 1 and 2).

Assisted body region

Hands If manual handling operations and grasping is the most common task, e.g., upholstery or assembly of heavy small objects.

Arms If manual lifting, holding, and carrying loads or manual pushing and pulling of loads are the main tasks. Static postures need support if working overhead or with the arms reached far out. Further, any high dynamic motions in the elbow or shoulder with forces or loads over the recommended limits according to the LMM (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2019).

Lower back and hips If manual lifting, holding, and carrying of loads in combination with bending down over 20° is the main task. For static postures, support is needed if working stooped over 20°. Further, any high dynamic motions in the lower back forward, sideways, or rotated with forces or loads over the recommended limits according to the LMM (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2019).

Legs If long distances and locomotion periods are the most straining tasks. If static posture support is needed if people are working in a kneeling position most of the time. Further, any high dynamic motions in the knees and ankles with forces or loads over the recommended limits according to the LMM (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2019).

Sitting Another possible kind of exoskeleton is the one that supports sitting in workplaces where the workers stand most of the time, and there is no space or possibility for furnishing with chairs. In terms of static postures, those exoskeletons support working in awkward operating heights, e.g., in maintenance.

Type of actuation

The choice of actuation type depends on the forces that need to be assisted and the dynamics of the repetitive motion. As discussed in Section 3.1, passive actuation is more suitable for supporting static postures or lower weights and movements with low dynamics. Passive exoskeletons have the advantage of being relatively lightweight. Therefore, the weight-to-assistance ratio of the exoskeleton is better when the forces are lower. But the principle must be followed that the passive actuators are pre-tensioned by

Table 1 Matching between posture and assisted body region. Fields marked with "x" show the potential matches.

	Body Posture								
Supported Body Part	Upright	Seated	Arms Over-head	Reaching Far	Upper Body Rotation	Stooped	Kneeling	Standing	Laterally Leaning
Grasping									
Arms			x	x					
Lower back					x	x			x
Legs							x		
Sitting								x	

Table 2 Matching between motion and assisted body region. Fields marked with "x" show the potential matches.

	Main Motion											
Supported Body Part	Grasping	Shoulder Eleva-tion	Shoulder Abduc-tion	Elbow Flexion	Wrist Flexion	Lumbar Rotation	Inklination	Hip Ab-duction	Knee Flexion	Foot Flexion	Walking	Elbow Supina-tion
Grasping	x											
Arms		x	x	x	x							
Lower back						x	x					
Legs									x	x	x	
Sitting												

bigger muscle groups or with gravity compensation, and the energy from recuperation supports smaller muscle groups. Active actuation is preferable if this principle cannot be fulfilled.

Kinematic structure

Anthropomorphic kinematics have the advantage of being closer to the body and, therefore, potentially more suitable for contexts of use in crowded spaces. The factor of aesthetic appeal might also play a role in that, since non-anthropomorphic structures might change the appearance of the wearer's body shape, as can be seen in the results from the "Robo Mate" Project (Altenburger et al., 2016). But depending on the supported limbs, building a structure that allows full degrees of freedom results in high complexity, for example, for the shoulders. Depending on the context of use, a middle ground between those two variations must be identified. Based on the literature, this provides an initial estimation of the suitable kinematic structure for the analyzed context of use. Suitability must be evaluated during the exoskeleton's development to determine the optimal type of structure for this specific application.

Basic materials

Literature suggests that soft exoskeletons are only suitable to support lower forces, and higher forces should be transferred with rigid material away from the body. So, lighter weights, postures, and forces can be considered to be supported with soft materials since the force in itself is not the issue but rather muscle fatigue due to static holding or the repetitiveness of the motion. As soon as the forces are in a critical area to damage joints, at least partially rigid structures should be implemented to reduce the strain on the joints. Since hybrids have a mixture of soft and rigid structures, another material might be more suitable depending on the context of use and the supported limbs. This can be verified with a preliminary calculation of the potential human-machine kinematic chain. This categorization based on the workplace assessment offers an initial estimation of the appropriate basic materials for the analyzed context of use. Hybrid designs, which incorporate both soft and rigid elements, are probably the most favored option. This initial estimation serves as a starting point for determining the optimal combination for this specific application, which must be further evaluated during the development of the exoskeleton.

This process that is matching the workplace assessment with exoskeleton categories offers the possibility to identify a starting point for the development process.

4.2.2. Additional Results from Assessment of Existing Exoskeletons

The checklist presented in Section 4.2.1 can be used to analyze workplaces and derive requirements for exoskeleton development. The matching process presented in Section 4.2.1 offers the possibility to assign exoskeleton categories to the assessed workplaces. It the context of the thesis it will be used to generate a starting point for the development process.

In the project "LEXO-FA" the matching process was utilized to identify, existing market-ready exoskeletons based on the exoskeleton categories for the analyzed workplaces (Harbauer and Bengler, 2022). Unfortunately, no exoskeleton on the market fits the requirements perfectly. This reinforces one fundamental motivation behind this research in occupational exoskeletons, addressing the need for exoskeletons specifically designed for individual contexts of use. Within the project, market-ready exoskeletons that closely matched the identified categories were identified. Two passive back support exoskeletons for lifting and carrying and one active hand exoskeleton designed to support gripping and holding tools or loads were selected. The exoskeletons were tested in three partner companies within the project, two of each exoskeleton for four weeks in each company. They were instructed to test them with the same two people over the whole four weeks to evaluate not only the initial usability and suitability but also get an insight into the learning procedures of the people and evaluate the usability and suitability after a more extended use time. Unfortunately, the full four weeks were never met due to various factors within the companies. In two companies, the acceptance was relatively low, and the workers did not want to wear the exoskeletons for a longer time. In one company the acceptance was relatively high in one workplace, so they decided to test it in other workplaces as well for two weeks.

The experience showed reasons for good or bad acceptance of the exoskeletons in the workplace:

Side tasks As already shown in literature, hindering side tasks with different movement patterns was one of the biggest issues. For example, workers wearing the passive back exoskeleton were not be able to fit into their forklifts due to the kinematic structures of the systems.

Collisions with the environment Some side tasks were hindered because users could not fit into places, e.g., to refill materials or do maintenance. In some forklifts, they could not fit in with the mechanical structures on their bodies and, therefore, could not fulfill related tasks while wearing the exoskeleton. But even during the main tasks of lifting loads, the exoskeletons collided with the tables or the containers from which the handled goods had to be put or provided.

Social factors The other reported biggest factors were social factors among the staff and between workers and their management. If the whole workforce was positive towards the exoskeletons, the acceptance was distinctly higher than in companies where either members of the leadership or influential colleagues were negative towards exoskeletons. Bullying due to the changed physical appearance and bad previous experiences from other workers led to people not even wanting to try or disregarding the exoskeleton even though they reported experiencing beneficial effects. A positive mindset and workers helping each other learn how to use the system positively impacted the long-term use.

Tool use The placement of the exoskeletons on the body led to workers being unable to access their pockets or the tools they need for their work, e.g., mobile devices or cutter knives.

Effort to use ratio The relation of use to effort must be very high. This relates to the percentage of time the assistance is needed throughout the time it is worn, and it also induces the effort to put the system on. The pain relief due to the exoskeleton has to be higher than the pain of putting it on and carrying the extra weight around Monica et al. (2021). The best acceptance of the system is reported when only the supported movement is done consecutively.

Easy and quick setup To achieve a high effort-to-use ratio, an easy and quick setup and adjustment is mandatory. Visits at the workplaces showed that exoskeletons were not adjusted correctly and therefore caused chafing, about which the workers complained and did not want to use them anymore. In workplaces with good acceptance, the exoskeletons were only used by one person, so they could just put it on and take it off easily when needed, and the hindrance with other tasks did not come into effect.

Duration of assisted tasks A good effort-to-use ratio was reported when the exoskeleton was only put on for that task needing assistance. But for this to be feasible in work processes, the assisted task requires a specific time frame for the worker to be willing to put on the system. Within the project, the task it was explicitly put on lasted around 1-1.5 hours.

Easy to use during their work tasks The assistance of the exoskeletons could be switched on and off while wearing it. That mechanism did not always work smoothly and disturbed users' workflow, leading to longer handling times and frustration.

Time for learning Training on how to use and adjust the system should take place outside of the work cycle so workers have time to learn and ask questions without pressure. Also, frequent check-ins in the first hours and days when the workers are still learning to work with the system are essential. So frustration can be avoided, and minor adjustments in wrong settings can be made before the resulting adverse effects appear in long-term use. Examples are the anthropometric adjustments made on the first day of use, which might not be the most comfortable ones in long-term use due to the different preferences of the users.

Setting realistic expectations The workers and the management must have realistic expectations about what the exoskeletons can and cannot do. If the ability to lift higher loads is expected, the disappointment will negatively impact the system's acceptance if that expectation is not met. The goal must be moderate assistance to relieve strain and improve long-term health. In one company, some workers within the study reported lower back pain at the end of the week when using the exoskeleton, which motivated them and others to use the systems even more.

Organizational requirements Time for learning, time for putting on and taking off, storage, especially for time-boxed use directly at the workplace, needs to be well communicated and cared for from the company side to take stress from the workers and make the use of the exoskeleton additional to daily work routine less bothersome.

The successful applications within the project for the exoskeletons were for consolidated tasks with the same motion pattern over a longer time. In this case, they were packing all the produced items at once for around 1 - 1.5 hours after testing them for a few hours without wearing the exoskeleton. Or when working with a batch of products of a certain weight and size had to be worked with. After the project, one company resorted to buying a soft lower back assistance system that could be consistently worn throughout the day. It only offers a little assistance compared to the bigger exoskeletons but does not interfere with anything else. With that system, a good acceptance is reported, even though it is also reported to not be quite "enough."

Not all of these findings can be solved by the exoskeleton design and must be cared for when the exoskeleton is implemented in the company. These are especially the organizational requirements and the social factors related to workers' expectations of the exoskeleton. Either from the developer's side with an implementation service or from the company side with the help of the developed guidelines that are the result of the project "LEXO-FA" (Harbauer and Bengler, 2022) or similar projects (Ralfs et al., 2022; de Looze et al., 2021; Kaupe et al., 2021).

The resulting list of requirements for exoskeletons in occupational workplaces is extensive, and designers need to keep many aspects in mind. Especially requirements that come from the workplace usability side and are not essential to human matching interaction or functionality, like the accessibility of pockets and other tools, are easily forgotten and have a low priority. Still, they have a high importance for future users. Additionally, international norms, which are only briefly mentioned in this chapter, also open another subset of requirements that designers must follow. The identified design principles in Section 4.1 give a guideline and with the presented method in Section 4.2, those can be translated into independent, quantified, and measurable requirements for each context of use.

5. Evaluation Methods for Early Development Stages

Now that the requirements are set, they must be implemented in exoskeletons for their specific contexts of use. As Lindemann (2005) declares, changes in product development are more expensive the later they are made in the process. Therefore, the requirements regarding human-machine interaction need to be evaluated in the early stages, where there is no physical prototype yet or where the exoskeleton is not yet usable with humans. Literature suggests several quantitative and qualitative tools to evaluate designs in early development stages, "In Vitro, In Vivo, and In Silico" (Zheng et al., 2021). The following chapters present state of the art methods suitable for evaluating exoskeletons in their early stages of development. Especially in the case of user observations and interviews (Section 5.4) and expert interviews (Section 5.5), it is essential to adhere to established rules and guidelines to ensure that these tools are valid, reliable, and objective.

5.1. Kinematic Analysis

One of the first steps in designing robotic devices is developing the kinematic chain for the desired trajectories. This approach is also represented in the exoskeleton development methodology by Heidari et al. (2018). Depending on the possible simplifications, that helps to understand the interactions between the human and the exoskeleton. For higher degrees of complexity, especially when integrating *dynamics*, this approach exceeds the classical "pen and paper" approach and benefits from being simulated. To design the exoskeleton in a human-centered way, as requested in Section 3.1, the whole kinematic chain of the human and exoskeleton needs to be modeled.

In the case of anthropomorphic exoskeletons, it is crucial that the axis of the exoskeleton and the human in every pose and during the whole movement align. An example of a thorough kinematic analysis and a resulting optimization of an exoskeleton is the work of Jarrasse and Morel (2011). Due to the complex structures of human joints, the rotation centers of the joints change during the motion Kapandji and Rehart, 2016. Thus, modeling is challenging and can only be done sufficiently with simulation tools. Complex mechanical structures are necessary to ensure the human joints' rotation centers are coaxial with the exoskeleton joints. Otherwise, the force is not transferred between the human and the machine in the intended way. It misaligns with the resulting adverse effects, as described in Section 4.1. Examples in the literature show that a thorough analysis of the kinematic human-machine-chain considerably increases the quality of the resulting exoskeleton (Jarrasse and Morel, 2011, Cempini et al., 2013, Li et al., 2017, Sarkisian et al., 2021).

The complexity of the model needs to be as simple as possible but as close to reality as necessary, especially for anthropomorphic exoskeletons that try to replicate human kinematics. Here, the rotation centers of the human and exoskeleton joints have to be coaxial Mallat et al., 2019. Due to the complex anatomy of the human joints, the models of the *dynamics (kinematics)* need to account for the changing rotation centers as explained in Section 4.1. The models of Cempini et al., 2013, Li et al., 2017 and

Jarrasse and Morel, 2011 account for that. The latter even includes soft tissue deformation through the forces acting on the human body at the *pHMI*. A solution for aligning the rotation centers is the inclusion of a self-alignment mechanism or additional joints, either at the joint itself (Cempini et al., 2013, Masud et al., 2021, Li et al., 2020, Vitiello et al., 2013 (three joints)) or at the *pHMI* (Näf et al., 2018, Sarkisian et al., 2021, Jarrasse and Morel, 2011).

Non-anthropomorphic exoskeletons do not need to adapt to complex joint geometries. Still, they must replicate the human trajectories without encountering singularities or shearing forces at the *pHMI*. Examples are Higuma et al. (2018), Christensen and Bai (2018), and Moser and Lueth (2019)).

5.2. Biomechanical Simulation

Biomechanical simulation is a tool to extend the possibilities of biomechanical analysis. It is utilized to show and predict forces and strain within the human body. Strain in joints and muscles can be calculated based on physical effects within the human body and forces acting on the body. Biomechanical simulations are multibody simulations consisting of bones as rigid bodies connected with joints associated with certain degrees of freedom and muscles, represented as line actuators, that drive the kinematic chains. The geometries of the bones and the resulting constraints are taken from scans from cadaver studies. Also, the effect of tendons acting on joints and resulting in internal forces during motion are implemented based on medical studies, as well as the motion behavior of the muscles and the individual power spectrum. In sports science and ergonomics, biomechanical simulation is a well-established tool to evaluate the effect of movement patterns, working tasks, and external forces induced by machines on the human body. The most developed software available is the commercial product Anybody Modeling System and the open-source application OpenSim (Delp et al., 2007) by SimTK and BoB simulation.

In literature, biomechanical simulation software such as OpenSim or Anybody is used to assess the effect of exoskeletons.

Fritzsche et al. (2022) used the Anybody Modeling System to evaluate the effects of the upper body exoskeleton "paexo shoulder" by ottobock during overhead tasks. They evaluated the results by comparing them with EMG data from a laboratory study with 12 participants. The defined simulation and laboratory study tasks were drilling overhead with and without the exoskeleton. The results between both tools were reported to be similar, showing a distinct decrease in relevant muscle activities. Further, the simulation provided insight into joint forces, a parameter that cannot be validated with a non-medical laboratory study. With this study Fritzsche et al. (2022) suggests that biomechanical simulation is a valid method to assess the effects of exoskeletons on the human body during working tasks. The accuracy of the predicted values is highly dependent on the used human model (Quental et al., 2013Roelker et al., 2020) and exoskeleton model, as Niessen (2021) showed with his work on an exoskeleton that was developed during this dissertation project. This will be described further in Section 7.3.3.

The study mentioned above uses already fully developed exoskeletons for biomechanical simulation, but the principle is suitable for evaluating new concepts or exoskeletons in early development stages. The works of the research team around Prof. Mombaur in the EU-founded exoskeleton project "SPEXOR" (Babič et al., 2017, Babič et al., 2019, de Rijcke et al., 2017) showed how biomechanical modeling can be used for developing and optimizing motor and spring characteristics, as well as control strategies (Harant et al., 2017, Harant et al., 2019, Manns and Mombaur, 2017, Manns et al., 2017, Millard et al., 2017, Schemschat et al., 2016, Sreenivasa et al., 2018, Sreenivasa et al., 2016). During this project, they further developed their own biomechanical models and simulations toward specialized questions for exoskeleton development, especially regarding *dynamics* and *pHMI*.

Also Agarwal et al. (2010) used a simulation-based design approach to simulate the effects of a simplified active elbow exoskeleton in four case studies on the human body. They focused on the effect of the applied torque and the impact of the exoskeleton structure. As parameters, the muscle forces and the elbow flexion moment are chosen. To create the simulation models, the authors used the AnyBody Modeling System. The baseline is an arm curl with a dumbbell, meaning the muscle performance values are the reference for the exoskeleton's performance in the other three cases. The simulation is then conducted with different assistive torques. The first case is the "Idealized Constant Moment Assistive Mode," a virtual torque at the elbow joint providing a constant moment. The second case is the "Idealized Variable Moment Assistive Mode," where the virtual torque exactly meets the torque requirement for ideal assistance for the human. Only in the last case, the "Assistive Mode," the exoskeleton is modeled, and the influence of the exoskeleton with the variable moment is simulated. Only there the effect of the kinematic constraints by the exoskeleton becomes apparent.

Tröster et al. (2020) used biomechanical simulation in two parts of their development process. First, they identified critical motions and positions with the Anybody Modeling System. They developed a preliminary exoskeleton concept for that specific application to support healthcare workers in the surgery waiting room. For this, they used motion data taken from the workplace. The active upper extremity exoskeleton was optimized with the person and application-specific data. The optimization method is a loop with different steps of implementing person and application-specific data, like anthropometrics, motion, and force data. The exoskeleton–human simulation model computes a kinematic and inverse dynamic analysis. The resulting muscle activation, joint reaction forces, and moments are used to evaluate and identify optimization potential in the exoskeleton iteratively. In Schiebl et al. (2022), they advanced the method to optimize a passive shoulder exoskeleton for overhead lifting tasks in logistics. The resulting joint reaction forces and muscle activities compared six concepts that varied in DoFs. Similarly, Bae (2013) used OpenSim to answer design questions for their gait support exosuit. The effect on the metabolic cost showed the most favorable configuration.

Biomechanical simulation can also be used to optimize and evaluate the motor control of active exoskeletons, as Gonzalez-Mendoza et al. (2019) showed for their use-case of elbow flexion. They used OpenSim to evaluate a proportional-derivative controller. As mentioned before, Agarwal et al. (2010) also used this method with Anybody Modeling System to identify the effects of the different assistive torques acting at the elbow, which sets the basis for future controller design.

Biomechanical simulations are good tools for evaluating the kinematic effects of exoskeletons. However, they do properly represent a realistic physical human-exoskeleton interaction. Those models do not sufficiently represent the influence of soft tissues between the exoskeleton and the bones Scherb et al., 2022. Inose et al. (2017), de Kruif et al. (2017), Tröster et al. (2018), and Zhou et al. (2017) show approaches to calculating the effect of the exoskeletons' *pHMI* in biomechanical simulations, but they need the actual pressure distribution or study data for a realistic implementation. Further, the force transmission concerning the non-linear viscoelastic behavior of the soft biological tissue is not yet considered in any published modeling approaches (Scherb et al., 2022). So, DHMs are not suitable to be used in early development stages for examining interaction forces between exoskeletons and humans.

5.3. Test Stand

With active exoskeletons, testing actuation set-ups and control algorithms directly on humans does not fulfill the three aspects of a good measurement method. Due to the human factor human in the testing system, it might not be reliable and objective. Depending on the exoskeleton setup, it might be a risk to the person wearing the exoskeleton. Especially when the exoskeleton frame is not entirely rigid, as for soft exoskeletons or exosuits. The use of test stands in early development stages is state of the art in many other research areas, like motor or turbine development. Using test beds and simulators is common practice in the field of ergonomics, especially when the well-being of humans is at risk. Therefore, test stands are a suitable tool to test actuation modules, assess sensor configurations, and evaluate the effect of different control algorithms in the early development stages of exoskeletons. However, only a few publications regarding the use of test stands specifically for exoskeleton design exist.

Jäger et al. (2023) uses an elbow test bench to test control algorithms for an antagonistic exoskeleton. The test stand consists of the arm exoskeleton experimental platform model fixed to a dummy "upper arm" and a dummy "lower arm" that the exoskeleton moves. The human joint is not represented in this test stand. So, the effect of the antagonistic actuation on the exoskeleton and the human trajectories can be studied. However, this kind of test stand does not account for the exact structure of the human joint. It remains to be determined whether more realistic models of the human arm in test stands would be more valuable for developing suitable actuation modules, especially if human biomechanics' active and passive components can be accounted for (Lenzi et al., 2011).

5.4. User Observations and Interviews

In Product development, a participative design of systems is commonly used, especially for user-centered design approaches. One way is to test early prototypes or concepts with users. Their interactions and exoskeletons' behavior in their desired contexts of use can be observed. An additional interview can bring insights about the perceived ease of use (Section 4.1) and the perceived usability. Further, they can give insights into optimization potentials or future challenges the design might encounter in their daily working tasks.

Participant observations are the "systematic description of events, behaviors, and artifacts in the social setting chosen for study" (Marshall and Rossman, 2016). They are a favorable tool for studying participants in the field (Kawulich, 2005; de Munck and Sobo, 1998), and they offer the possibility to learn about their activities in their day-to-day settings and situations (DeWalt and DeWalt, 2011; Schensul et al., 1999). Further, the exposure to the participants' work environments and tasks offers many insights into their requirements and needs for a new assistant system. It is crucial to understand how certain activities are performed and how much time they spend on them (Schmuck, 2006), especially in the research with exoskeletons, where not only the supported main task is of relevance, as described in (Section 4.2), but also the side tasks and the time percentages of them. So, this method is useful to define the potential and requirements for a new exoskeleton at a specific workplace and the usability of early prototypes in them. To conduct a participant observation, it is essential that the observers do not interfere too much and that the observed act as naturally as possible (Bernard and Ryan, 1998). This method depends highly on the perception of the observer and the observed situations, which are very individual and not reproducible (Mackellar, 2013). The validity and reliability of this participant observation are not given, and generalizations are not possible (McCall and Simmons, 1969; LeCompte and Goetz, 1982).

Based on the insights from the observations, interview guides can be developed to gain a deeper understanding of how the workers' environment works and understand why they are acting in specific ways (Kawulich, 2005; Schensul et al., 1999). In social science, using interviews is common as a qualitative research method to understand human behavior and impressions within a defined context (Alshenqeeti, 2014). It focuses on narrative data to explore and describe the quality and nature of people's behavior, experiences, and understanding (Dean Brown, 2008). They allow individuals to express their thoughts and feelings in their own words (Berg, 2012). Unlike quantitative methods, qualitative approaches analyze data while considering the social context of participants. Interviews are considered a key element in research design as they effectively explore constructs that are not directly observable (Kvale, 2005). Interviewing is seen as "a natural and socially acceptable" (Dörnyei, 2012)) method of data collection that can be used in various situations and topics. Interviews are a suitable tool for studying early design phases because they enable obtaining direct explanations for human actions through interactive and comprehensive speech interactions.

Shore et al. (2020) developed a tool consisting of three phases to evaluate exoskeletons, the so-called "Exoscore." The phases are first "Perception," second "Experience," and third "Perceived Impact." In "Perception," the participant is shown a prototype, design, images, or video of the exoskeleton and a questionnaire they must complete. The phase "Experience" is a usability test with the exoskeleton prototype and a SUS-based survey. The last phase, "Perceived Impact," contains a final questionnaire regarding the perceived impact they think the exoskeleton might have on them. As a result, a score that represents the exoskeleton's potential acceptance based on technology acceptance models is calculated. The application is repeated including an iterative evaluation during the development and testing.

Even though it is advantageous to get insights from future users with their specific social contexts, their contexts also need to be considered when analyzing the data. Especially when confronted with a new technology, industry workers might be unable to fully understand the purpose or functionality and, therefore, unable to grasp the implications of the presented system in their workplace. So when the prototype is not usable yet or in a very rough state, user interviews and observations might not lead to valuable data or even deter from taking the next necessary development steps. Additionally, in the field of exoskeletons, where social acceptance plays a big part, as described in Section 4.2, a not desirable or faulty prototype might prematurely scare off future users and their entire social working group. Tools for user interviews in exoskeleton evaluation range from standardized tools, like the NASA TLX, the Borg scale, or the System Usability Scale (SUS), pain detection threshold (PDT), or paint tolerance threshold (PTT), to custom questionnaires specifically designed for the study or exoskeleton (Massardi et al., 2022; Sposito et al., 2019; Schiele, 2009). Most are explored in Section 3.3. An alternative to that is the expert interview, which is described in the next Section 5.5.

For the evaluation of exoskeletons and their effects on the users body, a long term study is necessary. This is also necessary for evidence of efficacy, if the exoskeletons are achieving their goal of health benefits and reduced risk of developing musculoskeletal diseases. There are not enough studies to give a clear recommendation how long field studies with exoskeletons should be, with projects ranging from six weeks (de Vries et al., 2022) to 18 months (Kim et al., 2021).

5.5. Expert Interviews

As described before, depending on the development stage, the interview of experts is the tool of choice rather than the input of inexperienced users. Expert interviews are defined by the interviewees' unique selection and status. They provide insights from people who are experts in a particular field that is of interest to the research topic. In the case of exoskeletons, this applies to people with expertise with exoskeletons or physical assistance systems in general and people from industries with experience using those or similar kinds of assisting technologies in the field. As described in 5.4, they give the interviewer in-depth knowledge and opinions about their area of expertise. The interviews can be designed as a workshop, where new ideas for specific solutions can be generated with design sprints. Or they can be in the shape of traditional interviews. Often, they are in the style of an open-ended or semi-structured interview. In this case, the benefit of a semi-structured interview is the individual and subjective assessment from the expert. The approach helps in obtaining their perspective to answer the research question (Helfferich, 2011). Since the questions are not in a fixed order and can be adapted spontaneously, the flexibility in the interview makes it more natural and helps get deeper insights from the fields of interest (Helfferich, 2011; Mayring, 2016). The structure gives an outline, helps with documentation, and focuses the interview on the desired topic (Misoch, 2019). The designed guideline also helps with the expert interviews' comparability and repeatability.

5.6. Summary of Evaluation Methods for Early Development Stages

The evaluation methods presented focus on those executable at an early development stage, where only a concept of the exoskeleton or a rudimentary prototype exists. Kinematic analysis and biomechanical simulation are well-suited for assessing initial theoretical concepts. These methods can be performed using highly abstract models, relying solely on pen-and-paper analysis and computational resources. Test stands and expert interviews, on the other hand, can be used with basic prototypes to perform reality checks. For instance, force transmission can be evaluated using a test stand, while expert feedback can assess the exoskeleton's usability for the intended tasks. User observations and interviews require a more advanced prototype designed for user interaction. While not fully finished, these prototypes should be sufficiently developed to evaluate aspects such as comfort and usability.

Additional evaluation methods exist, such as test courses (Ralfs et al., 2021), motion tracking studies (Schmalz et al., 2019; Ralfs et al., 2021), or laboratory and field studies using specialized equipment like EMG (Huysamen et al., 2018a; de Vries et al., 2021; Ralfs et al., 2021) or heart rate monitoring (Moyon et al., 2018), but are not used in this thesis and are therefore not elaborated further.

The evaluation methods discussed are integrated into the development process. As outlined in chapter 5.4, long-term field studies require a nearly fully developed exoskeleton and are more appropriate at the later stages of development.

6. Development Process for Design and Development of Exoskeletons for Occupational Use

In the previous chapters, necessary aspects to build a development process for exoskeletons have been outlined. First, in 3.3, already available exoskeleton-specific processes were discussed and relevant methods isolated. Additionally the HCD process and agile principles were described to get a deeper understanding on both mindsets and and key features of both. In section 3.5, key components for HCD exoskeleton projects were defined, following Bengler et al. (2023) process, which emphasizes exoskeleton components building onto each other, thus breaking down the intricate project into more manageable subprojects. Secondly in Section 4.1, design principles for occupational exoskeletons were synthesized. The methods from Section 4.2 for workplace assessment and identifying fitting exoskeleton categories from Section 3.1 to workplaces, can be utilized to define requirements based on the design principles in Section 4.1. Thirdly, in Section 5, evaluation methods that are valuable in early development stages and their application for exoskeletons were described. In the following, these are united into one novel development process.

This aims to establish a novel development process that integrates agile methodologies and human-centered design (HCD) principles, specifically targeting the *key components* of exoskeletons that closely interact with the user. This process encompasses strategies for defining user and context-specific requirements through design principles and workplace analysis, as well as methods for early-stage evaluation of these requirements. Building upon the foundations of existing development processes outlined in Chapter 3.1, this approach synthesizes these elements into a comprehensive and innovative framework, addressing gaps in the current literature and offering a novel development process.

This will be applied in two case studies in Chapter 7 and 8 to develop ergonomic exoskeletons for lifting and carrying.

First the development process will be described for active exoskeletons (figure 6). Since they integrate all key components as defined in Section 3.5.
The novel development process consists of five steps. In the first step, the requirements for the decided context of use are defined based on the design principles from Section 4.1. These are translated into requirements for the key components. The second step is the design of the *dynamics (kinematics)* concept, since this is the baseline for all other components. The concept is evaluated on its own utilizing methods described in Section 5 and iterated, until the requirements of the *dynamics (kinematics)* are met. In step three the hardware components *dynamics (actuation)*, *pHMI*, *sensors*, and *UI* are developed and iterated in parallel. While *dynamics (actuation)* and *pHMI* start at the same time, the placement of the *sensors* and the necessary functions of the *UI* are dependent on the other components, therefore those start when the first designs of the other components are set. Similarly to step two all four key components are evaluated for themselves and iterated until all requirements are met for each key component. Although the components can largely be developed independently, there are interfaces between them that establish technical boundary conditions for one another. For instance, the integration of neces-

sary sensors may impact the design of the *pHMI*. This is illustrated by arrows connecting the boxes that represent the *key components* in figure 6. In step four all the independently developed components are joined into a full exoskeleton. Meanwhile the *control* is developed, integrating the inputs and outputs from the components *dynamics (actuation)*, *sensors*, and *UI*. The control is evaluated and iterated in itself, as well as with the fully integrated exoskeleton hardware, until the control requirements are met. Afterwards, the full exoskeleton is evaluated using user involved methods, as they are presented in Section 5.4 and 5.5. If the *general design* requirements are not met, the process is iterated. Depending on the identified issues, it can restart at any of the previous steps. If the requirements are met, a long term study can be conducted, evaluating the long term benefits of the exoskeleton. If the efficacy cannot be proven, the basic design premise of the exoskeleton needs to be reevaluated (not depicted).

Figure 6 displays the proposed development process.

Step one: Define requirements

Similar to the first two steps of the HCD, this step is based around understanding the context of use and deriving requirements based on it. With the design principles in appendix C and the method described in Section 4.2, all important requirements for the exoskeleton can be identified, defined, and, if possible, quantified. Therefore the checklist can be used to identify requirements in the considered workplace. These include:

- Motions or postures that need to be supported by the exoskeleton to identify necessary assisted DoF
- Forces that need to be supported
- Motions of side tasks to identify passive DoF
- Anthropometric adaptations for the limbs the exoskeleton supports
- Narrow places in the environment
- Tools that need to be used for the main and side tasks
- Operation times: if there is a shift system with a change of user and if whole shifts or time-boxed use is intended
- Available times for set up
- Available space for storage
- Environmental factors, like dust, chemicals, or outside use

Further, the matching between workplace requirements and exoskeleton categories (Section 3.1) can be utilized to identify what type of exoskeleton should be designed in regards to assisted body region, type of actuation, kinematic structure, and basic materials. The requirements can further be defined using tools like motion capturing (Tröster et al., 2018), simulation (Tröster et al., 2020), or fundamental literature like Kapandji and Rehart, 2016, Zeagler, 2017, or norms like DIN 33402. Another tool to define the requirements for the key components is defining a user story to understand how a future user could

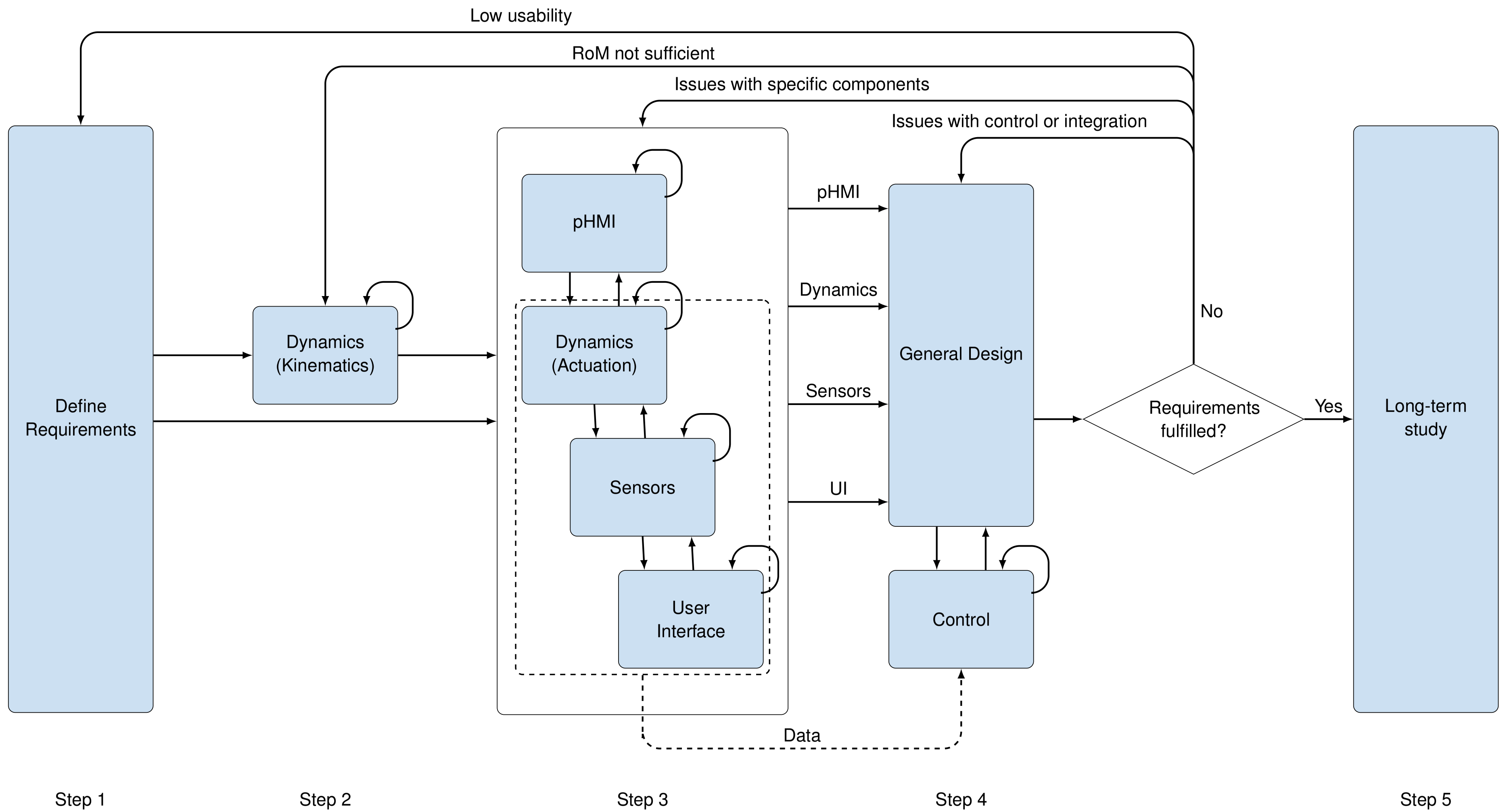

Figure 6 Five-step development process for active ergonomic exoskeletons in occupational context of use: Step 1 – Define requirements, Step 2 – Design and evaluate kinematics, Step 3 – Design and evaluate pHMI, actuation, sensors, and UI, Step 4 – Design and evaluate Control and integrate all components into the general design, iterate earlier steps if requirements are not fulfilled, Step 5 – Conduct long-term evaluation.

use the exoskeleton in the defined context of use. From this, more detailed requirements for the singular subcomponents can be defined. For example, how the structure should be put on determines the types of *pHMI*. Further, it can be defined which kind of data should be available to be detected by sensors, especially for detecting the exoskeletons' state and the user's intent.

Step two: Design of a kinematic concept

After defining all requirements of the users and the context of use, the next step is to find a suitable kinematic structure, since it is the basis for all other key components. As the literature shows, this key component needs the most attention. Similarly Bengler et al. (2023) start their iterative and incremental process for exoskeleton development with the kinematic structure without any actuation, to ensure biomechanical compatibility and full degrees of freedom. Based on this, it is the first step in the novel development process, where the other key components build upon. Therefore it has the most focus in the description.

First iteration: Opening the solution space and defining a new kinematic chain The matching method in Section 4.2 can be used to match requirements with exoskeleton categories. Based on these and the derived requirements, the solution space can be opened, and possible designs can be derived. It is recommended to include existing solutions, but also to find new opportunities. In the sense of design principle D.7 (low complexity), experimenting with function integration of different DoF in one exoskeleton joint should be explored. Several tools are suitable for this ideation phase, as described in Lindemann (2016) or Begnum (2021), such as creative methods or rapid prototyping. As described in 5.1, kinematics can be evaluated at a very early stage to determine the forces acting on the connections between human body and exoskeleton. Kinematic analysis verifies that the redistribution of forces within the body is consistent with the idea that forces are shifted from sensitive body regions to more resilient areas. Also, first estimations on the necessary material properties are possible.

Second iteration: Optimizing the structure Using numeric methods and simulation tools, like Matlab Simulink or biomechanical simulation tools as described in 5.2, the structure's design must be optimized. The goal is to optimize the force transfer between human and exoskeleton. The arrangement of various attachment points has an impact on how forces are distributed and, in turn, affects the reduction of muscle activity and joint reaction forces.

Third iteration: Kinematic prototype Before further developing other aspects of the exoskeleton, the kinematic structure should be built as a prototype, and its behavior should be tested in real life. This is the only way to assess kinematic compatibility and determine if the joints are responding in the intended manner. For initial testing, rudimentary *pHMI* are sufficient since no forces are acting on the structure. This should be evaluated with the intended users and context of use. However, as described in 3.4 in the HCD, this has to be conducted with diligence since users might get the wrong idea once they are confronted with a very early prototype and might not give valuable feedback. Further, it might reduce the intention to use the exoskeleton in future development states, as the experiences in Project LEXO-FA (Harbauer and Bengler, 2022) show. Thus, evaluation with experts is a suitable alternative.

Evaluation methods: Kinematic analysis, biomechanical simulation

Step three: Parallel development of actuation, pHMI, sensors, and UI

Since the kinematic structure is the basis for all the other concepts, it defines essential boundary conditions for the actuation part of the *dynamic*, the *sensors*, the *pHMI*, and the *UI*. Those together define the static and dynamic input parameters for the *control*. Since the subcomponents also influence each other multilaterally, they should be developed in parallel. However, since they have defined boundaries, they can be designed individually and tested separately from the rest. It is recommended to start with the actuation part of the dynamics, which also defines the start of the *control* development for active exoskeletons. Building on that, the *pHMI* can be designed next to the *sensors*, if applicable, and the *UI*. To ensure that the subcomponents are well brought together in the fourth step correctly, interfaces and interactions must be defined. A suitable tool would be describing them in a dependency matrix (Lindemann, 2016). Similar to step two, first the solution space should be opened up, explored, and a suitable solution that fits the requirements must be identified. Then they should be iterated to optimize the solution, by utilizing the methods described in Chapter 5.

Dynamic An actuation system has to be identified as active, passive, or both, that fits the kinematic structure and improves the capabilities in terms of **compliance**, **low inertia**, and **misalignment compensation** (see Section 4.1.2). First the solution space needs to be opened by identifying suitable actuation systems and exploring which one is most compliant with the *dynamics kinematics* and fulfills the requirements for the assistance.
These attributes can be evaluated and optimized using the test bench. The resulting inputs and outputs for motor control are part of the development of the *control* in step four.
Evaluation methods: Test bench

pHMI The pHMI needs to be designed with the identified requirements from Section 4.1.3, the requirements from the user story, and the boundary conditions from the kinematic structures. To open up the solution space, different ways to attach the *dynamics* to the human body and transfer the assisting forces need to be explored. Also suitable materials have to be identified and tested. The first design can be evaluated with biomechanical simulations or FEM to ensure an even pressure distribution, mechanical strength, and the absence of pressure peaks. In further iterations, the physical prototype can be evaluated in combination with the kinematic prototype and in expert interviews.
Evaluation methods: Test bench

Sensors With the dynamics and the *pHMI* being defined, available spaces to place sensors and potential data from the exoskeleton become obvious. The solution space depends on the assisted motions and the addressed limbs. There are various types of sensors and concepts to detect human intent suitable for the application. For example, for predicting a cycling motion like walking, some authors argue that the data of onboard sensors might be sufficient for motion prediction (Young and Ferris, 2017). But for other motions, a multisensory system including human biosignals is recommended to give a fast and reliable prediction (Young and Ferris, 2017, Chen et al., 2020, Viteckova et al., 2018, Massardi et al., 2022). Even though EMG is the best and most commonly used method of acquiring biosignals, there are several others with higher usability in occupational contexts of use and similar data quality, such as force sensing resistors (FSR) (Sun et al., 2022, Viteckova et al., 2018), Young and Ferris, 2017).

Evaluating the decided sensor concept can be tested without the other components in user and expert studies, especially for detecting the human state and intent. For the later development in step four of the control, the sensor concept gives essential input.

Evaluation methods: User and expert interviews

UI With the *dynamics* and the *pHMI* defined, boundary conditions for available spaces for the *UI* are defined. Further, with the *sensor* concept the necessary user input can be determined. If there is no sensor concept detecting the human intent, the control of the assistance needs to be included in the *UI*. In that case users need to be able to activate or deactivate the assistance provided by the exoskeleton. The requirements of high usability, low mental load, low distraction, and unambiguity have to be met. Further, the *UI* should not interfere with natural movements, be bulky or add unnecessary amounts of weight to the limbs. Further, the design of the *UI* needs to meet the standards described in the ISO 9355 Norm (ISO, 1999a, ISO, 1999b). The user's inputs play an essential role in the design of the *control* in step four. For example, the user may need to adjust to the actuation dynamics or the level of the assisting force.

To evaluate the usability and unambiguity of the *UI*, it can be tested separately without any other parts of the exoskeleton within expert or user interviews. This is beneficial so that **compliance** can be evaluated, whether the user correctly expects what the input operators should do, and whether the messages and signals are unambiguous. Unobstrusiveness, visibility, symbol sizes for accommodation and reachability can be evaluated in early design stages using digital human models, such as the RAMSIS digital human model.

Evaluation methods: User and expert interviews, biomechanical simulation

Step four: Combining into one Design With all the key components are developed, evaluated at least within one iteration and meet the requirements, they must be combined into one coherent design. The hardware of the exoskeleton as well as the software need to be implemented and adapted to each other.

Control For the development of the *control* the inputs and outputs of the *dynamics*, the *sensors* and the *UI* need to be combined in one *control* concept. The necessary calculations must be based on the physical model of the *dynamics* and the *pHMI*. Adaptations for different anthropometric settings, motion dynamics, and soft tissue characteristics for each person are required. For example, this can be implemented with a calibration routine. Until completed, a test bench can help to evaluate the exoskeletons' behavior without any risk for the human. The *general design* and the *control* mutually influence each other, which results in smaller evaluation cycles between these two.

Evaluation methods: Test bench

General design Finally all the key components are brought together in the *general design*. Then, the resulting exoskeleton incorporating all key components has to be evaluated to fulfill the requirements for the decided context of use. This requires a study involving the user at their workplace, as described in Section 5.4. An expert workshop in advance could reveal significant deficiencies that can be corrected before a user study is conducted. Thus, the evaluation effort can be reduced and the quality of the data from the user study can be increased.

Evaluation methods: Test bench, expert interviews, user interviews, user observation

Iterate

If user studies show that the requirements are not fulfilled, the entire process has to be gone through again, starting with steps one, two, three or four. In case the context of use is not correctly addressed and results in low usability, a new assessment of requirement is necessary in step one. If there are complications with the *dynamics (kinematics)*, as the full range of movement is not possible or the daily motions feel awkward for the user, the kinematics must be redesigned in step two. If other components reveal deficiencies in fulfilling the requirements, those have to be redesigned independently with no major adaptions on the rest since interfaces and boundary conditions were defined in step three. If issues with the integration of the components or requirements of the *general design* arise, despite the requirements of the components being fulfilled, improvements have to be made for the entire design in step four.

Step five: Long-term evaluation

If the requirements are fulfilled and acceptance of the system is testified via short-term user studies, a long-term user study should be conducted to evaluate long-term suitability and document influences on behavior and health. The study should be long enough for the user's body to show long term effects of exoskeleton usage. As described in Section 5.4, it is not known what timeframe those long term studies should have. Depending on the context of use, test times between six and 12 months seem reasonable to show effects, but even longer studies might be necessary (Kim et al., 2021). Here, proof of effectiveness should be conducted, including laboratory studies with occupational health physicians and methods as presented by Knott (2017) or EMG.
Evaluation methods: Laboratory studies studying physiological effects, long term studies in the field

The presented novel development process can be applied to passive exoskeletons as well. Solely, the key components *sensors* and *control* do not have to be considered, which results in the process as depicted in Figure 7.

In the following Chapters 7 and 8, this novel development process will be applied in two contexts of use in two case studies. Within these two case studies, new exoskeletons will be developed and evaluated applying the described human centered, agile methods. Based on the insights from these case studies, the developed process will be discussed and optimization potentials identified. This will be based on the applicability of the process, as well as the resulting exoskeletons and their suitability and acceptance within their desired contexts of use.

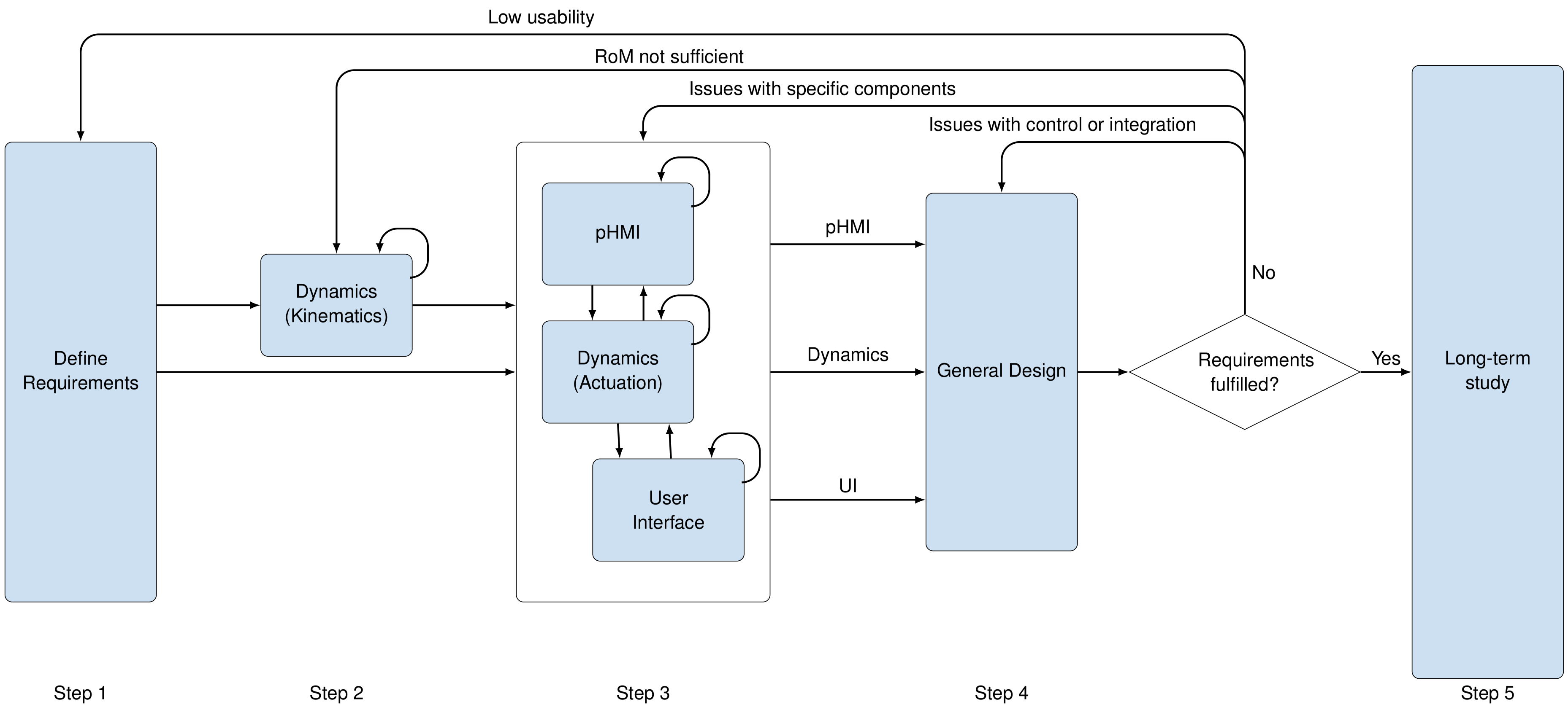

Figure 7 Five-step development process for active ergonomic exoskeletons in occupational context of use: Step 1 – Define requirements, Step 2 – Design and evaluate kinematics, Step 3 – Design and evaluate pHMI, actuation, and UI, Step 4 – Integrate all components into the general design, iterate earlier steps if requirements are not fulfilled, Step 5 – Conduct long-term evaluation.

7. Case study 1: Lifting and Carrying of Medium Sized Loads in Unstructured, Narrow Environments

The first case study describes the design of an exoskeleton within a university project. Within this project, 16 student theses were conducted following the novel development process described in Chapter 6. The project was funded by the Chair of Ergonomics of the TUM School of Engineering and Design, and the prize money from the Bioinspired Idea Competition 2019 was issued from the Institute of Zoology of the TUM Munich Institute of Biomedical Engineering. The project started in May 2018 and ended in December 2022 with a proof of principle and a laboratory prototype.

7.1. Definition of the Context of Use

The goal of the exoskeleton designed in this scenario is to be used in unstructured environments, e.g., craft trade workplaces, supermarkets or beverage distribution, postal services, or moving companies. Looking at those workplaces and applying the methodology in 4.2, the most straining task is carrying loads. Those range up to 25 or 30 kg but vary highly depending on the workplace, especially in craft trade workplaces. As a guideline, the weight handling in supermarkets will be focused on. There, the average weight is around 10 to 12 kg, while a full beverage crate weighs up to 20kg. Studies in distribution centers showed that even though bending forward while lifting loads is the most straining motion, it occurs less than 10% of the time (Glitsch et al., 2023, Winter et al., 2019). Most of the time, people lift and carry in upright positions. This time percentage is even lower in companies with increased ergonomic improvements, like height adaptive workbenches and pallet trucks in ergonomic improvements in those workplaces. The workspaces of those jobs are unstructured and tend to be crowded. Construction sites are especially different for every project and every constructor. The supplied material is delivered tightly packed on trucks and needs to be transported to the final place mostly manually, often along a scaffold. To develop requirements for this exoskeleton, the focus is on supermarkets and their distribution centers. In distribution centers, pallets are usually standing in close proximity to each other and are moved around with pallet trucks. To make their work easier and faster, the workers usually place the wagon very close to the storage space where they need to load or unload single packages of goods for commissioning. So the space between is very narrow. Further, the packages are stored in bigger bulks on pallets or mesh boxes. Their arms must fit in those tightly packed bulks to retrieve or place single containers.

A typical motion sequence in the context of use is illustrated in Figure 8 with the example of a person loading a specific order of beverage crates onto a pallet positioned on a pallet truck. The worker picks up the beverage crate with both hands and lifts it to stomach height. The elbows flex to approximately 90°, and the shoulders extend back up to 30°. Depending on the height of the pallet they are picking the crate from, they sometimes may either lift their arms above shoulder level for the highest layer or bend their back down for the lowest layer. Most of the layers are pickable without the back bending down and the arms below shoulder level. The worker rotates 180°, some workers taking one or two steps, some workers rotate only their back. They then place the crate onto the commissioned pallet, which is positioned with the pallet truck at an ergonomically favorable height. The crate is not placed down slowly and carefully but is instead dropped quickly and abruptly. Sometimes it is thrown. This results in a rapid extension of the arms from the initial 90° flexion to nearly full extension (180°).

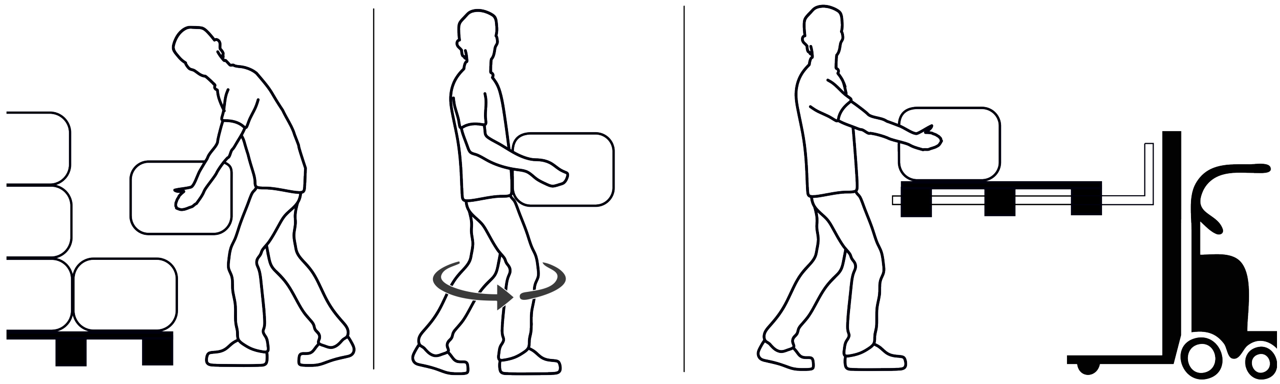

Figure 8 Depiction of the motion sequence of a person commissioning a crate from the storage pallet (left), turning around 180° (middle), and putting it onto a pallet truck with an elevated fork (right).

This workplace is described as representative of similar types of workplaces. Analyses conducted within the LEXO-FA project revealed that many workplaces, especially those involving commissioning and similar logistics activities, exhibit comparable work processes and motion patterns.

7.2. Step One: Context of Use Requirements for an Exoskeleton for Lifting and Carrying

The users of the systems at these workplaces are workers with no special training in technical systems. Their education ranges from no special training to specialists in logistics or specialized artisans. So, a high technical affinity towards the functionality and use of technical assistance systems like exoskeletons cannot be expected. Tests with other exoskeletons with logistics and production workers within the "LEXO-FA" project Harbauer and Bengler, 2022 showed that exoskeletons must be easily adjusted and usable during work tasks. Otherwise, it will lead to misuse or abuse of the systems.

In the described context of use, especially due to the unstructured nature of the workplaces- and tasks, the exoskeletons need to be taken on and off easily and quickly. This requirement is especially important to allow side tasks, whose effect has been described in Section 4.2. For example, the assembly of workpieces might not need the exoskeleton's assistance but the loading and unloading does. Therefore, the exoskeleton must only be worn for the load handling time, not the assembly. This requires the exoskeleton to be put on and switched on within seconds of the parts. Same for taking the exoskeleton off. As described in Section 4.2, this is also crucial in emergencies.

The quick taking on and off of the exoskeleton is only useful for side tasks that take a longer time. The exoskeleton must not hinder the necessary movements or exert forces in the wrong direction for shorter side tasks. This can also be a safety requirement when users operate machinery. For example, an accidental activation of the exoskeleton's assistance during tool or car handling can lead to accidents and injury. In conclusion, the exoskeleton must allow a full range of movement outside its assisted motion trajectory.

The aim of an exoskeleton is not to fully compensate for the weight but rather to reduce peak loads and the effect of repetitive moderate strain. In this case, that would mean reducing the high loads to the recommended maximum according to the German "Regulation on safety and health protection during manual handling of loads at work" (“Verordnung über Sicherheit und Gesundheitsschutz bei der manuellen Handhabung von Lasten bei der Arbeit (Lastenhandhabungsverordnung - LasthandhabV)”, 2013). This results in a maximum load for women of 10 kg and men of 20 kg. Therefore, the exoskeleton’s support of up to 10 kg during lifting and carrying tasks is sufficient to reduce the risk of overloading the human body.
Using the exoskeleton in unstructured and rather crowded spaces requires the design of the exoskeleton to be very close to the body to be useful in crowded places. Especially, the building room around the hands and the arms is limited and needs a very slim integration.
According to the workplace analysis, the exoskeleton must support lifting motion and the static holding of the arms. The main actors in these activities are the biceps and the biceps brachii, depending on the forearm rotation (Kapandji and Rehart, 2016). For this context of use, only active actuation makes sense. The functionality of a passive exoskeleton consists of bigger muscle groups inducing energy into the system by, e.g., increasing spring tension during a specific motion. The preserved energy supports smaller muscle groups in the opposite direction of the movement, thus reducing local strain and redistributing forces from weaker to more robust parts of the body (Argubi-Wollesen, 2021). In this context of use, the triceps would need to apply the force required to support the biceps by a passive exoskeleton. But, the triceps is a smaller muscle than the biceps, so the principle of passive exoskeletons is not applicable. The resulting requirement is that the arms for lifting and carrying must be supported by an active exoskeleton.

The following Table 3 presents an overview of most relevant requirements. These requirements are derived from the general design principles and translate into the components’ requirements. Further requirements for each component are directly derived from the design principles in Appendix C - H. In the following development process, design choices are directly referenced to the corresponding design principles.

Table 3 Requirements for an exoskeleton for lifting tasks in unstructured workplaces, referenced in the left column to the origin design principle from appendix C to I

	Requirement	Value	Source
G.1	Dynamic support of arms during lifting	<10 kg	Workplace requirement
G.1	Dynamic support of arms during lowering	<10 kg	Workplace requirement
G.1	Static support of arms during holding	<10 kg	Workplace requirement
G.1	Active support by mobile power supply	<10 kg	Workplace requirement
G.1	No big structures at the arms to reach in and between boxes		Workplace requirement
G.9	Less than three adaptions		Workplace requirement
G.9	Fast to put on when adjusted	< 1 Minute	Workplace requirement
G.11	Emergency Exit	< 1 Minute	Workplace requirement
D.1	Adaptability 5^{th} to 95^{th} percentile	Data selected from the iSize database	Human Solutions GmbH, 2009
D.4	DoF	Wrist: Dorsal extension <60°, Palmarflexion <70° Radial adduction < 30° & Ulnar adduction 40° Elbow: Pronation & Supination: 90° Extension: 10° & Flexion 150° Shoulder: Anteversion: <170° & Retroversion: <40° Abduktion: 180° & Adduktion: <40° Outside rotation: 60° (hanging upper arm) & 70° (abducted upper arm) Inside rotation: 95° (hanging upper arm) & 60° (abducted upper arm) Back: Rotation & Lateral inclination: +/- 30° Extension: 30° Upper back extension -2 cm & flexion +4 cm Lower back extension -2 cm & flexion +5 cm	von Salis-Soglio, 2015
D.7	Acceptable structure heights on the body parts	hands/palms: 2,54 - 6,35 mm Forearm: 6,35 - 12,7 mm Elbow: 50,8 - 101,6 mm Upper arms: 25,4 - 50,8 mm Shoulders & upper back: 50,8 - 101,6 Upper body and lower back: 25,4 - 50,8 mm Hip: 50,8 - 101,6	Zeagler, 2017
P.11	low pressure at pHMI	Upper trapezius below 0.8 kg/cm² Lower back <1,7 kg/cm² Middle deltoid <1,3 kg/cm² Upper back <1,1 kg/cm²	Fischer, 1987
P.12	Low shearing forces at the pHMI	Detectable threshold at 2 N over 6,35 mm	Chinello et al., 2016

7.3. Step Two: Design of the Kinematic Structure of a Soft Exoskeleton for Lifting and Carrying

An initial design was developed based on the requirements in 7.1 and 7.2. It is detailed in Harbauer et al., 2021a. The main focus during the development was a rather attractive design for future users. The most promising approach was a soft design that looks not like a machine but rather like an ordinary work jacket that workers deal with daily. According to the literature, a soft exoskeleton offers intrinsic compliance, low inertia and stiffness, lower weight, and does not constrain the wearer's joints (Masia et al., 2018, Viteckova et al., 2018).

With the requirement that the hands need to be rather unobstructed, attaching motors or rigid kinematics at the arms was not an option. To still actively support the arms, a cable or rope-driven actuation was the most feasible option (Del Sanchez-Villamañan et al., 2019). This actuation method reduces the needed construction space around hands and arms and reduces weight and the resulting inertia at the arms. According to Zeagler (2017), the best place to put heavy and bulky items is the back of a person. This is where the motors and electronics are placed.
As described in Chapter 6, the second step is the design of the kinematic structure. In the case of a soft exoskeleton, this means the fabric structure and the rope design. Fabric layers are made from Cordura "rip-stop" for good force transfer and bike jersey for good fit and wearability. Further, the concept for the integration of the Dyneema ropes was developed. For a better overview, the a picture of the resulting prototype is shown in Figure 9.

Figure 9 Final laboratory prototype of case study 1 without the FSR *sensor* strap. The black underlying jacket showcases the textile design (Section 7.3.1) and the rope design (Section 7.3.2) as result of the kinematic design of step 1, the back-structure and a brace at the forearm as part of the result of the pHMI Design (Section 7.4.2) in step 2 of the development process.

Few other upper body exoskeletons achieved good results with cable-driven designs since they comply more easily with the complex elbow and shoulder joints, saving weight and complexity. Examples are the CADEN-7, the CAREX from rehabilitation, and the projects from Masia et al. (2018).

7.3.1. Textile Design

The biggest challenge in designing a soft exoskeleton is fitting it to the human body. On the one hand, the force must be transferred between the exoskeleton and the human, requiring a tight fit with no elasticity. On the other hand, the changing circumferences around the muscles and elongation around the joints of the human body need to be accounted for (Chapter 4.1). For a solution, the mixture of two fabrics is developed. The Cordura fabric is used for the areas of the exoskeleton where the assistive force is transferred along the arms with the cables, and no relative movement between different parts should occur. Where room for movement is needed, a very elastic bike jersey is integrated. So, elastic inlets around the elbow and armpit allow a full range of movement while the Cordura®fabric keeps every functional element in the necessary place. To be able to put the jacket on and off, the hand needs to be able to fit through the sleeve. When the rope pulls on the fabric, it needs a tight fit around the human wrist to prevent the sleeve from sliding up. This conflict of requirements was solved by inserting elastic inlets at the forearms and a wrist cuff. The resulting setup is presented in Figure 10. (Harbauer et al., 2021a; Nguyen, 2018)

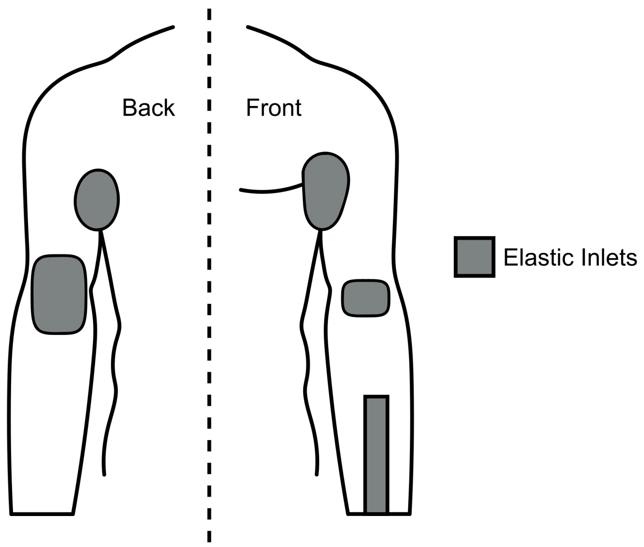

Figure 10 Design of the textile base layer of the soft elbow exoskeleton, first design. The dark grey areas show the placement and shape of elastic inlets that allow a full range of movement (D.1), while the white areas represent stiff Cordura fabric that holds its shape when forces are applied.

The presented design fulfills requirement D.3 only if it fits the person well. To meet requirement D.1, the exoskeleton must be fabricated in different confection sizes, especially for the different lengths of individual body parts. But even within the same percentile of lengths, there is a high variation of circumferences, especially around the biceps. It is even subject to change for individual people. System tests showed that a loose fit around the upper arm greatly impacts the stiffness of the whole system. This would be a challenge for the motor *control*, so there needs to be more adaptability by design or by adjustment possibility for the user. So, in the next iteration, more elastic fabric was integrated to achieve a tighter fit for more circumferences. The resulting design is presented in Figure 11.

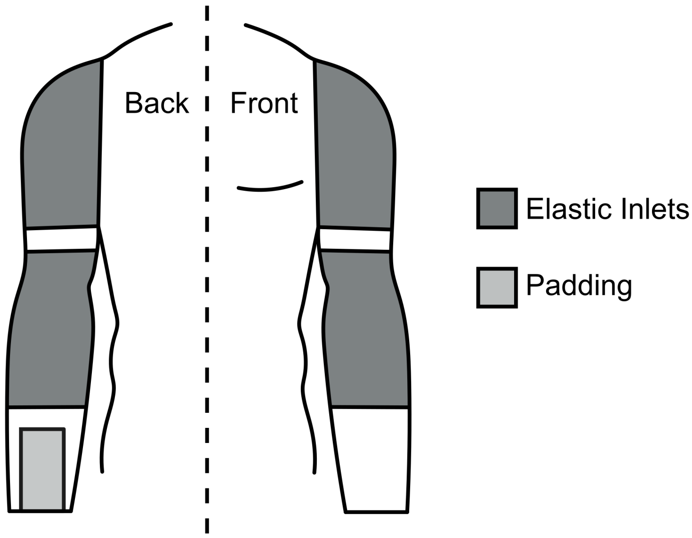

Figure 11 Design of the textile base layer of the soft elbow exoskeleton, second design. The dark grey areas indicate the placement and shape of elastic inlets, which allow a full range of movement (D.1). The white areas represent stiff Cordura fabric, designed to hold its shape when forces are applied. The new light grey areas denote padding, which provides improved and more comfortable pressure distribution (D.11).

7.3.2. Rope Design

Since the load is carried in the hands, the support must start as close to the point where the force acts on the body. The rope must apply forces at the hand or the wrist and go all the way over the arms to the back. The direct connection would be the easiest and the most preferable regarding force transmission. But a cable running straight from wrist to shoulder has a great potential to be very irritating and would, in the described workplaces, entangle with the workpieces and surroundings. So, it needs to be guided closer to the body. The solution was inspired by the natural course of the muscles that the exoskeleton will support. To have symmetric support for the arm, the design of the rope was chosen to run along both the outer and inner sides of the arm. As described in Harbauer et al. (2021a) and Nguyen (2018), it is one rope starting at the motor at the back, going over the shoulder, and detaching at the middle of the upper arm, reconnecting at the forearm, going around a loop at the wrist and then back the same way at the other side of the arm. With the loop at the wrist, requirement D.3 is still fulfilled since it allows the outside rotation of the shoulder to be free. The two-dimensional presentation of the rope's path is shown in Figure 12.

7.3.3. Evaluation of the Kinematic Structure by Biomechanic Simulation

After the kinematic structure is set, the effect of the exoskeleton on the human body needs to be evaluated. As described in 5.2 and 6, it can be done with biomechanic simulation. Due to the soft design of the exoskeleton and the direct support of the cable in the same direction, the joint reaction forces in the elbow are the critical value. The exoskeleton must not increase them and they should be reduced by assistance since the elbow lifts the lesser load. In Harbauer et al. (2021b), it was evaluated using a similar method, as Agarwal et al. (2010) with the simulation tool OpenSIM and the "Upper Extremity Dynamic Model" (Saul et al., 2015). The basis is a quasi-static model that calculates the supporting torque around the elbow depending on the angle the rope takes to the arm. Based on these input data,

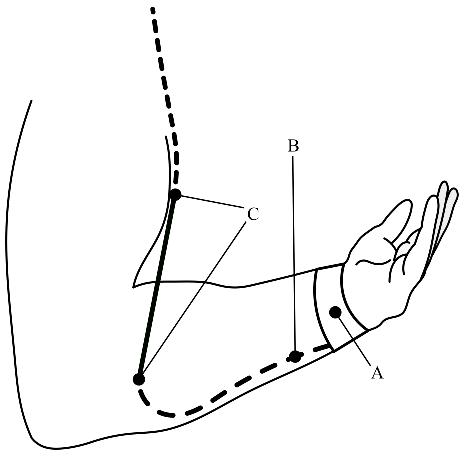

Figure 12 Design of the rope design of the soft elbow exoskeleton, A: wrist cuff, where the rope loops to the other side of the arm, B: rope runs within the PTFE tubes connected with the textile, C: points where the rope exits and enters the tubes

the joint reaction forces are calculated. The method is described in Harbauer et al. (2021b). The results showed a reduction in the loading of the elbow. In the simulation, peak compression forces are reduced up to 11.45% and, on average, around 7.41%. For a virtual load of 5 kg, the simulated peak forces without exoskeleton were calculated up to 2478 N and, on average, 775 N. With the simulated exoskeleton support, those were reduced to 2195 N in peak and to 718 N in average. The described approach uses some simplifications. Therefore, the calculated values do not represent realistic values but give a general direction of the exoskeleton effect on the joint reaction forces.

The biggest simplification of Harbauer et al. (2021b) is the simulation of the support. Instead of cables pulling the lower arm to the upper arm, a supporting torque, like a motor, is simulated at the elbow. Niessen (2021) examined the effect of the used exoskeleton model on the calculated joint reaction forces in OpenSIM with the model "MoBL-ARMS dynamic upper limb model" (Saul et al., 2015; McFarland et al., 2019). This time, the exoskeleton is simulated via OpenSIMs path actuators, which are also used for muscle simulation. Similar approaches are found in the literature for the simulation of cable-driven exoskeletons (Bae, 2013; Agarwal et al., 2013). Several ways to attach the path actuators to the body model were tested, including the torque actuator from Sugiarto (2020), one and two-stringed actuators, as well as three *control* methods: full support, constant torque, and computed muscle control optimized. The tests show that the *control* methods influence the joint reaction forces the most. While most attachment methods showed similar results, two configurations produced forces that differed strongly. Attaching the path actuators to the radius and the ulna simultaneously in the middle of the lower arm increased the joint JRFs in every instance. This is due to the pronation-supination coordinate since both path points apply forces between the ulna and radius. Doing so at the wrist had a much lower effect on the simulation. This effect is due to the rigid attachment point at bones not involved in the motion. This results in additional forces that would not be present in the real scenario. The methods used, and a more detailed analysis can be read in Niessen (2021).

The results of Niessen (2021) show that building the correct model is imperative for reliable simulation results. Significantly, the *control* method used in the simulation should be relatively realistic since the simulation offers data that might not be available in a real-life setup in high quality. But even rather simplistic models allow an estimation if the exoskeleton assists the human body in the desired way.

7.3.4. Optimization of Rope Design by Biomechanical Simulation

The results of Harbauer et al. (2021b) showed that, especially at the beginning of the motion, the forces were still noticeably high. At the beginning of the movement, the elbow is completely stretched at 180°, and the rope cannot generate any supportive force around the joint. Therefore, it was decided that the point where the rope re-enters and exits at the lower arm needs to be optimized. First, it needs some distance ventral from the lower arm, so there is a lever arm that results in an assisting force, even when the elbow is stretched out. Further, the distal position of that point from the elbow should be improved so that a higher reduction of JRF can be achieved due to the increased lever in bent elbow positions. But while doing so, the requirements of D.7 and D.3 must be fulfilled. That means the point should not be too far away from the elbow and the lower arm to avoid entanglement with the rope and collisions of the lever arm with the environment or the user's body. In Harbauer et al. (2022), a method to optimize the attachment point using biomechanical simulation is presented.

The methodology described by Harbauer et al. (2022) for optimizing the point on the forearm utilized the OpenSim software with the "Arm26" model (Holzbaur et al., 2005). Although this is a relatively simplified model, it is adequate for conducting a comparative analysis of different potential points on the forearm. The joint reaction forces were used as the optimization parameter, specifically focusing on the compressive force along the bones, defined here by the y-axis of the co-moving reference coordinate system of the elbow (Figure 13). Since the exoskeleton supports only elbow flexion, the simulation was limited to this motion. The exoskeleton support was represented by a single path actuator pulling between the shoulder and the upper arm. A load of 5 kg was simulated, by a ball connected in the hand of the biomechanical model. The motion in the simulation began at full extension (0°) and proceeded to 145° flexion before returning to full extension. This complete movement cycle lasted 7.4 seconds, with an average velocity of 39.14°/s. The simulation was executed using the static optimization feature provided by OpenSim, and the elbow joint reaction forces were calculated using the integrated Joint Reaction Analysis tool. A total of 99 positions were simulated, distributed in 2 mm increments along the forearm (y-axis) and orthogonal to it (x-axis) in the ventral direction. Unrealistic position that would collide with the upper arm during the full movement were excluded from the analysis.

The results showed that putting the point at the most distal and ventral reduced the resulting JRF the most, which was to be expected (Harbauer et al., 2022). However, the resulting matrix allows the selection of a suitable place where the forces are still considerably reduced, but the placement at the arm is not too obtrusive. Since the "Arm26" (Holzbaur et al., 2005) model is a simplistic model for educational purposes, the resulting JRF are not representative of natural forces. However, the reduced effort and computing time resulted in sufficient results to optimize the design of the exoskeleton.

Based on the calculations, some further usability considerations were made. The attachment point is now decided on a location of 150 mm distal and 50 mm ventral within the project. This represents the

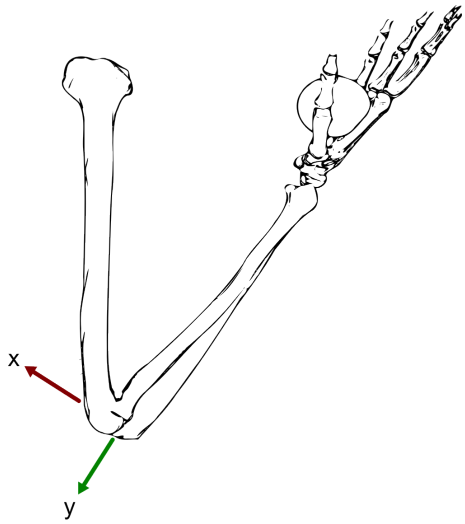

Figure 13 Orientation of the co-moving coordinate system of the biomechanical model. Y-axis is defined along forearm, X-axis is defined orthogonal to it in ventral direction.

compromise, with tolerances, between relatively good assisting forces while not being too far from the body according to requirement D.7 (Zeagler, 2017).

7.4. Step Three: Development of further components for a soft exoskeleton for lifting and carrying

Now that the kinematics of the exoskeleton are defined and optimized, the next steps are to implement a fitting actuation system for the exoskeleton *dynamics*, as well as developing a *sensor* system that provides sufficient data to the *control* together with the *UI*.

7.4.1. Dynamics

Based on simulations in Matlab a motor was designed and a rudimentary test bench to implement a first speed controller with torque controller was built (Cetin, 2021, Gücükoglu, 2021).
The required torque for the motor was determined with the Simulink Multibody Simulation Toolbox. The open source human body model was modified with cylindrical structures attached, that represent the fixpoints around which the cable slides to model the exoskeleton structure as a pulley system. The lower arm has a tare weight of 2 kg with an extra 5 kilograms of load attached. The cable elasticity and friction are neglected. Due to limitations in the simulation environment, the model moves with an input spool that winds up the simulated rope at 4.3 rad over 1.5 seconds. The initial phase of the simulation causes a temporary force overshoot due to discrete movements. Afterwards, the cable tension maintains values below 200 N and 120 N in median. This results in peak values for the motor power after the spool of 150 W at the beginning of the movement and below 50 W afterward. The dimensions of the spool and the gear influence the required power of the motor. The spool was decided on a diameter of 45 mm, which is a compromise between a low number of revolutions and construction space. A robust off-the-shelf motor was selected according to the remaining necessary power of 40 W and torque of 4.5 Nm. Additionally, efficiencies of the motor and gear, friction of the cables, and a security value were added, resulting in

a necessary motor power of 180 W. Due to possible operation outside for short periods of time, which might cause overheating, brushless DC motors by Maxon Motors were selected. The operating voltage is 24V, and an off-the-shelf available electrical power of 200W. With its compact size, the Maxon EC-60 flat BLDC Motor with a stall torque of 4.3 Nm and a nominal torque of 536 mNm was selected. A two-step planetary gear was implemented with a 19:1 ratio to achieve the necessary torque. This resulted in an output torque of 9.5 Nm and 170 rpm at the spool. (Cetin (2021))

A test bench made from aluminum profiles was constructed, with two profiles representing lower and upper arm connected utilizing a hinge joint as the elbow. On top of the upper arm, there are two pulleys representing the shoulder, over which the Dyneema rope is led within the PTFE tubes to the back of the test stand, representing the back of a user. This test stand was used to evaluate the selected motor.

Gücükoglu (2021) developed a *control* algorithm to test the motor. It simulates the input of a potential intention recognition or active user input via the *UI* with three commands: "raise," "hold," and "lower." In those cases, the actuation unit moves a static payload with an elbow rotation speed of 120°/s. Friction and backlash from the cable need to be compensated during that motion. A closed speed control loop and an open torque control loop were designed for that context of use. The speed loop uses the current speed readings from the encoder and a manually adjustable input for the desired speed. This is used for the dynamic cases "lift" and "lower." For the static case "hold," the open torque loop was used. In that loop, the reading from a gyroscope and an accelerometer placed on the profile representing the lower arm gives the current rotation angle of the arm. The necessary torque is calculated within the computing unit to hold the current payload, which was manually entered, in the current position. The use of the gyroscope and the accelerometer was disregarded during the test since the friction within made holding the load possible with the same holding torque in any position. The suitable holding torque was experimentally identified for each payload. Further, the *sensors* were delivering inaccurate data over time due to drift and measurement errors. Those preliminary tests showed that the motor had sufficient power and torque to assist the context of use. (Gücükoglu, 2021)

In soft cable-driven exoskeletons, friction is a challenge to implement in the *control* since it changes continuously due to the changing curvature of the tubes (Dinh et al., 2017). The curvature also changes for every user and potentially every time the person puts the suit on since the exact same position of a soft system cannot be ensured. This led to the design of a test bench that represents the human anthropometries better and leads to more natural and broader curves of the cable. With the help of that bench, in the following design, iterations of the *dynamics*, the *pHMI* and especially the *control* with realistic friction values can be conducted. Another influence factor on the friction is the abrasion of the rope and the tube and dirt entering the system. Those influences could be determined using the test bench in long-term testing. Still, a calibration routine will be necessary for every new setup of the system to calculate the influence of friction in that specific scenario, including environmental factors like temperature and humidity.

The test bench is depicted in Figure 14. It consists of the upper torso and the left arm of a 50^{th} percentile European man. The structure consists of aluminum profiles with anthropometric lengths, to which shells with the corresponding anthropometric surface are adhered. The elbow joint in this version consists of a hinge joint placed in flight with the profiles. The joint of the test stand is designed modular so that the implementation of more complex representations of the elbow joint is possible. This simplified joint is sufficient to test *control* algorithms and the behavior of the *dynamics* of the exoskeleton. Only if the transmission of forces through the structure and the joint is measured, with the implementation of force *sensors*, the design of the mechanical joint, including ligaments might play a role.

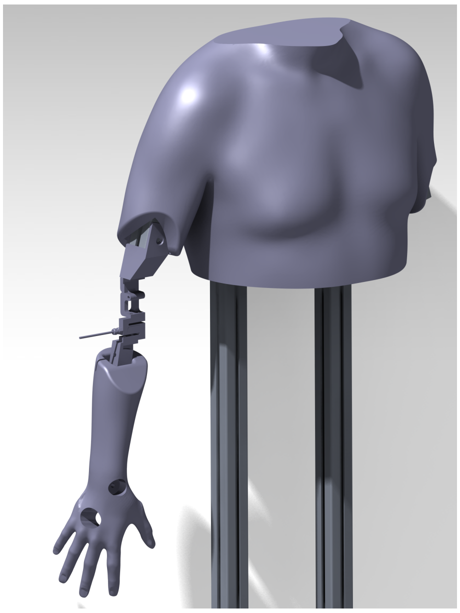

Figure 14 Anthropomorphic test stand, 50th percentile European man, for a realistic representation of tube lengths and curvatures of the soft exoskeleton for testing *control* algorithms, *dynamics*, and *pHMI*

The same actuation configuration described above was tested on the anthropomorphic test stand. The influence of friction was drastically reduced, leading to lower power consumption and higher velocities with the same amount of torque as before. This results in the chosen motor configuration being overdimensioned and new calculations to be made in the next iteration. But for the first iteration, this configuration is sufficient to develop further aspects of the exoskeleton.

This shows that testing with a test stand that represents important anthropometric features is crucial to evaluate realistic system behavior when implementing active but also potentially passive actuation systems. This might not only relate to friction but also the behavior of the *dynamics' kinematic* structure when forces of actuation units are acting on it.

7.4.2. pHMI

Due to the nature of a soft exoskeleton, the kinematic structure also fulfills the role of the *pHMI* for most parts. It still needs special attention in the areas where forces act on the human body. In this case, this is at the following points of interest::

- The hand, where the rope is looping around
- The lower arm, where the rope leaves or enters the fabric structure

- The upper arm, where the rope leaves or enters the fabric structure
- The back, where the motors and electronics are attached

pHMI lower arm: Breitsameter (2020) designed a lightweight brace for the lower arm that allows the cable to enter at the calculated point from Section 7.3.4. The first iteration turned out to be too bulky, so the dimensions were reduced and the sides removed to conform to the requirements P.4, P.5, P.13, and P.14. But with requirements P.1 and P.11 in mind, the area of contact between the brace and must not be too slim to avoid uncomfortable pressure. The final result of several iterations within the work of Breitsameter (2020) and afterward is shown in Figure 15. As of now, it does not offer adjustments or different anthropometries. Since the whole suit needs to be made in confection sizes, this also applies to the lower arm brace to fulfill P.2, P.3, and P.4. If adjustments are needed within those confection sizes, it has to be evaluated within a study containing a larger population. To reduce size and weight, the pHMI is done without adjustments (P.13, P.14). Detailed adjustments about compliant design P.6 and the pressure P.11 must be done with padding. The brace is part of the soft exoskeleton structure, so the hygiene concept of P.8 and the thermal comfort of P.7 can only be addressed when bringing everything together. The whole suit should be washable without the electronics, and sufficient ventilation should be ensured.

Figure 15 pHMI lower arm: Implementation of the optimized cable entry (A), the connection to the pHMI Hand (B), and material reductions for a lightweight design (C) and exit point of the exoskeleton at the lower arm. The pictures on the right show the implementation on the sleeve of the soft exoskeleton.

pHMI hand: Wechsler, 2020 developed a glove that prevents the sliding up of the sleeve when the cable is pulling on the fabric (P.12). A more comfortable transmission of forces (P.1) is possible even if the sleeve is not a tight fit. The cable stays in one place, which simplifies the *control* component of the exoskeleton. The glove can be detached and reattached to ensure an easy and quick setup of that *pHMI* (P.9, P.10) and the whole system (G.9). The part where the cable loops at the wrist is implemented with soft silicone for low discomfort (P.11) that is covered in Velcro and can be stuck to the wristband of the glove (P.9, P.10). The glove is a generic off-the-shelf type, that is used for weight lifting and CrossFit. It stabilizes the wrist without disturbing the motion (P.14) and distributes forces over the whole palm (P.1, P.11) with the fingers being free (P.14), therefore contributing to thermal comfort (P.7). The material is Neoprene, which has good padding capabilities while being robust against getting wet and completely washable (P.6, P.8, P.11) (Xiloyannis et al., 2019).

pHMI upper arm: Using only the support the jacket offers was found sufficient, especially with the adaptations in 11 and considering the adaptation into confection sizes. Especially with the implementation of *sensors* for intention recognition, this part of the *pHMI* depends on the developments in the following Section *sensors*. If further developments and studies show that the fit is insufficient, an option is to include a tightening band with an easy adaption mechanism like Velcro. However, due to the biceps' relevant volume change, these attachments cannot be too tight (P.4).

pHMI back: Gerullis (2022) developed a backpack-like system that includes the motors, electronics, processing unit, and batteries, while keeping the full range of motion of the user's back (P.5). Based on the harness of a trekking backpack, the *pHMI* offers padded shoulder straps (P.11) with a chest buckle (P.9, P.10) and a padded hip belt (P.11) with a buckle in the front (P.9, P.10). All straps and buckles have the standard off-the-shelf adjustment possibilities (P.3). Since the motors induce forces, especially when changing directions, the backpack had to be designed, that no compression forces are acting on the spine. Thus, all the components are mounted on a rigid backplate connected with the shoulder straps and the hip belt. To ensure full mobility of the user, the connection at the shoulder belts has a translation joint that allows for the elongation of the back when the person is bending down (von Salis-Soglio, 2015; Klepser and Morlock, 2020). At the hip belt, the back plate is connected with a ball joint that allows rotation in all three dimensions for the rotation, lateral flexion, and extension of the back (D.3). Due to the design, the forces generated by the motors and the weight are only transferred to the hip (P.1). The backpack itself is designed as small as possible (P.14). Preliminary tests showed, that sitting is possible. Due to the light 3D-printed casing, leaning is not yet possible, but it would be if more sturdy materials and closing mechanisms were used (G.18).

7.4.3. Sensors

An intention recognition helps to identify the state of the human and allows predictions of movements, resulting in a faster and more robust *control*. At this stage, the exoskeleton only uses the data from the motor and the encoder to retrieve information about the current torque and position. The main actor in lifting, holding, and lowering a load are the biceps brachii and the triceps. Both are located at the upper arm. The activation of the muscles starts, and the increasing stiffness starts before the actual movement. This can be used to detect the intention of lifting or lowering the load. As discussed in Section 4.1.5, sEMG would be a good choice but is not usable in the intended context of use. Another way of detecting muscle stiffness, which results from muscle activation, is force-myography. Based on this principle Kopfinger (2019) developed a system that uses force sensing resistors in combination with inertial measurement units to detect the muscle stiffness of the biceps and the current position of the upper and lower arm. Additionally, a push button in the palm detects the presence of a load in the hand to reduce the risk of false activation. The principle is also briefly described in Harbauer et al. (2021a). The data interpretation was implemented with a state machine that had the states "holding up," "holding

down," "lifting," and "lowering." The transitions between the states were determined with a calibration routine, where the individual muscle stiffness for each weight in each position is measured and saved as thresholds. In a study, different scenarios were utilized to test the detection of a certain intention versus no intention. The intentions of holding, lifting, and lowering different weights were investigated, as well as similar movements where no power assistance by the exoskeleton should be triggered. Similar movements were pushing a door handle, supporting oneself on a table, and clenching the fist. The weights were represented by boxes and crates with loads of 0.1 kg, 1.5 kg, and 3 kg per arm. The sensitivity was calculated to 0.78, which means that in 78% of the cases, an intention for lifting, carrying, or holding was present and the system correctly interpreted it. The specificity accounts for 0.35, meaning that in 35% of the activities where no intention of handling loads was present, the system interpreted those correctly. Preliminary tests showed that the FSR at the triceps has no beneficial value, therefore the data was not recorded in the study.
Based on this system the design was further improved (Kappelmeier, 2021). Several types of FSR were tested, as well as different configurations. The most clear data was generated with three FSR placed in a line along the biggest movement of the biceps brachii. The most suitable FSR are those with a high resolution, even in the lower force range, and a linear characteristic. In this case, the Tekscan FlexiForce A301 Sensor best fits the desired characteristics. The sensitivity and specificity were evaluated in a study, and the influence of soft tissue and clothing between the *sensors* and the muscle was evaluated. Tests show that overall, the system presents an average sensitivity of 72,69 % (SD: 9,05 %), representing the percentage that the intention of lifting loads was detected correctly. Further, it did not interpret the side tasks as lifting intentions on average of 79,16 % (SD: 13,75 %). The sensitivity increased with the lifted weight, with 81,02 % on average (SD: 24,73 %) for datasets with 4 kg of load. The group of five people wearing thin, form-fitting clothing had, on average, a sensitivity of 1,11 % lower than the seven people where the system had direct skin contact. The difference in the sensitivity due to the rotation of the hand is 1,55 %, with the fully supinated hand position having the higher values. For people with more soft tissue between the muscle and the *sensors*, the sensitivity was slightly higher at 73,15 % (SD: 28,56 %) than those with lesser 72,45 % (SD: 23,08 %). The used state machine was very suitable for laboratory settings, where the motion sequence is set by the study design, and the load is always known beforehand. However, this is not the case for applications in the field. Their motions can suddenly change, or the lifting motion will not be fully executed. Now with the proof of concept with an FSR-based intention recognition, the data interpretation needs to be adapted to the context of use. A reference of the *sensor* unit build is presented in Figure 16. (Kappelmeier, 2021)

The FSR configuration with a pushbutton in the palm was further improved by adding one IMU and two soft Angular Displacement Sensors (ADS) (Kumar, 2022). With the overall *sensor* system, the position of the arms and the upper body is monitored in addition to the load in the palm and the muscle stiffness of the biceps brachii. The two ADS monitor the angular displacement due to the elbow flexion and the shoulder's vertical flexion. At the same time, the IMU tracks the relative position of the upper body to the ground. Additionally, a data collection study for motion data with 10 people was conducted using the CAPTIV system by Tea Ergo. This study recorded data for three cases for each lifting, holding, and lowering. Every trial consisted of 10 repetitions of each motion or position, resulting in 100 data sets

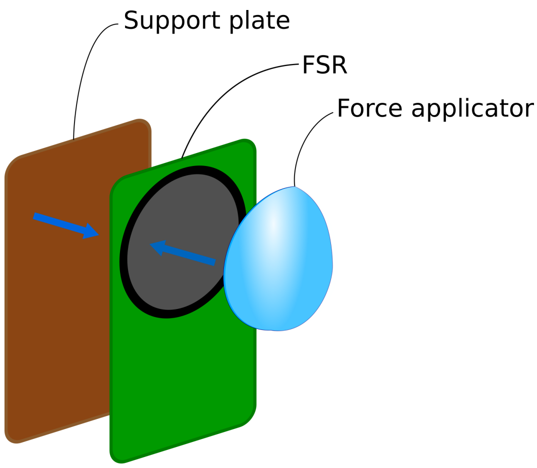

Figure 16 *Sensor* unit configuration. The support plate gives a counterfeit for the *sensor* to be pressed against. The force applicator increases the soft tissue's pressure onto the FSR reading area. (Kappelmeier, 2021)

for every case in total. Afterward, the data was classified to differentiate between the recorded cases. A Hidden Markov Model (HMM) was developed and trained on the retrieved data to identify the current motion intention based on the live data the *sensors* deliver during exoskeleton usage. The recorded trajectories are the output as reference values for the motor controller after the intention recognition based on the HMM correctly identifying the person's task. (Kumar, 2022; Schaefer, 2022)

Another aspect that had to be developed around the *sensor* system is the attachment of the FSR at the upper arm. They were attached via an elastic velcro band around the arm in all three iterations. To collect precise, distinguishable data, the FSR needs something to be pressed against to measure force. Since there is soft tissue at the arm, where the *sensors* are placed, force applicators are required that concentrate and amplify the force that the soft tissue is pressing against the FSR surface. This issue was solved with rubber blocks placed on the FSR sensor surface that press into the soft tissue (Kopfinger, 2019). This led to moderate discomfort for wearing times of 1 hour, so higher discomfort was expected for usage for a whole work shift. In the second iteration, the force applicators were made by using softer half spheres at the surface of the FSR sensing area (Kappelmeier, 2021). Due to the relative surface enlargement of the round surface at the soft tissue and the flat surface pressing onto the FSR, the FSR delivered good readings, and the softer material ensured reduced discomfort. The force detection was even further improved based on the research from Beil et al. (2015). A 3D-printed structure around the FSR simultaneously increased the pressure of the soft tissue on the FSR detection area, stabilized the sensor, and reduced shear and transverse forces on the FSR (Kumar, 2022). This improved the readings and reduced discomfort but made the *sensors* bulkier and possibly intrusive for people with smaller or shorter arms. This needs to be evaluated with a field study.

7.4.4. UI

Due to the successful development of intention recognition in the last chapter, the *UI* needs input options for personal adjustments of the user and outputs for communicating systems statuses. An *UI* was developed and evaluated in a qualitative participant study (Patzauer, 2019). First, the different states in which the exoskeleton can be were defined since those define the available settings and inputs.

An input device attached to the arm was developed to design an easy-to-use but relatively slim human-machine interaction. In total, the exoskeleton can be in six states: 1) Power off, 2) Stand-by, 3) Stand-by working mode, 4) Active working mode, 5) Calibration, 6) Error. Power off describes the state where the system is completely shut down or disconnected from its power source. Stand-by is the lowest of the operation modes. Power assistance is not available in this state. It serves to start calibration or to set the system up in other ways. It also serves as a security mode if the user is in a state where an accidental influence by the exoskeleton could induce critical situations, for example, while driving a car. After the setup procedure is completed, the user can go to the stand-by working mode, where active support by the system is possible. The exoskeleton enters the active working mode as soon as the intention recognition detects a supportable movement. The motors shorten or lengthen the cables and unburden the user. Even though they are unfavorable, errors can occur. Depending on the severity of the error and the state where the error occurs, different measures have to be taken, for example, a required recalibration or immediate shutdown. The interactions between the states are depicted in a flow diagram in Figure 17.

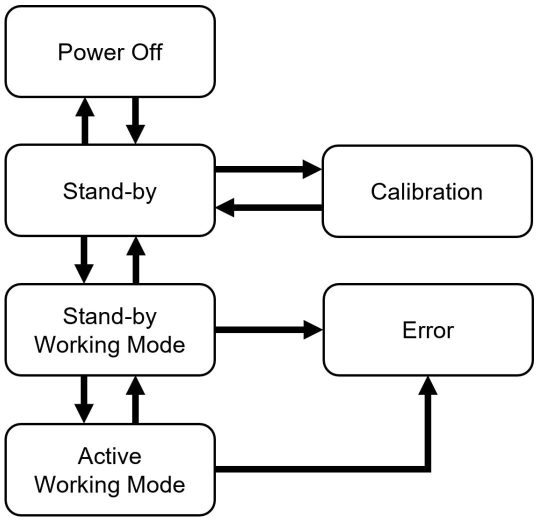

Figure 17 Flow chart or the different exoskeleton states and the available transitions

The *UI* has a total of five buttons, a status display, and a Near Field Communication (NFC) tag plus an NFC reader. The panel is placed at the lateral side of the lower arm and can be used and seen when the user moves its arm in front of the body. The user navigates through the stand-by, calibration, and errors by buttons and status display. They enter or leave the stand-by active mode by putting their wrists together. The NFC reader detects the tag and unlocks the power assistance. This allows the usage of gloves and activation without having to look at the display. When an error occurs, the corresponding error prompt appears on the status display, and a tactile cue warns the user. 22 out of 25 participants (88%) completed all tasks correctly and seemed to have understood the information given on the interface from the observers' point of view. The average of the SUS score was 82 (SD ±10), which can be considered “Good” according to literature (Bangor et al., 2009). A key finding is that participants tended to ask for less technical information, especially error prompts, which should be formulated as action prompts to give guidance. Regarding the calibration, it was suggested to change the word "Calibration" as it was perceived as too technical. A possible replacement could be "Personal adjustments." Regarding the technical background of the participants, this effect amplifies if the users have a lower affinity for technology. One participant expressed that the many detailed steps in setting up and using the *UI* gave a feeling of safety. The participants had problems with the setting of the power level. 10 participants (40%) expressed that they thought they were regulating the support depending on the weight they wanted to carry. The NFC technology was regarded as positive by 44% of the participants, making the control seem more "cool [sic!]". Only two (8%) participants would have preferred a button. Both were observed to have bigger arms, which obscured the display. Thus, placing the NFC reader somewhere else would be beneficial, but this could increase the risk of activating the exoskeleton by accident, which was a concern for one participant with the presented design. To 11 people (44%), the smartphone that was used to implement the concept for the study was too heavy (n=9), clumsy (n=1), or bulky (n=1).

Additionally two emergency stops at the shoulder straps of the *pHMI* system were implemented. They are positioned at both sides of the chest where they can still be reached by the user's hand even when the cable is completely rolled up (Gerullis, 2022).

7.4.5. Control

Based on the *dynamics' kinematic* model and the data from the data collection study for the intention recognition (C.1), a controller was developed to implement the intention recognition and the motor control (Schaefer, 2022). With the HMM classifier, a transition between the defined states is possible (C.3). The input by the *UI* is not considered yet. Still, a transparent operation mode that follows the user's motion without adding supporting force is implemented (C.1). The active assistance control is based on an individually tuned PD controller with gravitation compensation. The controller uses the reference trajectories as input based on the state communicated by the intention recognition and compares them with the position input by the *sensory* system. The PI-controller used in the motor control is further implemented and tuned for a robust trajectory following (C.1, C.8). The goal of the first iteration was to make the exoskeleton work and implement the intention recognition. It was not focused on the fulfillment of further requirements. (Schaefer, 2022)

7.5. Step Four: Integration into one Prototype and Concept Evaluation by Expert Interview

The combined prototype resulted in an exoskeleton with one actuated arm, intention recognition, and a basic *control* scheme. Due to the prototype not having a battery system yet and being bound to a power cable, the tuning and calibration are also done by a cable-bound laptop. The electrical integration of all mechanical and electrical concepts is described in Gerullis (2022), and the combination of the intention recognition with the motor *control* is explained in Schaefer (2022). Further, Döring (2022) did a first analysis of safety aspects, developed solutions for requirements by the safety norms, and expanded the *UI* with conditions for transitioning between states. The final prototype can be seen in Figure 18 and 9.

The proof of principle was achieved with this setup, but user testing in the workplace was not possible. Therefore the evaluation of the system was done with an expert interview. Semi-structured interviews with seven experts of five different companies were conducted to evaluate the usability, potential acceptance, and suitability for the addressed context of use. The experts were chosen since they already have

Figure 18 Final laboratory prototype of case study 1. Additionally to Figure 9, it showcases the FSR sensor strap as result of the sensor design in Section 7.4.3 and the emergency stop as implementation of the safety requirement (G.11)

experience in the field with testing exoskeletons and conducted field tests within their respective companies in the past. Two were ergonomic experts, two were production managers, two were team leaders, and one was a security officer at their company. First, they were presented with a short pitch of the core functionality and aspects of the exoskeleton, with the option to ask as many questions as they liked until they fully understood the concept and the features of the soft elbow exoskeleton. Afterwards, the semi-structured interview was conducted to let the experts freely speak their opinions on the exoskeleton while focusing on certain aspects. The guideline questions focus on potential contexts of use for that specific exoskeleton and the theoretical usability of that exoskeleton concept, including side tasks. The interview was conducted in German since this is the native language of all participants. The interviewer noted the answers. The pitch and the guideline questions for the semi-structured interview are in the Appendix I and J.

7.5.1. Suitability for Application in the Company

Six experts immediately thought of defined workplaces in their company in which they would find a system like that useful. The workplaces are in the area of intralogistics (1), picking (3), unloading machines (2), and assembly (3). One expert confirmed that the workers feel strain in their arms when lifting parts. One expert proclaimed that a system "like that would be the best version (of an exoskeleton)." One expert in the area of logistics did not call for specific workplaces since they are changing continuously depending on orders. That expert was reserved regarding the suitability for the company but still wanted to test it.

7.5.2. Usability for the Main Task

Five experts estimated that the system would fit the workplaces well. Five agreed that the assistance of 10 kg would be sufficient in supporting the contexts of use. One mentioned that the exoskeleton design would be beneficial in confined spaces, as other exoskeletons they tested were too bulky for the context of use. One expert thought the exoskeleton would be perfect for handling cartons, while one thought the system would be well-usable for unloading from pallet cages. One expert feared that with the support of 10 kg, the staff thinks that they have to lift more now and that the load should not increase with the implementation of the exoskeleton. One expert again referred to having to test the exoskeleton before they could give an estimation.

7.5.3. Usability for Side Tasks

Four experts saw the backpack, where the electronics are stored, as a potential for being disturbing during side tasks. Two described that being able to sit down is a high-priority requirement to be suitable for the side tasks in the context of use. One expert explained that sitting down is unnecessary, but the backpack might bump into surroundings in confined or crowded spaces. Therefore, it should be scratch-proof and not too bulky on the back. One expert set as a requirement that there has to be a full range of motion in the back, especially the rotation. Further, they should not have to work against the system to move their arm freely, as would be the case for passive exoskeletons. Three experts did not specifically mention side task issues in the estimation of the exoskeleton usability.

7.5.4. Degrees of Freedom

In this stage of development, the experts could not estimate if the exoskeleton allows all DoF.

7.5.5. Weight and Size of the System

Four experts assessed that the goal weight of the exoskeleton of 5 kg would be acceptable, if the support is around 10 kg. One reported that even with lower-weight exoskeletons of 2 to 3 kg, the workers described the weight as an issue. Another one said that 2 to 3 kilograms already are well noticeable, but there are cases where workers barely noticed exoskeletons of that weight. Both agreed that the weight really needs to be well distributed so that the people barely recognize it, and then 5 kg might still be accepted. But a weight lighter than 5 kg would even be better.

7.5.6. Positive Aspects of the Design

Two experts found the use of ropes as a good design. One especially liked that the rope runs on both sides of the arm. That reduces the chance of shear forces. Two found the design very promising since it is close to the body and not bulky. One described it as more subtle and not as machine-like as other exoskeletons, which draws less attention to the fact that the person is wearing an exoskeleton. One expert explained that it might be a success factor if the employees did not see it if another worker wore something unusual. Three found that the support of the arms addresses a good context of use. Two reiterated that the arms really need assistance and that the system has much potential in a broader range of workplaces than other exoskeletons. The third one mentioned that the included wrist stabilizing is a good aspect since the most strain is on the shoulder and the wrist. One expert found the intention recognition as very promising and found it well thought out. Two experts saw great potential in the soft design since it offers the inclusion of individualization and better personalization to perfectly fit the individual user. One pointed out that the exoskeleton might be combinable with an exoskeleton that supports the lower back, if necessary.

7.5.7. Negative Aspects of the Design

Six experts saw the thermal comfort of the jacket as a big potential issue, especially in the summer. A reduction of fabric, especially in sweat-prone areas, was recommended, and a discarding of the jacket-like design. One expert pointed out that the system itself might generate heat in high cycle times. That could even increase the issue of thermal comfort. One expert explained that they had the described thermal issue with one exoskeleton, but it was still worn because the support by the system was extremely well received. But the cleaning possibilities need to be very good in that case. Other experts described increased sweating as a reason exoskeleton trials failed, especially in the summer. Three experts pointed out that the glove design with all fingers in fabric loops might be perceived as problematic depending on the context of use. On the one hand, it might increase sweating, and on the other hand, it might be disturbing during tool use, especially if work gloves need to be worn over them. One expert reported good results in another project, where only a thumb loop was well accepted and sufficient for the purpose. Two experts saw the ropes as potentially disturbing during tasks but would recommend further testing. One pointed out that they must be sheathed when working close to sensitive products. Another issue might be using workwear over the exoskeleton, especially when working outside or where additional protective wear is necessary. One expert asked if lifting the arms overhead might cause issues with the current design. Another one asked if the motor's pull is noticeable at the stomach since that would be a big issue. One expert reiterated that the size of the backpack may not be too bulky so that the exoskeleton can be used in forklifts.

7.5.8. Predicted Acceptance

Four experts expected the acceptance to be better than with previous exoskeletons. Two were unsure but assured their workers would at least be excited to try. One saw the jacket design as a big issue, even though it would be easier to put on, but most of their staff prefer working short-sleeved. They reiterated that discarding the jacket design and instead using a backpack with straps would result in better acceptance. Two experts pointed out that the exoskeleton will not be accepted by everyone from the start, which lies in the nature of how new technology is perceived in the workplace and the personal preferences of individual people. All experts agreed that the previously described improvements are imperative to achieve acceptance in the workplaces. Two stated that in the end, the acceptance depends on whether the exoskeleton really is perceived as useful and beneficial by the workers, as intended. This can only be examined in field trials. One expert stated that the context of use of holding loads is something that workers asked for assistance in the past. Therefore, they would be more accepting of such an exoskeleton. An essential factor of acceptance is that the exoskeleton is easy and quick to put on. One expert explained that exoskeletons have a bad reputation in their department since trials in the past made them think exoskeletons are unnecessary and disruptive. But if the system turns out to be as "genius" as intended, they might still accept it.

7.5.9. Future Directions for Development

The experts stated important factors that, in their opinion, needed to be paid attention to for the exoskeleton to be well accepted. Numbers in brackets show how many experts mentioned that topic independently:

- Fast and low effort putting on and off (especially for work brakes) (4)
- Low effort for changing settings, existing systems are too complex due to unnecessary adaptation mechanisms, but exoskeletons need to be customizable and fit well without too complex adaptation that requires too much time (3)
- The system does not need to be a whole jacket or be made from very light, breathable material (2)
- Work gloves need to be wearable (e.g., for dirty tasks or protection), which should not interfere with the exoskeleton (2)
- Easy and fast adaptation to different workplaces and settings, e.g., for workplace rotation or different assembly tasks
- The system should not be bothersome when assistance is switched off
- The system should not become too stiff
- It has to be ensured that the system is only used as strain relief, not as a means to carry even more load. This might only be manageable with organizational processes surrounding the system implementation in the workplace, as described in Section 4.2.2.
- The rope might be confusing since it is in the field of view
- The ropes could entangle with anything (itself, own body, or environment)
- The chest straps should not be too tight and result in the user feeling restricted
- The system needs to stay in place without having to tighten the straps too much
- It has to be possible to wear other work gear over it (vest or jacket). Some need special noticeable colors or reflective elements on their work gear, or there might already be workwear specifications in place that the exoskeleton has to follow regarding material or color
- When handling load with only one arm, it should not result in an asymmetrical feeling for the user. Forces on the body still need to feel symmetrical, especially at the torso
- There should be no noticeable pressure on the shoulders due to ropes being guided over
- Grabbing objects with hands should not be disturbed
- Anything negatively impacting the workers during their tasks will reduce acceptance

All seven experts expressed high interest in testing the system at their companies despite having past negative experiences with other exoskeletons. They agreed that the system is something new and addresses a context of use with no other feasible solution yet.

7.5.10. Results of the Expert Evaluation

The experts confirmed the exoskeleton concept as a suitable solution for the addressed context of use. They mostly predicted good usability and preventable interference with side tasks. However, they disclosed major issues around the *pHMI* and *dynamics (kinematics)* structure, which results in the next development iteration needing to start at step two again with the improvement of the fabric structure. They also addressed workplace requirements, like wearing protective gear and work gloves over the exoskeleton, which did not get enough attention in the last iteration cycle. The slim design of the system was found to be not too bulky, except for the backpack, which needs to be kept in mind in further development iterations. The distribution of the weight and the forces induced by the motors need to be well distributed, especially for asymmetrical lifting cases. On the one hand, the ropes need to be sheathed to reduce potential entanglement and optical disturbance to the user, but on the other hand, to protect the shafts from dirt and erosive materials entering. The necessary freedom to move can only be evaluated in a realistic working setting with users using the device.

As a result, the general design requirements are fulfilled as follows in Table 4. "Fulfilled" indicates that the requirement has been met completely. "Good" signifies that the requirements are met with only minor optimizations required. "Medium" suggests that the requirements are partially met, with a few significant aspects necessitating revision. "Low" conveys that the design falls short of meeting the requirements, although some elements show potential. "Not fulfilled" indicates that the design doesn't meet the requirements and needs major revisions.

Table 4 Fulfillment of requirements for an exoskeleton for lifting tasks in unstructured workplaces by the presented soft elbow exoskeleton design

	Requirement	Fulfillment	Comments
G.1	Good Usability	good	potential described by interviewed experts
G.2	Good User Experience	N.A.	UI not implemented
G.3	Ease of use	N.A.	UI not implemented
G.4	Positive aesthetic appeal	good	positive comments of experts
G.5	Low weight	good	four experts deem acceptable, two prefer lower / perfect distribution
G.6	Compact size	medium	sitting needs to be possible, backpack size crucial
G.7	Adequate use Time	N.A.	battery not designed yet
G.8	Transportable and storable	N.A.	not evaluated
G.9	Quick Set Up	N.A.	UI not implemented
G.10	Safe State	medium	ropes do not restrict flexion, motor can be overpowered by human strength but actuation unit is not backdrivable
G.11	Emergency Exit	good	reachable emergency stops and exoskeleton can be thrown off within a short matter of time but over 7 seconds for inexperienced users.
G.12	Support rate	N.A.	only measurable in field study
G.13	Low Discomfort	N.A.	only measurable in field study
G.14	Mobility and Independence	N.A.	only measurable in field study
G.15	Low Noise Emission	good	below limits, but still noticeable and potentially irritating to users
G.16	Low Vibrations	fulfilled	subjective evaluation
G.17	Safety	not fulfilled	design concepts in Döring (2022)
G.18	Compatibility with side tasks and tools	not fulfilled	use of protective gear and and forklifts not possible

7.6. Limitations and Further Development Case Study 1

Due to the nature of soft exoskeletons, the order of iterations was not as well structured as described in 6. For the development of the kinematic structure, rapid prototyping was necessary to evaluate the possible DoF and the fitting of the soft structure. Therefore, the aspects of *pHMI* and *dynamics* merged since the optimization of the rope design resulted in the implementation of the *pHMI* of the lower arm brace. This function integration helped with a lower design complexity and better achievement of the requirements, but showed the weakness of the development process. The singular aspects are not as well separated from each other as they might seem. Due to the nature of the project, a university-based research project with limited funding and workforce, the final integration into a whole prototype was not entirely possible within the given timeframe. Further limitations were set by major events happening during the project duration that restricted the availability of parts as well as restricted accessibility of public facilities. A partially mobile prototype showed already promising results in addressing the context of use with the correct measures. It reduced development efforts since crucial design flaws, like the thermal comfort of the whole jacket and the compatibility with work gear, were uncovered as early as possible. This increases the chances of developing an exoskeleton that will receive good usability, user experience, and user acceptance as a final result.

For the development process, this means that the first full integration of the exoskeleton in step four only needs to be as good as necessary. Not every aspect needs to be implemented to evaluate the general design aspects. This will be discussed further in Section 9 in combination with the insights of case study 2.

That proof of principle state of the exoskeleton was well received by the Federal Ministry for Economic Affairs and Climate Action and got accepted as a research transfer project for government funding. The funding approves the project as a potentially profitable product that should be developed market-ready and transformed into a company. The next goal is to create a field prototype in different confection sizes to carry out field tests while prioritizing the experts' feedback. The most relevant development goals are the further optimization of the *dynamics*, the intention recognition and its *sensors*, as well as the data classifier and the *control* algorithms behind natural, unhindered movements.

8. Case study 2: Occupational exoskeleton for heavy lifting and carrying in industrial environments

The second case study was conducted in a research and development joint project with J. Schmalz GmbH. The described research methodology was used, but the Chair of Ergonomics (TUM School of Engineering and Design) conducted only parts of the project. The work packages conducted on the university side focused on workplace and task analysis, requirements synthesis, kinematic design, UI design, and evaluation studies. Within three projects that lasted from October to December 2019, April 2020 to September 2021, and January 2022 to December 2022, potentials in specific workplaces were identified, a kinematic demonstrator was developed, pHMI were designed, and control strategies were evaluated.

8.1. Definition of the Context of Use

For the definition of the context of use, workplace analysis in five companies was conducted using the method described in Section 4.2.1, but an earlier version of the described checklist. Three companies are from the sector of production, one in the logistics sector and one in the craft trades sector. Eight workplaces were analyzed in these companies, and their potential for exoskeleton development was evaluated. Three specific workplaces (WP) were chosen, and three companies were selected since they had similar processes and side tasks. All of them involve lifting weights up to 30 kg and are in structured environments where the pace of work is determined by the machines they are working with.

8.2. Step One: Context of Use Requirements for an Exoskeleton for Heavy Lifting and Carrying

8.2.1. Workplace Analysis

WP 1: Single-piece goods must be separated from bulk and individually packaged. Most of the time, the work is done in an upright upper body position, but the placement makes it necessary to rotate the lower back. For lower levels, the worker has to bend down and pick the items out of mesh box pellets. Facilities to lift the boxes, where the bulk goods are provided, are present and used in most cases. The piece goods differ in shape and size, having complex shapes, e.g., a compressor, and weighing up to 12 kg on average and up to 30-40 kg maximum. They must be single-packaged into tight boxes with packaging material, leaving little space at the hands and lower arms. The machine provides the pre-folded boxes on a roller conveyor, where the workers take the boxes from, package the items, and further transfer them into the packaging machine. Side tasks include machine maintenance, gathering the packaging materials, restocking the machine, cleaning the machine, and taking away trash. Used tools are carpenter knives.

WP 2: Providing and filling a machine with different components according to individual recipes. A machine has to be used and provided with components at times and in quantities given by the machine. The necessary input materials vary depending on the ordered end product and quantity. The handled materials are primarily provided in bags with 25 kg weight and need to be poured in a funnel positioned around chest height, which requires lifting the hands to shoulder height with the full bags. Over-shoulder lifting is only necessary for completely emptying the bags or sometimes buckets. Means for lifting the pallets, where the bags are stored, are provided. Therefore, bending down is only required in side tasks without lifting heavy weights. Sometimes lighter loads need to be measured into buckets at a nearby scale and then filled into the machine. Side tasks include cleaning, preparation, and taking away garbage. The walkways include walking stairs and confined spaces. Used handheld tools include carpenter knives, scales, and chutes.

WP 3: Remove hot goods from molds and transfer them to the next machine. A roller belt delivers hot casting molds to the workplace, where the worker has to extract it following a specific routine and clean the mold. The goods needs to be carried 3 to 10 meters to the next machine and placed on another conveyor belt. The weight of the goods varies between 0.5 to 18 kg, and they arrive in a random order. The extraction workplace is a very confined space on both sides, and part of the machinery is in the field of view of the worker due to a lifting mechanism from above. The placement of the goods in the second machine requires the worker to hold the goods while reaching far out, being an unnatural, straining body posture. The workers also have to handle the casting mold for cleaning and use extraction pliers. No regular side tasks have to be done. They have job rotations due to the high temperatures.

All the workplaces display the handling of loads with the maximum ranging around 25 kg with the hands, most of the time in an upright position. Following the classification from Section 4.2.1, the exoskeleton must support the arms during load handling. Due to the high loads, it needs an active actuation, and the structure should be rigid. Due to the shoulder being part of the kinematic chain, a non-anthropomorphic design is chosen to reduce complexity and weight. Due to the confined workplaces and to reduce inertia, it was decided on a cable-driven actuation system since it enables the motor to be placed on the back of the person, and cables at the arms allow for inherently compliant actuation and lower weight and construction space at the limbs.

8.2.2. Motion Analysis

Similar to Tröster et al. (2018), a laboratory study was set up to analyze the motions during the main and side tasks in the three described workplaces. The study was designed and conducted by Oberbauer (2020). The main characteristics of the workplaces, like the dimensions, placements, and confining or disturbing structures, were represented. Knowing the trajectories, velocities, and accelerations of the limbs defines requirements for the exoskeleton to enable natural motions with and without loads of representative size and weight of the handled goods.

The motions were tracked using the VICON OMC System (VICON, Oxford, UK), a motion-capture system that uses reflective markers on characteristic body fixpoints recorded by infrared cameras. The recording was conducted with a frequency of 100 Hz. For the study the whole body of the participants were marked according to the plug in gait model, incorporating 34 markers. For each of the three workplaces described in Section 8.2.1 mock-ups of the workplaces were built, utilizing tables and constructions made of aluminum profiles, wood plates and cardboard. Nine cameras were positioned around the study area so that all the markers were at least visible by two cameras at all times, despite occlusions by the workplace mock-ups. The recording was conducted with the Vicon Nexus Software 1.8.5.

The workplace mock-ups were designed to accommodate the following workflows. For the purpose of the study, the weights for WP2 were reduced compared to the original weights to avoid overloading the study participants. WP1:

1. Picking up an empty cardboard box from the supply area (height: 150 cm) and placing it on a roller table (dimensions: 160 x 60 cm, height: 60 cm)
2. Taking filling material from the supply area (height: 110 cm) and placing it into the cardboard box
3. Turning around 90° to the right
4. Opening a box with a carpenter knife (length: 65 cm, operating height: 122 cm)
5. Picking up an item (height: 104 cm, weight: 12 kg, 16 kg, 18 kg)
6. Turning back to the roller table 90° to the left
7. Placing the item into the carton box
8. Pushing the carton box 60 cm away to the back of the roller table
9. Side task: exchange of the roll providing the filling material
10. Repeating the whole process, but step 5 with bending down over an obstacle (height: 104 cm) to pick up an item from the bottom of the bulk bow area (height: 15 cm, weight: 12 kg, 16 kg, 18 kg)

The study mock-up of the workplace WP1 is shown in Figure 19.

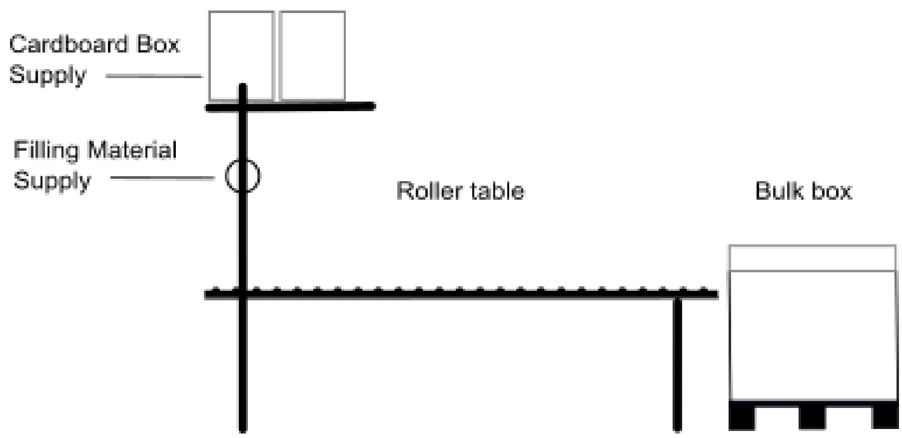

Figure 19 Experimental set up to represent the described work-flow for WP1. Showing a bulk box for item pick up, supply for the pre-folded cardboard boxes and filling material, and the roller table for conveying the filled boxes further

WP2:

1. Picking up a bag full of coarse grit (height: 60 cm, weights: 10 kg, 15 kg)
2. Turing around 180°and walking 100 cm

3. Placing it on the edge of a funnel mock-up (height: 86 cm)
4. Opening the bag with a carpenter knife
5. Emptying the bag into the funnel
6. Turing around 180°and walking 100 cm

The study mock-up of the workplace WP2 is shown in Figure 20.

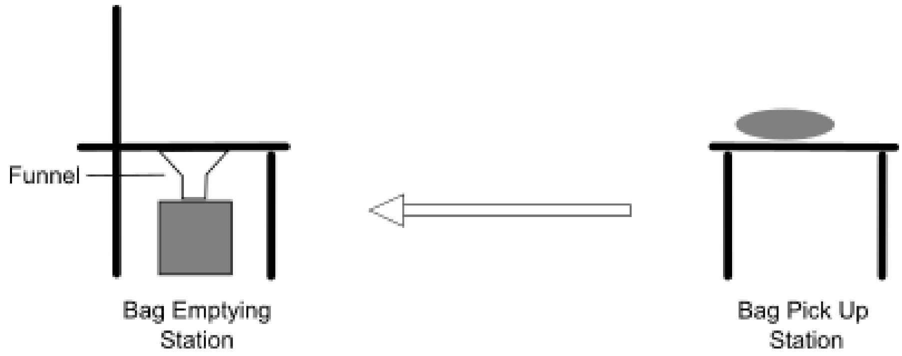

Figure 20 Experimental set up to represent the described work-flow for WP2. Showing a table to pick up the filled bags, 100cm walking distance in between, another table with a funnel, to put down the bags, cutting them open and filling them into the funnel.

WP3:

1. Taking the lid off an item (height: 95 cm), with an obstacle hanging over it (width of obstacle: 30 cm, same depth as item)
2. Placing the lid on the left side of the workplace on a side table, 30 cm to the side, maneuvering around a wall on the left side of the workplace.
3. Picking up the provided item (weights: 0,3 kg, 1,5 kg, 12,2 kg)
4. Turning around 180°
5. Transporting the item up to 300 cm
6. Placing the item onto the drop off station ((height: 86 cm, surface area: 60 x 100 cm), 20 cm away from the edge
7. Pushing the item to the back of the drop off station
8. Repeating the process two times with different weights
9. Stacking the items that were transported to the oven

The study mock-up of the workplace WP3 is shown in Figure 21.

Nine participants with experience handling loads in a broader range of anthropometric measurements were invited to the study. Their body length ranged from 1,62 m to 1,83 m and represented the 15th to the 82th percentile of the German population aged 18 - 65 according to the iSize database, men and women combined (Human Solutions GmbH, 2009). More details on the study and pictures are described in Oberbauer (2020).

The data was analyzed afterward, and the results are incorporated in the requirements list in Table 5.

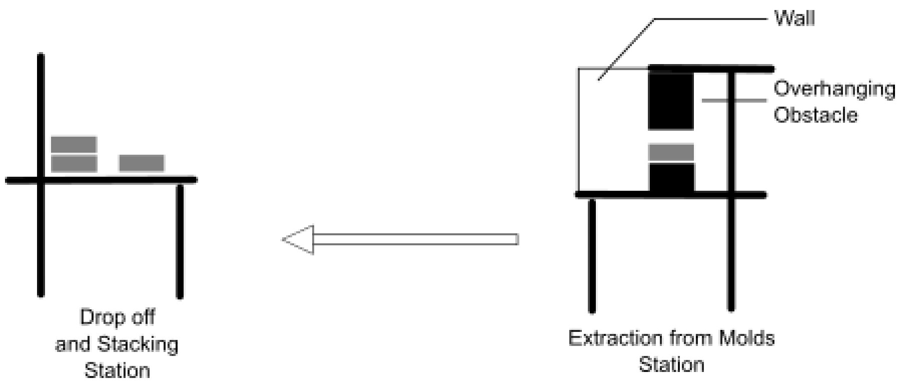

Figure 21 Experimental set up to represent the described work-flow for WP3. Showing a table with an overhanging obstacle, where the produced item is extracted from simulated molds, a walking distance of three meters to a drop off station, where the items are collected, pushed to the back of the station and stacked. Drop off table, left of the extraction station for the dropping off the lid is not depicted in the figure.

8.2.3. User Story

A user story was developed to better understand the requirements of the kinematic structure and the pHMI. The setting is the average day of a production worker who works inside a factory using the future exoskeleton. The story includes the preparation before the start of the shift, where the worker arrives at the location, the actions during his shift, including different types of side tasks, as well as shorter or longer breaks, and the aftercare after the shift ends until the worker leaves the premises.

I. Before of the shift:

1. Arrival at the production plant, putting on work gear in locker rooms
   - Safety footwear
   - Protective work gear
   - Work jacket
   - **if applicable:** individualized items of the exoskeleton (e.g., padding)
2. Going to the central storage location of the exoskeletons and adapting the exoskeleton to individual size and settings
   if applicable: automated adaptation via RFID chip or employee ID card
3. Putting on exoskeleton without help from another person.
   if applicable: within a storing station that also charges exoskeleton
   if applicable: exoskeleton is in a locked position. Moving components are secured and do not interfere with the putting-on process.
   - Worker positions themselves in the docking station
   - Connects themselves to the exoskeleton with the pHMI
   - Leaving the docking position wearing the exoskeleton
   - If necessary, minor adjustments, depending on inter-individual changes of the body and preferences
4. Worker wears the exoskeleton, which is in a locked position and switched off until they are ready to switch it on
5. Execution of tasks before shift begins (e.g., preparing food, drinks, toilet break, clocking in)

II. Start of the shift:

1. Arrival at the workplace and preparation of the workplace (Set up machines, restock materials, retrieve orders)
2. Switch on exoskeleton (**if not part of step 3 in "before the shift"**)
   result: exoskeleton switched on, still in locked position
3. worker releases moving parts of the exoskeleton from the locked position and attaches them to the pHMI on arms and hands
   if applicable: pHMI at the hands/wrists part of the working gloves or extra to be put over or under standardized working gloves
4. Calibration of the exoskeleton, adaptation to upcoming order, adjusting settings to individual preferences
5. Execution of side tasks with switched-on exoskeleton but without assistance of the exoskeleton ("free mode")
6. Switching into "work mode"

   Option 1: Worker deliberately activates assistance by exoskeleton: input modality or gesture necessary

   Option 2: Exoskeleton automatically switches between "assistance" and "no assistance" conscious input by the worker: intention recognition necessary

III. During the shift:

Small side tasks: Switching to "free mode," no accidental assistance activation possible (safety) (return to II.5.)

Big side tasks: Disconnecting pHMI at the limbs, putting exoskeleton to the locked position (return to II.2.)

Small breaks: Disconnecting pHMI at the limbs, putting exoskeleton to the locked position (return to II.2.)

Big breaks: Putting off exoskeleton, putting it into the docking station (process see in IV. afterward return to I.3.)
batteries can load during break (quick recharge times within 30 minutes necessary, but capacity only needs to last up to 5 hours)

IV. After the shift

1. Execution of tasks after shift (e.g., food, drinks, toilet break, clocking out)
2. disconnecting pHMI at limbs
3. putting exoskeleton into its locked position
4. switch off exoskeleton
5. clean up the workplace
6. got to the docking station
7. put off exoskeleton without the help of someone else
   - Worker positions themselves in the docking station wearing the exoskeleton
   - Disconnect themselves from the exoskeleton at the pHMI
   - Leaving the docking position
8. Worker documents wearing times and, if necessary, maintenance requests

9. Putting off work gear in locker rooms
    - Safety footwear
    - Protective work gear
    - Work jacket
    - **if applicable:** cleaning of individualized items of the exoskeleton (e.g., padding) or disposal to centralized cleaning services by the company
10. worker leaves the premises

8.2.4. Requirements for an Occupational Exoskeleton for Heavy Lifting and Carrying

The most relevant requirements are outlined in Table 5. These requirements are derived from the general design principles and translate into the components' requirements. Further requirements for each component are directly derived from the design principles in Appendix C - H. In the following development process, design choices are directly referenced to the corresponding design principles.

Table 5 Requirements for an exoskeleton for lifting tasks in semi-unstructured workplaces, referenced in the left column to the origin design principle from appendix C to I

	Requirement	Value	Source
G.1	Dynamic support of arms during lifting	25 kg	Workplace requirement
G.1	Dynamic support of arms during lowering	25 kg	Workplace requirement
G.1	Static support of arms during holding	25 kg	Workplace requirement
G.1	Active support by mobile power supply	25 kg	Workplace requirement
G.1	Point of assistance as close as possible at the hands	25 kg	Workplace requirement
G.1	No big structures at hand for reaching in boxes		Workplace requirement
G.1	Free fingers to pick up boxes from flat surfaces		Workplace requirement
G.7	Battery capacity	5 hours	User story requirement
G.7	Battery loading time	30 minutes	User story requirement
G.8	Exoskeleton has a locked position of the moving parts		User story requirement
G.18	Compatibility with work gloves: pHMI at hand can get dirty, is easily washable, or standardized work gloves can be worn over/underneath		User story requirement

D.1	Adaptability 5th to 95th percentile	Recent data selscted from the iSize database	Human Solutions GmbH, 2009
D.3	Room of motion of the hand (distance between shoulder and wrist)	max: 845 mm	Section 8.2.2
D.4	DoF	Wrist: Dorsal extension <60°, Palmarflexion <70° Radial adduction < 30° & Ulnar adduction 40° Elbow: Pronation & supination: 90° Extension: 10° & flexion 150° Shoulder: Anteversion: <170° & Retroversion: <40° Abduktion: 180° & Adduktion: <40° Outside rotation: 60° (hanging upper arm) & 70° (abducted upper arm) Inside rotation: 95° (hanging upper arm) & 60° (abducted upper arm) Back: Rotation & Lateral inclination: +/- 30° Extension: 30° Upper back extension -2 cm & flexion +4 cm Lower back extension -2 cm & flexion +5 cm	von Salis-Soglio, 2015
D.8	Acceptable structure heights on the body parts	Hands/Palms: 2,54 - 6,35 mm Forearm: 6,35 - 12,7 mm Elbow: 50,8 - 101,6 mm Upper arms: 25,4 - 50,8 mm Shoulders & upper back: 50,8 - 101,6 Upper body and lower back: 25,4 - 50,8 mm Hip: 50,8 - 101,6	Zeagler, 2017
P.11	low pressure at pHMI	Upper trapezius below 0.8 kg/cm² Lower back <1,7 kg/cm² Middle deltoid <1,3 kg/cm² Upper back <1,1 kg/cm²	Fischer, 1987
P.8	Individualized components of the pHMI that can be easily switched		user story requirement
P.11	Low shearing forces at the pHMI	detectable threshold at 2 N over 6,35 mm	Chinello et al., 2016
C.1	Velocities of the dominant hand	max free: average max 1,7 m/s max free peak: 3,41 m/s max with load: 0,33 m/s	Section 8.2.2
C.1	Positive accelerations of the dominant hand	max free: average max 5,0 m/s² Max free peak: 8,2 m/s² Max with load: 3,2 m/s²	Section 8.2.2

8.3. Step Two: Design of the Kinematic Structure of an Exoskeleton for Heavy Lifting and Carrying

8.3.1. Mechanical Structure

The design goal of the exoskeleton is to support the lifting, carrying, and lowering of loads at the hands with a cable-driven actuation. The forces are supposed to be transferred via a mechanical structure that goes around the shoulders and the back and rests on the hip of the user, where the forces are transferred back into the body. So the basis of the structure is the pHMI at the hip, "vertical structures" going cranial parallel to the back, and "horizontal structures" that reach from the back of the human to the front, arching over the shoulders without putting a load on them. From those "horizontal structures," the cable running inside the structures exits them and is connected directly to the hands, where they can exert pulling forces. The structure resembles a lightweight body-worn crane and is sketched in Figure 22. Note that the naming of the structures as "horizontal" and "vertical" comes from their orientation in an upright body posture of the user.

The "vertical structures" are attached to the upper body at the shoulder belt and the hip. The kinematics at these attachment points are designed to allow a full range of movement for the user despite having long, straight, rigid structures running along their back. Those were designed with misalignment compensation strategies as described in Näf et al. (2018), and the resulting designs are patented. The corresponding patents are Eberhardt and Harbauer-Riess (2022a, 2022b) and describe the used kinematics in more detail.

The ball joint at the hip is positioned at the furthest lateral point that does not impede the arm's lateral movement along the torso (D.3). In the first iteration, the vertical supports were one long, straight tube where the cable runs through and a length adjustment mechanism. However, preliminary tests showed that the elbows collided with the vertical supports during motion because the waist is slimmer than the hip. Therefore, a second iteration was made, where the lowest part of the vertical supports curves inward in an S-shape to follow the body's natural silhouette. Since the structure has to be suitable for the 5^{th} to 95^{th} percentile of the European population, only a small solution space was available since most of the length of the vertical structure is needed for a fitting length adaptation mechanism (D.1).

The horizontal structures are very controversially discussed within the project. Making them too long interferes with the field of view of the user and increases the risk of colliding with the environment or other body parts. But for tasks where loads have to be put down far away from the body, the user has to work against the assistance because the rope not only pulls the load up but also back to the point where it exits the mechanical structure. So, having the horizontal structures always directly above the hands would increase the assistance in the described scenario, like a crane, but reduce acceptance in every other situation. It was decided to offer both solutions to the workers in later iterations so the users could pick their favorite. This requires a modular design of the vertical structures and a corresponding interface, a user-friendly strategy to switch them out and thread the cable through, and a calibration routine for the exoskeleton.

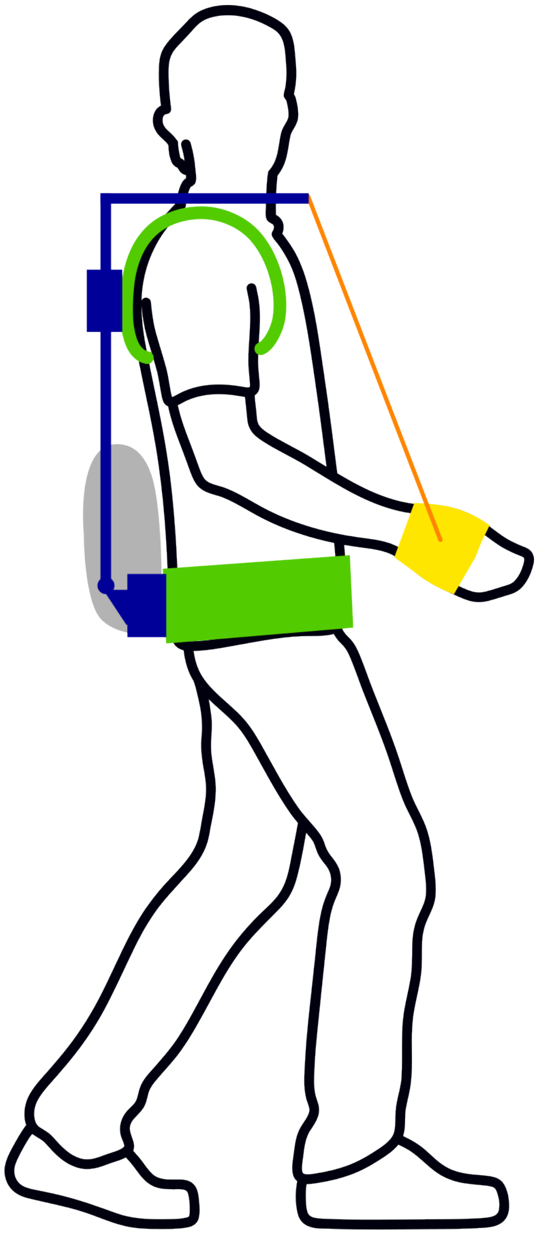

Figure 22 Kinematic structure of the occupational exoskeleton for heavy lifting and carrying, containing a rigid frame (blue) for load redistribution and cable-driven actuation. It entails pHMI for the upper and lower back (green), and the hand (yellow)

8.3.2. Evaluation of the Mechanical Structure Using Analytic Methods

The forces acting on the pHMI at the back are calculated using a two-dimensional static model of the exoskeleton with a load of 25 kg pulling on the cable at an angle. The pHMI at the upper body is modeled as a roller support that only transfers forces orthogonal to the human back. The bearing at the hip is modeled as a pinned support since it offers free DoF in all rotation movements but no translation movement. Figure 23 displays the resulting free-body diagram.

This results in a simple equation for $B_v = -F\frac{a-r+b}{h}$. For F being 250 N, the relation of the force to the other measurements can be described.

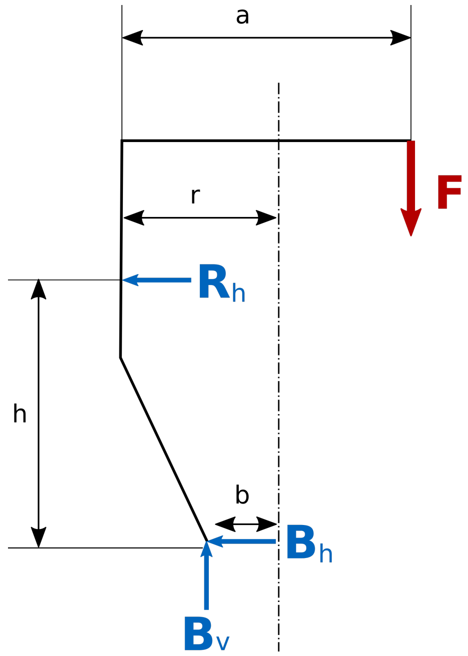

Figure 23 Free body diagram of the horizontal and vertical structures of the exoskeleton.

R_h and B_h point in different directions. This means that the force R_h is perceived as pressure on the back, while B_h is perceived as a pull backward on the hip. For a<r-b, it is the other way around. For $(a - r + b) < h$, the force $B_h < F$ is being transferred on the back and hip, so it is recommended that r and h should be as large as possible, while a and b should be as small as possible.

- The further in front B lies, the better
- The higher R lies, the better
- The outrigger A should be as short as possible
- The overall height of the exoskeleton has no influence. The position of the back support should be chosen as high as possible

A plot of the straight line shear B_h over a for different values of h is shown in Figure 24 (for b=0m) and shown in Figure 25 (for b=0.15m).

8.4. Step Three: Development of the Components of an Exoskeleton for Heavy Lifting and Carrying

8.4.1. Dynamics

The actuation was developed by J. Schmalz GmbH and tested using a test stand consisting of a vertical board, where all the actuation components are mounted, and a vertical beam is sticking out horizontally. At the tip of the beam, the cable exits the structure. The behavior of the actuation system and the control can be tested by a person standing under the beam and being connected with a hook on a glove.

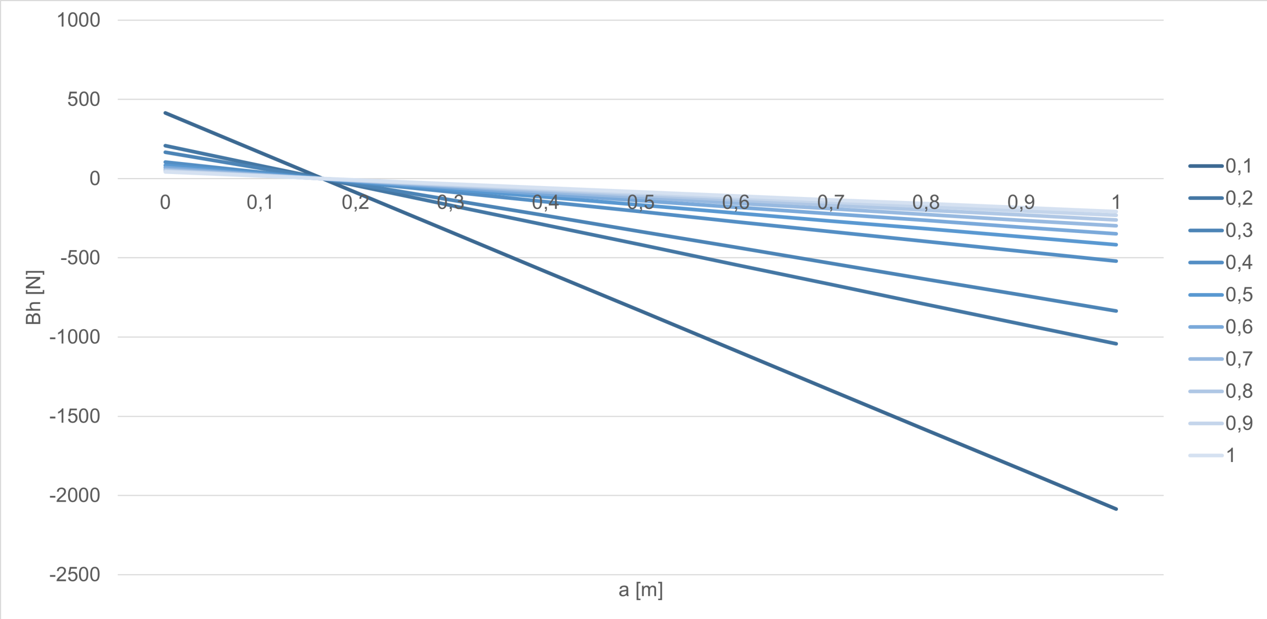

Figure 24 B_h over a for F 0 250 N, r = 0.17 m, b = 0 m for different values of h.

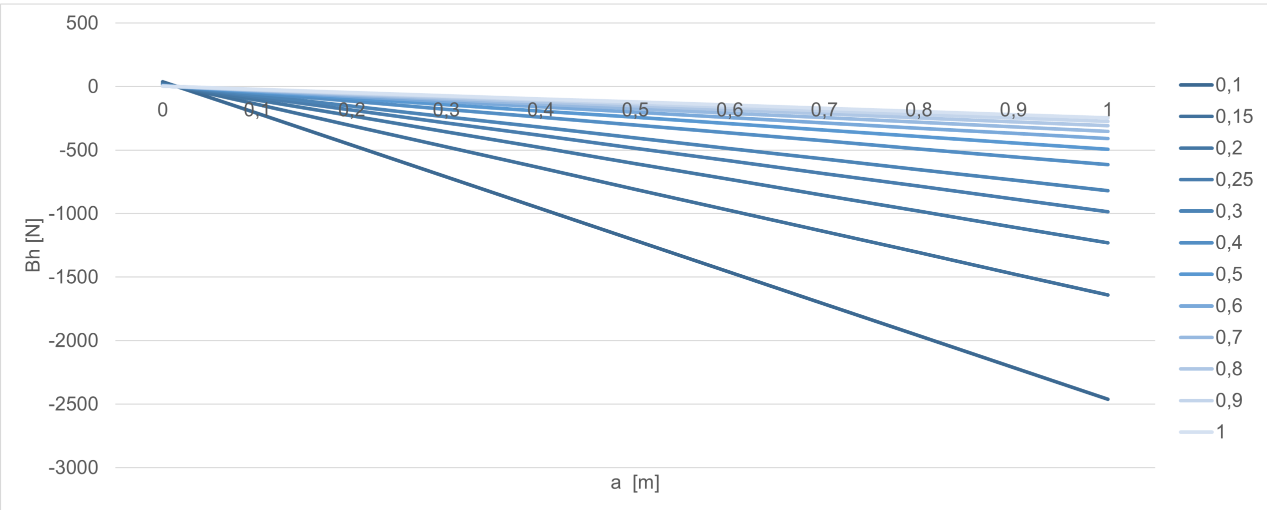

Figure 25 B_h over a for F 0 250 N, r = 0.17 m, b = 0.15 m for different values of h.

8.4.2. pHMI

The pHMI of the exoskeleton are as described in Section 8.3.1 the following points of interest:

- The hand where the cable is attached
- The upper back where the exoskeleton is supported for stability
- The hip where the exoskeleton is attached tightly and transfers the load from the assistance as well as the own weight

pHMI upper back

The placement of the pHMI for the upper back was placed in the upper back area, where it does not constrain the motion of the shoulder blades (P.4, P.6) but is still pressing on the chest area, where no movement is happening due to the rip cage. The area where the pHMI acts on the back is chosen as big as possible to reduce the pressure per cm^2 (P.11). Since only forces orthogonal to the back are being transferred and none pushing down on the shoulders (P.12), the pHMI is held in place with two shoulder straps. Those do not need to be fastened very tightly. Hence, special care for physiology and anthropometry is not necessary (P.2, P.3, P.4, P.5, P.6). This results in easy and fast slipping in and out as well as thermal comfort since they are only covering a small area (P.7, P.9, P.10).

pHMI hip

The first iteration of the pHMI consisted of the hip part of a utility military belt. Due to the forces acting on the belt, as described in Section 8.3.2, the thin belt pushing into the lower abdomen was perceived as highly uncomfortable. Therefore, a second iteration implemented a soft, off-the-shelf orthosis for supporting the lower back. With the rather broad textile design, the pressure was well distributed over the body (P.11). With the Velcro closing system, it was easy and quick to put on but could be adapted by every person individually (P.3, P.9). additional straps makes it possible for the user to ensure a tight, but comfortable fit so that the pHMI stays put over the changing volume of the stomach without causing discomfort (P.1, P.3, P.4, P.11, P.12, P.13). Due to the soft structure it adapts to every body shape and the motion of the lower back (P.6). The orthosis has a support structure with a little more rigidity in the back, that supports the lower back, similar like a softer corset. This allowed attaching the rigid connection of the hip pHMI bearings for the mechanical structure. It also offers space to attach the housing for the motors and electronics.

pHMI hand

In the first iteration, a glove from a former project was used, consisting of a standard working glove with a strap sewn across the back of the hand. A hook could slide along the strap, and the supination and pronation of the hand was freely possible while the hook was attached to the cable. However, this design reduced the user's bloodstream when a load was pulling on the strap on one side, which resulted in the band cutting into the hand on the opposing side. Further, the pull at the back of the hand resulted in the hand being pulled in unwanted directions. It introduced a torque that tried to turn the hand back into a position orthogonal to the pulling directions. That might result in a safety hazard when handling loads.

Due to the many requirements for the glove design, a workshop with six experts from product development and exoskeleton development from J. Schmalz GmbH was executed to identify new designs. From the user story, the requirements for the glove were again specified as presented in the Table 6 to be correctly understood by all experts. Therefore, some other terms were used in Table 6 as in the design principles from Section 4.1 since they were better understood than the scientific terms.

Table 6 Requirements for the pHMI of the exoskeleton for heavy lifting as defined by the experts in the design workshop

arrival	work gloves underneath or integrated in pHMI hand Independently to put on comfortable hand still "normally" usable
start of the shift	independently connectable with exoskeleton even distribution of pressure and adequate in all directions robust against heat or chemicals or special gloves put over robust against environmental factors fine motor skills usable safety: emergency release from exoskeleton
break/side tasks	fast disconnect from exoskeleton especially for special side tasks like reaching into a shelf fast drying materials
end of shift	completely or partially washable

The experts were separated into two interdisciplinary groups where they developed a new design, each in design sprints, and prototyped them. Afterward, they evaluated each other's design, and in a second design sprint, each team redesigned their prototypes. In the end, a final evaluation of each other prototypes, including a test at the test bench with the actuation system, was conducted.

Prototype 1 consists of two braces connected with a rope. One brace is located around the palm, the other around the wrist. Both braces allow the connection to the rope to slide around the hand or the wrist. Therefore, the supination and pronation are possible. The rope is connected to the cable of the exoskeleton. Due to the flexibility of the rope the support was observed to be always in the right direction, and no unwanted torques were introduced (Figure 26). The user's thumb obstructed the full sliding on the brace around the hand. Therefore, the range of sliding needs to be adapted.

Prototype 2 consists of a quick lacing system at the back of the hand connected to a stiffer textile patch in the palm; see Figure 27. The laces are connected with the textile between the user's fingers, tensioning it and distributing the force from the pHMI over the whole hand. A wristband hinders the glove from sliding up when the lacing system is tightened. The waistband is connected with the central point of the lacing system at the back of the hand with another strap. The connection between the strap and wristband can slide around the wrist. This resulted in no unwanted forces and torques when the glove was connected to the exoskeleton at the strap. However, the singular attachment at the back of the hand still results in the

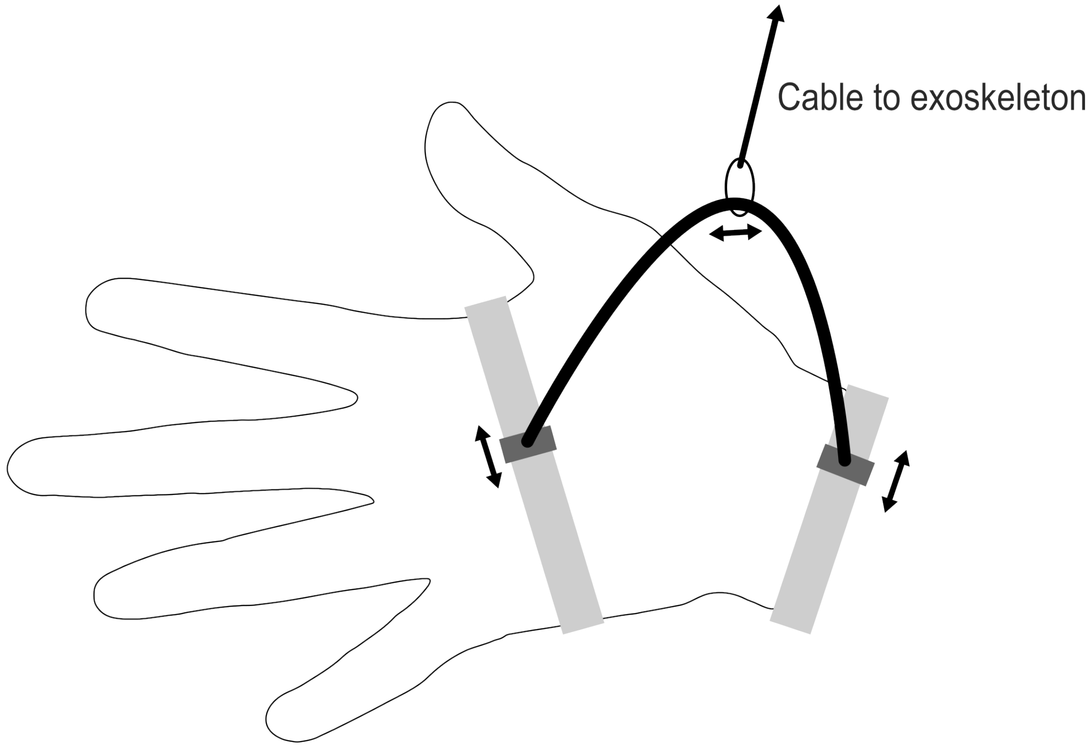

Figure 26 Schematics for prototype 1 for the pHMI hand of the exoskeleton (preliminary picture)

hand being forced into a pronated position. But when closing the hand, the user must work against the stiffness from the lacing system. Therefore, more elasticity should be implemented. The laces between the fingers and the textile at the palm result in difficulty in putting the system on and reducing thermal comfort.

In the final evaluation, the experts concluded that there is great potential in combining the two prototypes into one. The pressure distribution over the whole hand and the two anchor points that can fully slide around the hand and wrist while being connected with a flexible element promises a feasible solution to most requirements. For the hand's pHMI, the exoskeleton's attachment point must always fit with the hand's position while holding a load. Further, the full range of motion is still possible with both concepts, and the distribution of forces is comfortable over a larger area with no pressure peaks. The experts further discussed that an "ergonomic" feeling is essential from the first moment when the exoskeleton introduces forces without constraining forces and torque acting in unwanted directions. The free motion of the hand is as important as the support of the hand.

8.4.3. Sensors

J. Schmalz GmbH developed the sensory concept which is proprietary and not part of the project.

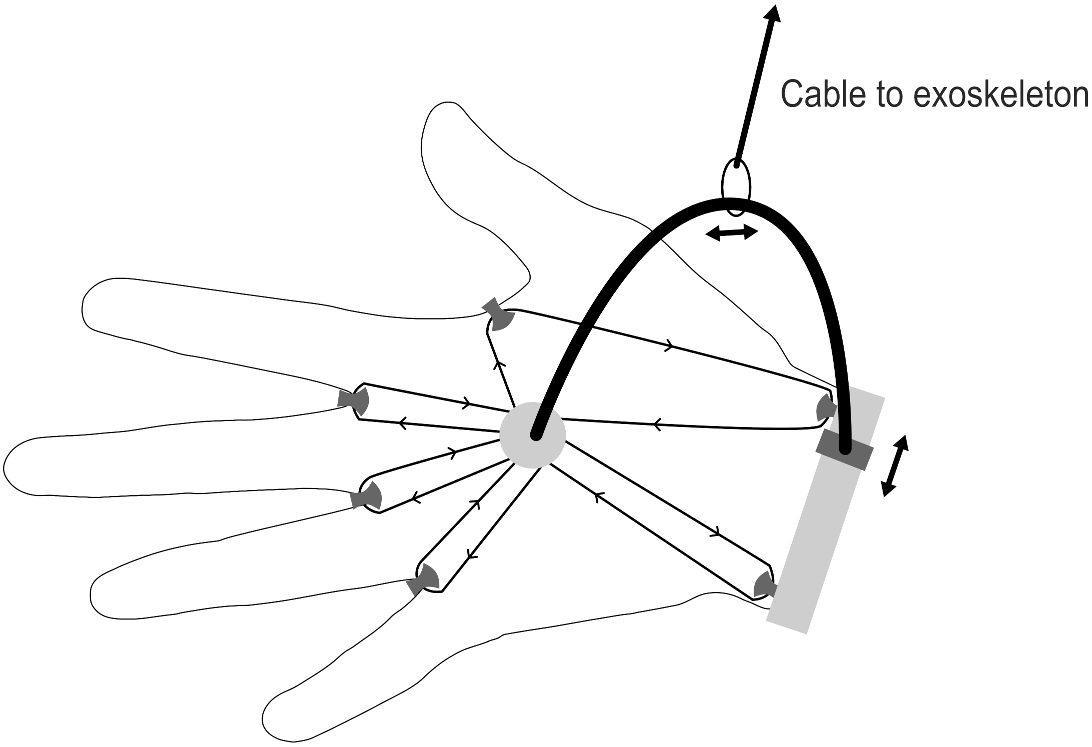

Figure 27 Schematics for prototype 2 for the pHMI hand of the exoskeleton (waiting for approval of publication, until then ugly sketch)

8.4.4. UI

An UI was developed by Klein (2022). It was designed in a way that uses the existing structure of the exoskeleton. An emergency stop button, as well as an activation gesture, was implemented, which changes between the "free mode" and the "work mode," which are described in the user story (Section 8.2.3). The mechanical components should not interfere with the context of uses described in the workplace analysis (Section 8.2.1) and offer good usability in themselves, following high effectivity, efficiency, and user satisfaction. Three concepts were designed and implemented as function prototypes in a passive exoskeleton prototype and evaluated in a usability study. The study was conducted with 18 participants with no previous experiences with exoskeletons.

The three designed concepts showed no significant differences in their effectiveness, meaning they are all usable without the user making more or less mistakes (U.2, 7.8). One of the three concepts showed to be significantly more efficient and had a significantly better user satisfaction (U.1). In a qualitative data from the study showed that the participants had a positive attitude to the mentioned UI. So, this concept will be described further.

The UI is supposed to switch between the following modes:

- System turned off
- System in standby
- System in "free mode"
- System in "work mode"

The switching within the "work mode" between "assistance" and "no assistance" will not be addressed by the UI. Since the change between "free mode" and "work mode" is supposed to be via an activation gesture, only a physical input to switch the system on and off and standby must be provided. The user must be able to change the amount of assistance the system delivers for each side individually, as well as sync them if wanted. Further, the user can change the system's dynamic, represented by different "work profiles." These "work profiles" mean that the system reacts quicker or moves faster in one setting than in the other, depending on the task ahead and personal preference. Those four modes, the level of assistance, the active work profile, as well as error signals, and the battery capacity, should be communicated by the system to the user.

Activation gesture The activation gesture is implemented via two conductive foils placed on each glove's ulnar and radial sides. When the sides of the hands touch, the activation gesture is recognized, and the modes switch from "free" to "work" and back. The gesture is not cumbersome and can be done with gloves and full hands. Still, the placement of the foils and the necessity of the opposing sides of the hands having to touch means the activation cannot happen involuntarily or by accident.

Input modalities The input of the assistance level and the work profile are realized with rotary dials. For the assistance level, a 70 mm rotary dial (U.15) is placed on both sides of the hip to adjust the level individually for each side. A button to sync both sides is positioned laterally on the dial. Those two are placed as far ventral as possible on the hip (U.3), without them bumping into the machine or table if the user is standing close to one (U.3, U.11). Representative symbols are displayed on the dial to give the user feedback on the current level of assistance. The work profiles can be changed with one smaller rotary dial (50 mm, U.15), placed on the right side dorsal behind the bigger dial because the work profile does not have to be changed as frequently (U.14). Due to the difference in size, they can be changed without looking (U.9). The button for switching the system on and off is placed on top of that. The visibility (U.11, U.12) was calculated according to DIN EN ISO 15008 DIN Deutsches Institut für Normung e.V., 2017 of the symbols. The reachability (U.10) was evaluated using the anthropometric digital human model RAMSIS. The study participants also confirmed both. The symbols representing the "work profiles" were evaluated in the user study for their ambiguity (U.7). Between numbers, animals, and geometric shapes, all participants preferred the numbers.

Output modalities Feedback about the Standby- or On/Off-Mode is represented via a status LED at the "horizontal structures." The battery capacity and uncritical errors are also communicated via LED displays at the "horizontal structures." For more critical events, the displays start flashing, and acoustic warning sounds are part of the concept. Another critical error is the overload of the system when the user is lifting too much, which is also signaled via a blinking error display. The activation of the emergency stop button is also displayed there, with its own LED display. This way, the displays are in the worker's field of view (U.11) and are noticeable even in a noisy environment (U.8). With increasing urgency, the signals become more noticeable due to flashing lights and the additional use of the auditory sense.

Emergency stop The standardized emergency stop was placed on the shoulder straps of pHMI upper back in the chest area. Therefore, it can be reached even when the cables are fully reeled in. Due to the flexibility of the structures, one emergency stop is sufficient since it can be reached with both hands (U.10). The placement does not disturb natural motions and is not irritating to the user (U.1, U.3., U.9). But the placement also prevents accidental pushing of the emergency stop (U.15)

8.4.5. Control

The control was developed by J. Schmalz GmbH and is based on admittance strategies. For tuning the control parameters so that future users best accept them, a study was conducted within the company. The control parameters were implemented on the actuation module on the test bench described in Section 8.4.1. Three different control variations were tested with prototype 2 of the pHMI hand and a weight of 5 kg, which is supposed to be lifted with the assistance of the test stand.

The performance of the control variations was measured using a questionnaire and with an IMU-based motion capture system (CAPTIV motion). The questionnaire consisted of three questions after the person tested each control variation five times. Those were to be answered on a Likert Scale. For the questions about the perceived support and natural motion a four point scale was used, while for the assessment of their feelings towards the system and the support, a five point scale was used.

- I have felt supported by the system
  does not apply at all - rather does not apply - rather applies - fully applies
- The lifting/lowering felt natural
  does not apply at all - rather does not apply - rather applies - fully applies
- How did they feel about the support during lifting/drop-off?
  Very bothersome - a little bothersome - felt nothing at all - a little supportive - very supportive

At the end, they were asked to give an order of the experienced variations, which they preferred from most to least. They were asked to give further comments accompanied by two finishing questions:

- How do you feel about the system?
  Very positive - Rather positive - Neutral - Rather negative - Very negative
- Has your attitude towards the system changed compared to before the study? *To the positive - exactly the same - to the negative*

17 participants from different departments of the J. Schmalz GmbH were invited. All of them are right handed. Twelve work in the offices but are closely related to production and 5 work in the production. 14

identify as male and 3 as female. First, the anthropometric data of shoulder height and arm length were measured since the test stand has a fixed height, and an influence on the participants' perception might be possible. After they were introduced to the test stand and the study, they had some time to get used to the test setting and moving with their right hand in the pHMI hand and attached to the test stand in the "free mode," with and without weight. Afterward, a baseline was conducted with them lifting the weight in "free mode." The motion started with a relaxed elbow hanging down lateral of the body to lifting it to a 90° flexion of the elbow ventral of their body. Afterward, the three control variations were tested randomized, accompanied by the questionnaire described above. They were asked to think aloud about what they were experiencing and thinking during the trials. Those comments were noted during the study.

The results of the questionnaires show no significant preferred variation. There is no significant better variation regarding natural feeling, agility, or perceived support. Further, the anthropometries of the participants also showed no significant influence. Neither did the field of work. The motion capture data was examined for a correlation between the lifting velocity and the preferred control variation. It showed that the preferred control variation and the velocity are not dependent.

Even though the quantitative data gave no insights, the analysis of the comments gave valuable insights.

- The most compliant expression is perceived most positively, especially in the beginning
- The medium expression received the most positive comments, especially in the last run
- Negative comments were more specific than the positive ones, which allowed direct derivation of improvements
- Most comments were related to the test bench and not the control (awkward wrist posture, high vibrations, feeling like a puppet)
- The different control variations were perceived as different levels of support, although the support force remained the same
- Strong influence of adjustment effects, too few repetitions in the study design for good familiarization

8.5. Step Four: Concept Evaluation by Field Trial

8.5.1. Passive Prototype for Field Testing

A passive prototype was put together to test the kinematics and the pHMI in real work settings. The structure and pHMI were combined, and as an actuation module, two balancers supporting 0.5 kg were attached on both sides. The spring-driven return actuators are mounted at the lowest part of the "vertical structures," the steel cable is threaded through the structures and leaves them at the tip of the "horizontal structures," ending in a hoop. At this part, they can connect with the pHMI hand using a snap hook. Using this passive prototype, WP 2 and WP 3 were visited. At each, workers were asked to try the prototype and do their work as usual. Further, production managers and team leaders from all three companies were asked to test and evaluate the system using their experiences. Due to the unstructured settings, those field evaluations were conducted as open interviews with a user observation if possible.

8.5.2. Results of the Field Trial

The general feedback was good, stating that the prototype shows potential to be usable in the desired context of uses. The range of motion was shown to be acceptable. The overall comfort was rated as acceptable to good. Parts of the horizontal structures collided with the faces of the workers and with the environment. Also, the cable shows the risk of entanglement. The "horizontal structures" in the field of view were described as irritating. Further, crossing the arms was impossible due to the cables and the "horizontal structures" coming in the way. Parts of it moved uncontrolled and made it bulky. The exoskeleton was too unstable, which made putting it on and off bothersome and time-consuming. The pressure of the pHMI at the upper back was perceived as too high, pHMI upper back chafes under the armpits, and sweating under a large area between shoulder blades occurred. The thermal comfort of pHMI lower back was low due to the covered surface area. Therefore, exchangeable and washable components were wished for. The same feedback was given for the gloves, including the possibility to easily change gloves or put specialized gloves over them. Further, the pHMI lower back did not fit well for people whose waist circumference is bigger than the circumference of the lower body. The forces were not evenly distributed, leading to the pHMI lower back sliding down when high forces were transferred via the structures. It also slightly disturbed the bending down in the lower back. The exoskeleton was described as too heavy. The anthropometric adjustment mechanism was also unsuitable for slim users. Some experts mentioned that when leaning forward, there is a risk of the actuation accelerating the load into the user's face. The passive actuation was described as bothersome, since the users have to work against the spring actuation. The exoskeleton should have protection against dirt and dust in dirty environments, and it needs to be quick to put it on and off. Especially in an emergency, the pHMI hand should disconnect instantly, and the exoskeleton should come off within seconds. The exoskeleton should be usable with a forklift. Further the context of use needs to be considered that one hand is handling a load and needs assistance, and the other is pushing buttons and should not be assisted. Few experts addressed concerns that the exoskeleton with the cable coming from the "horizontal structures" might come across as puppet-like, which implies a perceived loss of autonomy for the user.

8.5.3. Optimization Potentials

The field trial showed that the exoskeleton addresses the correct context of use, and users confirmed that the exoskeleton might be a suitable solution. However, they focused on self-evident early prototype problems, like passive actuation, and had trouble imagining it with a fitting control. The general feedback showed optimization potentials in the kinematic structure and the pHMI. Even though the full range of motion can be archived, the structure misses rigidity and integrity, which needs to be improved while still representing the designed kinematic. For example, some DoF are not guided or restricted where they are not required, which leads to uncontrolled behavior and overshooting of the necessary DoF. Together with improved pHMI, the usability of the exoskeleton will increase.

As a result, the *general design* requirements are fulfilled as follows in Table 7. "Fulfilled" indicates that the requirement has been met completely. "Good" signifies that the requirements are met with only minor optimizations required. "Medium" suggests that the requirements are partially met, with a few significant aspects necessitating revision. "Low" conveys that the design falls short of meeting the requirements, although some elements show potential. "Not fulfilled" indicates that the design doesn't meet the requirements and needs major revisions.

Table 7 Fulfillment of requirements for an exoskeleton for lifting tasks in semi-unstructured workplaces by the presented soft elbow exoskeleton design

	Requirement	Fulfillment	Comments
G.1	Good Usability	good	potential described by interviewed experts
G.2	Good User Experience	N.A.	actuation, sensors, and UI not implemented
G.3	Ease of use	N.A.	actuation, sensors, and UI not implemented
G.4	Positive aesthetic appeal	low	"puppet like"
G.5	Low weight	medium	2 kg but described as too heavy, better distribution
G.6	Compact size	low	collisions with environment
G.7	Adequate use Time	N.A.	battery not designed yet
G.8	Transportable and storable	N.A.	not evaluated
G.9	Quick Set Up	not fulfilled	strategies not implemented, assistance needed
G.10	Safe State	N.A.	actuation, sensors, and UI not implemented
G.11	Emergency Exit	good	reachable emergency stops, detachable pHMI hands, exoskeleton can be thrown off within a short matter of time but over 7 seconds for inexperienced users.
G.12	Support rate	N.A.	only measurable in field study
G.13	Low Discomfort	N.A.	only measurable in field study
G.14	Mobility and Independence	N.A.	only measurable in field study
G.15	Low Noise Emission	N.A.	actuation, sensors, and UI not implemented
G.16	Low Vibrations	N.A.	actuation, sensors, and UI not implemented
G.17	Safety	not fulfilled	
G.18	Compatibility with side tasks and tools	not fulfilled	usage of protective gear and forklifts not possible

8.6. Limitations and Further Development Case Study 2

Design sprints in work were proven to be a good tool to develop a new design concept for a specific aspect, like the pHMI of the Hand. The possibility to generate and evaluate several design ideas within the participating expert group and with rapid prototyping fits very well with the intended dynamic of the development process, where the singular aspects should be designed and evaluated on their own before being tested in the context of the whole exoskeleton. This also helps define and mark out specific requirements for the considered subsystem.

Using a test stand for control optimization with user participation is a promising approach, but the study in Section 8.4.5 shows that the test stand significantly interferes with human perception. Therefore, the stand should be redesigned so that user studies can be conducted where the participants can focus on the control parameters. Also, more extended testing periods with a more natural work process would be beneficial.

The exoskeleton itself needs to undergo another iteration of the development process, focusing on the kinematic structure and the pHMI. Further, the put-on-and-off strategy must be made more usable. With that higher fidelity prototype, another field trial with users will be very beneficial and deliver more detailed and specific data. That way, users can use the system on their own and use it over a more extended period of time with all their usual breaks and side tasks.

Similar to case study 1, this means for the development process that the first full integration of the exoskeleton in step four only needs to be as good as necessary. Not every aspect needs to be implemented to evaluate the general design aspects, but the evaluation methods have to be chosen and the prototype needs to be suitable to measure the desired effects. This again shows that prototypes have to be designed with a certain evaluation goal for the designed solutions in mind. This has to be represented more in the development process. This will be discussed further in Chapter 9 in combination with the insights of case study 2.

9. Key Findings in the Case Studies

The two case studies show that the development process is suitable to generate novel ideas in a limited time frame for specific contexts of use. However, the process needs to be adapted in terms of the weighting of the different phases and the evaluation methods.

9.1. Methodology Revised

As the results of case study 1 and case study 2 show, the exoskeleton prototype does not have to be complete yet to get valuable insights from users and trials in workplace environments.

This means that the method must not only be an iteration, but also a spiral, leading each time to prototypes with an ever increasing degree of product readiness. This also results in different evaluation methods that can or should be used and other types of data that can be acquired. The first iteration can end with a prototype just working, moving, and displaying its basic function. Therefore, some kind of actuation is necessary to get feedback on the kinematic compatibility or compliant actuation or the correct application of force by the actuation or the comfort of the physical attachments with a load. However, advanced control strategies or a sophisticated operation concept may not be necessary since the influence of the other premature components is too high. This was shown in the study for tuning the control parameters in case study 2 (Section 8.4.5). The influence of the untested test stand itself lessened the quality of the feedback on the control. Prototypes have to be built for specific purposes, to evaluate the design of the whole exoskeleton or focus on one component. Thereby it has to be designed in a way, that enables the valid, reliable, and objective measurement of a design choice and evaluate it according to the design principles. It has to be represented in the development process which components need to be focused on in which iteration. The case studies showed, it is beneficial, that the components can be prototyped, evaluated and iterated on their own, which reduces the number of evaluations with the full exoskeleton and therefore the number of iterations of the whole process.

It also may not be beneficial to go too early into field trials if the most prominent features of the exoskeleton are only roughly prototyped. Sufficient feedback on the general *dynamics* and the *pHMI* can be achieved with expert interviews or simplified laboratory trials. The time and effort for user studies in the field might not be necessary to get valuable feedback with the first low-fidelity prototype. It is similarly proposed, as in Bengler et al. (2023) and other development processes (see Section 3.3), that exclusively test in the laboratory before going in the field. For HCD, it is necessary to go into direct user contact earlier, as proposed in the mentioned development processes. But the field trial in Section 8.5 showed a state where it is too early. It also showed that going into field trials with a low-fidelity prototype is a possible way of involving users in early development stages. It reduces the effort of the users to participate, shows early potential interference with the industrial environment but increases the effort of the investigators. Therefor this type of evaluation is recommended, if potential issues of the exoskeleton design within the industrial environment is suspected. Still, feedback with similar quality can also be achieved with lower effort for the developers and, just as importantly, for the users.

These fundamental principles are now integrated in a human centered, agile development process. The case studies showed how the criteria and the development goals in each iteration should be designed to give a guideline in development projects.

Therefore, the development process is adapted to generate a higher quality prototype every time the development cycle is undergone. Further, the focused components of each iteration are stated, giving a design goal for the prototypes in each iteration. The criteria to enter the next stage, is the fulfillment of the requirements of those specific components. Since the evaluation methods for each individual component are already set up in the first iteration, the individual evaluations in the following iterations result in less effort. For example, the test bench for testing *control* algorithms already exists for further prototype iterations. Similarly, this applies to biomechanical models used for examining *dynamics*, pressure sensors employed in assessing *pHMI*, and test configurations designed for evaluating *sensor* concepts.

The combination of the development process within each iteration in Section 6 and defined focused components for each iteration result in a novel multilayered development process, specifically for exoskeleton development. By segmenting it into *key components* (Section 3.5), incorporating the defined design principles (Section 4.1, a method to define requirements (Section 4.2), evaluation methods (Chapter 5), implementing agile principles at each phase (Chapter 6), and establishing specific criteria for each iteration (Chapter 9), this represents an innovative approach to the exoskeleton development process.

The process of iterating the steps 3 and 4 sequentially of the process proposed in Chapter 6 is presented in the following Figure 28.

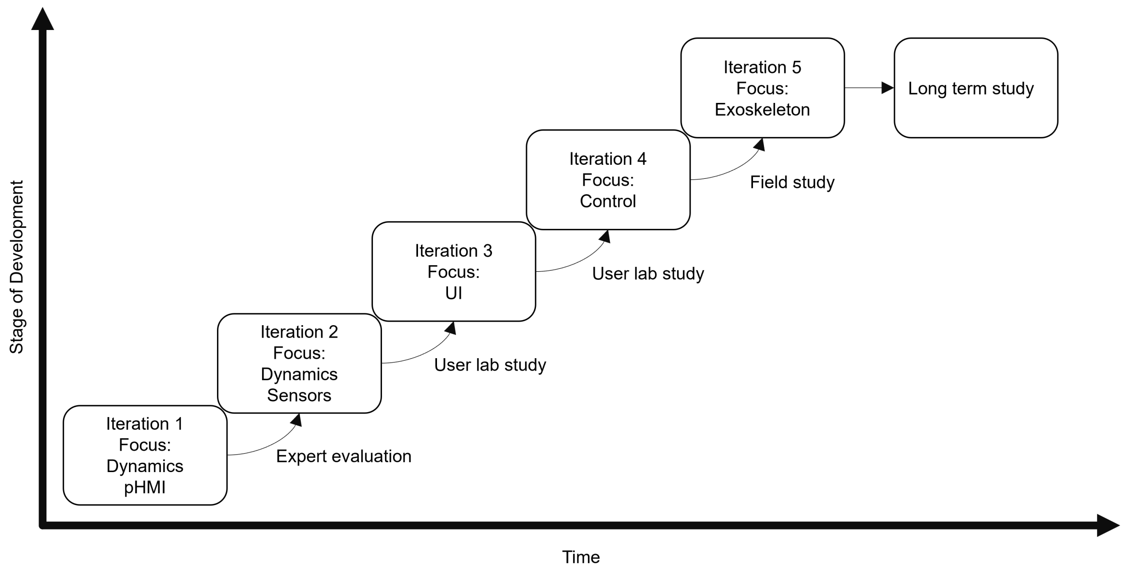

Figure 28 Refined development process for occupational exoskeletons under ergonomic aspects for specific contexts of use with sequential iterations of development steps 3 and 4

9.2. The Next Steps of Exoskeleton Development

The final step in the described development process of an exoskeleton for the workplace means implementing the exoskeleton into the workplaces' processes and testing it in long-term trials (Crea et al., 2021). To be usable in long term trials, it is recommended, that all *General Design* principles are fulfilled, including requirements regarding general safety requirements (G.17), safe states (G.10) and an emergency exit (G.11). Further workplace regulations need to be fulfilled, like low noise emission (G.15) and vibrations (G.16). Those have to be tested, according to the currently applicable standards (DIN Deutsches Institut für Normung e.V., 2001,DIN Deutsches Institut für Normung e.V., 2015). These include measurement methods and principles, that are not further detailed in this thesis, but are are necessary due to safety reasons prior to long term field testing. To fulfill these requirements, further iterations of the steps 3 and 4 of the development process (Chapter 6) are necessary for full maturity of the exoskeleton. This could look like shown in Figure 29.

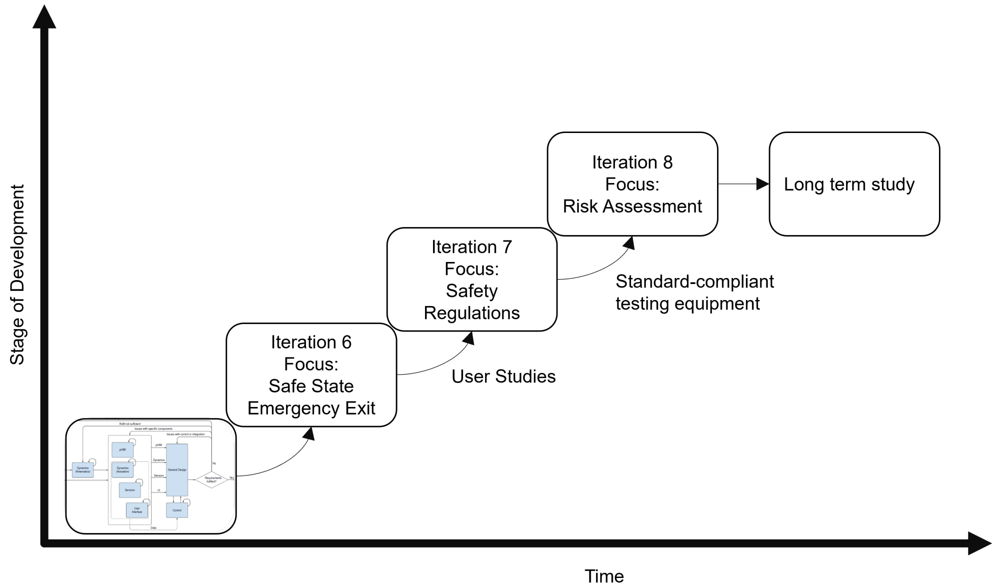

Figure 29 Proposal of further development steps within the development process, focusing on requirements regarding safety and workplace regulations

Long-term trials are necessary to evaluate if the pursued health benefits come into effect. Further use-case-specific usability and acceptance can be proven with these studies, over effectiveness, efficiency, user satisfaction, perceived ease of use, and perceived usefulness. Also, the effectiveness of reducing strain on the body and freedom from harm must be evaluated with further investigations, including regular health assessments, EMG studies, or studies as proposed by Knott, 2017.

This way, the novel development process can be evaluated, and its effectiveness in designing exoskeletons faster and better suited for specific contexts of use. Since the developed exoskeletons in Chapter 7 and 8 are in further development, this will be possible in a few years.

10. Discussion of the Novel Development Process for Occupational Exoskeletons

In this thesis, an agile, human-centered development process to the design ergonomic exoskeletons for occupational use was proposed and applied in two case studies. Further methods for collecting context of use specific requirements, evaluation methods for early development stages, and a literature-based requirement analysis were presented and applied within the contexts of use. This thesis acquired and defined essential design principles based on insights from literature to develop occupational exoskeletons that are potentially high in usability, easy to use, have low discomfort, and thus are better accepted in the work environment. It presented methods to translate these into requirements and to evaluate those requirements in early development stages to generate faster iterations and accelerate the development process.

10.1. Discussion - State of the Art

Despite other development processes already existing, as presented in Section 3.3, this novel development process focuses on a more detailed process that addresses every key component of an exoskeleton. It also entails methods that enable developers to gather specific requirements in each context of use and guidance on evaluating those on their own in early development processes. General requirements that exoskeletons and the individual components should follow are also provided. In the state of the art, development processes only target one aspect of exoskeletons or evaluate the system as a whole. The presented process focusing on HCD and agile development includes early and frequent evaluations that contain user involvement as early as possible. These aspects are unique in the proposed development process. They are necessary for more advanced and useful exoskeletons better suited to real work scenarios and their users.

This novel development process is based on the HCD, as it is proposed in literature (Meyer, 2019; Gupta et al., 2020; Fosch-Villaronga and Özcan, 2020, and Monica et al., 2021). It combines the hardware focused HCD DIN EN ISO 9241-210 (DIN Deutsches Institut für Normung e.V., 2019) with the agile principles (Kent et al., 2013) to achieve faster design iteration and more frequent user involvement, while focusing on defining human centered requirements. Since the agile mindset bears the risk of not defining requirements properly, but the HCD mindset tends to be too slow, integrating both perspectives led to a process that achieves quick deliveries while also dedicating time to effectively understand and define the context of use and prioritize user needs (Begnum, 2021). Both approaches prioritize the user, so they include methods to define and assess user needs, therefore distinguishing themselves from engineering models like the V-model.

Similar to the HCD process and existing exoskeleton development processes, this novel process incorporates discrete, sequential steps that build on one another (Drees et al., 2021; Tröster et al., 2020; Martínez and Avilés, 2020; DIN Deutsches Institut für Normung e.V., 2019), as well as iterations between these steps (Otten et al., 2016; Otten, 2023; Meyer, 2019; Drees et al., 2021; Heidari et al., 2018; DIN Deutsches Institut für Normung e.V., 2019). Additionally, the new process introduces iterations within individual steps, enhancing its agility and enabling the parallel development of *key components*. Similar to Bengler et al. (2023), dividing the entire exoskeleton project into smaller key components that build onto each other, improved the agile approach and makes the development more manageable. Compared to Bengler et al. (2023), the development of the key components is paralleled and evaluated and iterated on their own. This improves the dynamic of the whole development process, leads to faster iterations within the component and increase the progress for each iteration of process.

The methods and guidelines presented in existing exoskeleton development processes contributed methods for specific components. Building upon these, this novel development process includes all key components, and methods for defining requirements (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018; Linnenberg et al., 2018; Meyer, 2019) as well as evaluation methods (Otten et al., 2016; Otten, 2023; Tröster et al., 2020; Martínez and Avilés, 2020; Klabunde and Weidner, 2018; Meyer, 2019; Sposito et al., 2019). Drawing on these established evaluation methods for exoskeletons found in the literature (Otten et al., 2016; Otten, 2023; Klabunde and Weidner, 2018; Linnenberg et al., 2018; Tröster et al., 2020; Martínez and Avilés, 2020; Drees et al., 2021; Meyer, 2019; Sposito et al., 2019; Heidari et al., 2018), this novel process defines tailored evaluation methods for each *key component* as well as for different stages of development, as detailed in Chapter 9. Insights from Case Study 2 (Chapter 8) demonstrated that not every evaluation method is appropriate for all development stages. This resulted in the concept in Chapter 9, where steps 3 and 4 of the development process (Chapter 6) are iterated consecutively with a focus on different objectives. These iterations facilitate progression in development stages and the maturity of the exoskeleton.

The proposed development process sets goals for each iteration and results in a long-term study. This represents the first exoskeleton-specific development process to integrate all these elements from the literature while building upon them. The approach is more agile by incorporating iterations within development steps. It also defines more key components beyond kinematics and pHRI to include sensors, controls, and UI, that were until now not specifically included in exoskeleton development processes. It further incorporates established evaluation methods, recommending their use not only for suitable *key components* but also in alignment with the development stage.

These features make the development process presented in this thesis both novel and innovative.

10.2. Results of the Case Studies

Case study 1:
The development process resulted in an exoskeleton that is unique. Similar approaches of cable-driven soft exoskeletons for elbow motion are found in literature but mainly as research prototypes (Pérez Vidal et al., 2021; Park and Cho, 2017; Panariello et al., 2022; Lessard et al., 2018; Kim et al., 2020; Jäger et al., 2023; Ismail et al., 2019; Masia et al., 2018). The combination of one singular cable, that pulls on both sides of the arm is, to the author's knowledge, not developed. It is a novelty, especially in combination

with an intention recognition based on force myography. In the exoskeleton market, there is no similar system available. As proven by the expert interviews, an exoskeleton like that is in high demand, and they see potential contexts of use in which it would have high usability. In some instances, the aesthetic appeal and possibly higher acceptance of the soft but active design were stated.

The proof of principle is provided, but further development and evaluation are needed for an actual proof of concept. Even though a reduction of strain was calculated using biomechanical simulation, evidence of efficacy has to be verified in a study setting utilizing EMG or spiroergometry. The addressed issues of thermal comfort and the proper fitting of the textile structure have to be improved. Further, a robust control with a flawless intention recognition algorithm must be developed. This is a challenge due to the complexity of natural motion, in addition to the non-linearities that are characteristic of soft robotics and human tissue. Those can be solved with a calibration routine, as well as the implementation of machine learning. The basis is set with the HMM, which classifies the intentions based on recorded data with the current readings of the sensors. But this can be further expanded by implementing algorithms that learn in real time and adapt the control during usage to the user and the specific scenario.

Case study 2:
The development process resulted in a new design that addresses the context of use of lifting loads to 25 kg. With the cable-driven actuation in combination with a rigid frame that relieves the arms and the back from these high, harmful forces from the heavy loads, it promises to be a feasible solution for several contexts of use. Similar exoskeletons exist in the market and research, but none achieved full freedom of motion in the back for the user. As the user and expert interviews indicate, the design promises to be a desired solution for the addressed contexts of use.

With the full range of motion, designing the exoskeleton's kinematic structure is challenging. It needs several iterations. Especially the adaptation mechanisms to individual anthropometrics have a negative impact on the stiffness, size, and weight of the system. In future iterations, more function integration, meaning integrating several mechanisms into one part, could be a solution. In combination with the various requirements for the physical attachments, such as thermal comfort and hygiene concepts, the exoskeleton's further development mainly needs to address these. Thanks to the rigid frame, the *control* development has to address fewer non-linearities than the other case study. However, the robust detection and prediction of the users' natural motion still pose a challenge. The system's aesthetic appeal is not yet met, so further design choices must be made to reduce the seemingly "puppet-like" feeling a user might get.

Summary of the case studies:
Both case studies with the development process resulted in feasible solutions confirmed to have high potential and usability in the addressed workplaces. Both lack a suitable *UI* and *control* and need to improve their *pHMI* regarding thermal comfort and hygiene. Due to their very rough prototype states, not all requirements could be tested for fulfillment yet. Even though they address similar contexts of use and have a seemingly similar approach, they are different in the design of their components and therefore have very different challenges. This shows again that exoskeletons have to be designed for their specific

contexts of use, and a "one-size-fits-all" design will not be useful in the reality of occupational workplaces. Both still need to prove their efficacy and usability in long-term field studies.

Even though the development process was well usable in both case studies, both exoskeletons do not fulfill the requirements yet. More development of the exoskeletons is needed to gather insights whether the development process resulted in high usability and well-accepted exoskeletons. To apply the development process and get insights into its suitability, it was sufficient to focus on the early development stages.

However, the resulting exoskeletons of both case studies show promising results in terms of usability in the decided contexts of use, as evaluated in expert and user interviews. Those experts and users also formulated a positive attitude towards the systems and willingness as well as curiosity to try the exoskeletons, which is a building block for good user experience (DIN Deutsches Institut für Normung e.V., 2019) and acceptance (Venkatesh and Bala, 2008). This is promising for workplaces where no other assistance system has been successfully implemented yet. This means, that the development process is suitable to generate novel designs with potentially high usability. This can be further confirmed if the exoskeletons are fully developed and safe to use in a field study. Additionally, the development process still had to be adapted to the individual conditions of both case studies. This was easily accomplished and followed the proposed process by evaluating the single components and the overall system.

10.3. Evaluation Methods in Different Stages of Development

Different evaluation methods were proposed and applied within the development process. In the case studies those showed to be suitable to give valuable feedback on designs for individual key components, as well as the whole exoskeleton. The kind of insights they offer depends on the development stages and components, which are discussed in the following:

Kinematic analysis In the first design stages, numeric calculations help understand forces at the *pHMI*. Based on those, design directives can be derived, as already proven by Jarrasse and Morel, 2011.

Biomechanical Simulation Due to the high dependence on the human and exoskeleton model, biomechanical simulations are not a tool to estimate the resulting forces from exoskeleton use. But especially in early development stages and for design optimization, they are suitable for comparing different designs. Also, they allow estimations of how an exoskeleton changes the forces acting in the human body compared to those without an exoskeleton.

Test Stand The test stands showed to be a valuable asset in both case studies. It assisted in optimizing features of the *dynamics* and the *control*. The combination with user studies is possible and promising but comes with higher effort in designing the stand in itself. Both case studies showed that the test stand can be somewhat abstract. Still, relevant features should be represented, like representative anthropometry of the users (Section 7.4.1) or resemble the context of use more (Section 8.4.5).

User observations and interviews Even though user studies with an early prototype of the whole exoskeleton cannot only be recommended for very specific matters. Examples are the evaluation of the *dynamics* with the workplace environment or the acceptance of isolated design choices. Therefore user studies can be utilized to evaluate individual components. In both case studies, user studies with singular exoskeleton components gave valuable insights and led to further design choices. The participants need to be able to focus on only one aspect of the exoskeleton without being distracted by aspects not relevant to the study, especially if they are inexperienced with the tested subject.

Expert interviews Expert interviews gave valuable insights into very early stages of development or with very rough prototypes. They cannot substitute for field studies with users, but they help increase the agility of the development process with smaller iterations and faster feedback with lower effort.

10.4. Future Development and Directions for Exoskeleton Design

As already discussed, the further development of AI promises better intention detection and motor control possibilities for the exoskeleton. Real-time detection and adaptation to human motions is a complex task that requires a large database, high-quality data, and massive computing power. This results in the necessity of extensive user studies when building the intention detection. Real-time learning during the usage of the exoskeleton would result in high-performance controllers that need to be integrated into the exoskeleton. This increases weight and the necessary battery capacity, potentially eliminating the benefits of better intention recognition and motor control. With more advancements in machine learning algorithms, those drawbacks in necessary development and computing power can be reduced, and more potent exoskeletons can be developed.

Smart textiles are also becoming more advanced, showing more potential with sensory capabilities and actuation potentials. With further improvements, sensor-based sensors, actors, and microchips increase the potential of soft exoskeletons, increase the potential implementation of more sensors for intention detection, and reduce the weight of existing concepts.
With the same potential benefits, soft robotics are discussed as enablers for lighter and compliant exoskeleton actuators (Ham et al., 2009; Walker et al., 2020). An example are the McKibben muscle actuators for lower limb exoskeletons, a well-researched topic. However, the implementation barrier for occupational contexts of use is the necessity of a compressor, which results in added weight and noise.

Another way to improve the exoskeleton's assistance and prediction of the natural motion is for the system to know the handled weight beforehand. The described workplaces in both case studies suffer from varying weights that must be processed in unpredictable order. This challenges the correct motion prediction of the exoskeletons since the weight influences how the human moves. Even though this should be equalized when using an exoskeleton, this can only be achieved if the exoskeleton applies enough assisting force from the beginning. Otherwise, the trajectory will change. Some companies already use means to track their products, especially in the recent developments of Industry 4.0. Examples are barcodes or RFID chips. The same type of detection could be included in the exoskeleton. On the one hand, this would give the control valuable data about the load that is supposed to be handled. On the other hand, this includes the exoskeleton in the production process as part of the IoT structure of future companies.

But even with existing technology, there are more means to include the exoskeleton in the production process. Especially in logistics and in picking, hand scanners are a mandatory tool for the workers. Including necessary tools, like the scanner, into the exoskeleton structure reduces the load on the worker, frees their hands, and therefore further impacts exoskeleton acceptance positively.

10.5. Conclusion

The proposed and evaluated development process is promising to develop suitable exoskeletons for specific contexts of use in the future. With further advancements in technology and exoskeleton research, designing more exoskeletons with lesser development costs will be possible, so even smaller contexts of use or markets can be addressed.

The human will be part of the industrial environment for decades, and exoskeletons are a useful tool to support them physically and improve their quality of life. This applies to industrial workplaces, where automation has been implemented for decades, and especially to workplaces where automation was not or only partially possible, like craft trade and agriculture. Therefore, exoskeletons will be essential in providing workplaces suitable for aged workers and keeping young workers healthy. This principle is known as age- and aging-appropriate workplaces. This leads to more sustainable workplaces where every age demography can work equally. With workers staying longer at the same workplace and older workers not having to switch to less straining activities, specific knowledge is preserved at the workplace, and practical knowledge can be attained. In general, exoskeletons have the potential to lead to a better quality of life until retirement and enable more people to retire healthier. This is beneficial not only for companies and insurances but for society as a whole.

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A. Checklist for Workplace Assessment for Exoskeleton Potential

Checklist workplace analysis

Designation of the workplace:

____

1. **Description of the working space (sketch + designations):**

Note: Please consider possible distances that have to be covered during the activity and how individual stations are arranged in relation to each other (e.g. does the worker's body twist during the activity, where are possible bottlenecks for the person)!

Notes on the sketch:

____

____

____

Narrow spaces or obstacles in the work area

Are there any obstacles in the work area: ☐ no ☐ yes

Please name the narrowest point that the worker has to cross during the work shift (also outside the main workplace)

Width passage shoulder height (in cm): __________________________________

Width passage hip height (in cm): _____________________________________

2. Description of the work activity

Description of the activity in process steps:

1. ____

   ____

2. ____

   ____

3. ____

   ____

4. ____

   ____

5. ____

   ____

6. ____

   ____

7. ____

   ____

8. ____

   ____

9. ____

   ____

10. ____

    ____

Number of individual activities: ___

Working time: _______________ Cycle time: _________ Shift operation: ☐ no ☐ yes

Workstation rotation: ☐ no ☐ yes, number of work stations: _____; Rotation time: ___

How is the main activity carried out:

☐ standing ☐ sitting ☐ frequent change between standing and sitting

Are tools carried on the body: ☐ no ☐ yes

If so, which ones and where: ____

Comments:

____

____

____

3. Analysis of the individual process steps

For each process step, please analyze what type of work is performed and, if applicable, how much load is placed on the body in the process. (Pages 4 and 5 can be printed several times if more than five process steps are part of the main activity).

Process step__

Type of work	Affected body parts *(sorted by frequency or greatest amount of movement/pos-ture).*
◻ large movements of individual body parts un-der load (___ kg) *(e.g., lifting a component from a squatting position, machining the component with a hammer, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
◻ extreme static postures (>5s) of individual body parts (if necessary under load ____ kg) *(e.g. strongly bent forward posture for ma-chining the component, working in half-knee-ling position, holding the component for a long time, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
◻ none of this occurs	

Process step__

Type of work	**Affected body parts** *(sorted by frequency or greatest amount of movement/pos-ture).*
□ large movements of individual body parts under load (___ kg) *(e.g., lifting a component from a squatting position, machining the component with a hammer, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ extreme static postures (>5s) of individual body parts (if necessary under load ____ kg) *(e.g. strongly bent forward posture for machining the component, working in half-kneeling position, holding the component for a long time, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ none of this occurs	

Process step__

Type of work	**Affected body parts** *(sorted by frequency or greatest amount of movement/pos-ture).*
□ large movements of individual body parts under load (___ kg) *(e.g., lifting a component from a squatting position, machining the component with a hammer, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ extreme static postures (>5s) of individual body parts (if necessary under load ____ kg) *(e.g. strongly bent forward posture for machining the component, working in half-kneeling position, holding the component for a long time, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ none of this occurs	

Process step__

Type of work	**Affected body parts** *(sorted by frequency or greatest amount of movement/pos-ture).*
□ large movements of individual body parts under load (___ kg) *(e.g., lifting a component from a squatting position, machining the component with a hammer, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ extreme static postures (>5s) of individual body parts (if necessary under load ____ kg) *(e.g. strongly bent forward posture for machining the component, working in half-kneeling position, holding the component for a long time, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ none of this occurs	

Process step__

Type of work	**Affected body parts** *(sorted by frequency or greatest amount of movement/pos-ture).*
□ large movements of individual body parts under load (___ kg) *(e.g., lifting a component from a squatting position, machining the component with a hammer, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ extreme static postures (>5s) of individual body parts (if necessary under load ____ kg) *(e.g. strongly bent forward posture for machining the component, working in half-kneeling position, holding the component for a long time, etc.).*	______________________________ ______________________________ ______________________________ ______________________________ ______________________________
□ none of this occurs	

Summary

Based on the analysis of each process step of the main activity, the body parts are rather:

□ moved with load or □ held statically.

Which parts of the body are mainly affected:

____

____

____

Note: Contradictions in the necessary support can occur due to different directions of force. Such a contradiction exists, for example, if both a lot of pushing and pulling must be done at the same time, or if the activity requires both a lot of sitting and walking.

Please analyze your process steps for such possible contradictions:

Identified contradictions:

Process step(s)_______ vs. process step(s)______

Type of contradiction: ____

Process step(s)_______ vs. process step(s)______

Type of contradiction: ____

Process step(s)_______ vs. process step(s)______

Type of contradiction: ____

4. Side tasks

Please mark with a cross all side tasks that the worker must perform during the work process. If any important secondary activities are missing from the list, please add them.

	Frequency of activity per working day
☐ Paths (>5m) must be walked (e.g., to obtain materials)	__________________
☐ Use of forklift trucks	__________________
☐ Operation of a terminal / computer	__________________
☐ Operation of a wearable / mobile device Storage location: ☐ worn on the body ☐ in clothing	__________________
☐ Cleaning of machines	__________________
☐ configuration of machines	__________________
☐ Troubleshooting on the machine	__________________
☐ Other	
____	__________________
____	__________________
____	__________________

Please state the percentage of side tasks in relation to the total working day:

Percentage of side tasks: __________% at this workplace

Can you identify secondary activities that conflict with the primary activity (e.g., primary activity involves a lot of static bending far forward or lifting from the legs, but secondary activity involves using a forklift very frequently).

Identified contradictions:

____

____

____

Other comments:

____

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B. Relevant Literature for Identifying Design Principles

Dynamics (Kinematics and Actuation)

Asbeck et al. (2014); Cenciarini and Dollar (2011); Chen et al. (2020); Chiri et al. (2012); Crea et al. (2021); Del Sanchez-Villamañan et al. (2019); Gopura et al. (2015); Gull et al. (2020); Gupta et al. (2019); Gupta et al. (2020); Hensel and Keil (2019); Jarrasse and Morel (2011); Kapandji and Rehart (2016); Kapsalyamov et al. (2020); Klabunde and Weidner (2018); Klepser and Morlock (2020); Li et al. (2020); Liang et al. (2022); Masia et al. (2018); Massardi et al. (2022); Monica et al. (2021); Moreno et al. (2022); Näf et al. (2018); Plaza et al. (2021); Pons (2008); Rodríguez-Fernández et al. (2021); von Salis-Soglio (2015);. Sarkisian et al. (2021); Schiele and van der Helm (2006); Schiele (2007); Schiele (2009); Schnieders and Stone (2020); Sposito et al. (2020); Sun et al. (2022); Tijjani et al. (2022); Toxiri et al. (2018); Toxiri et al. (2019); Viteckova et al. (2018); Young and Ferris (2017); Zanotto et al. (2015); Zeagler (2017);

Control

Anam and Al-Jumaily (2012); Chen et al. (2020); Del Sanchez-Villamañan et al. (2019); Fosch-Villaronga and Özcan (2020); Gull et al. (2020); Gunasekara et al. (2012); Gupta et al. (2020); Kapsalyamov et al. (2020); Kumar et al. (2019); Liang et al. (2022); Masia et al. (2018); Massardi et al. (2022); Monica et al. (2021); Moreno et al. (2022); Nizamis et al. (2021); Plaza et al. (2021); Rodríguez-Fernández et al. (2021); Schnieders and Stone (2020); Sun et al. (2022); Tijjani et al. (2022); Toxiri et al. (2018); Toxiri et al. (2019); Viteckova et al. (2018); Young and Ferris (2017); Zanotto et al. (2015); Zhang et al. (2021);

Sensors

Chen et al. (2020); Fosch-Villaronga and Özcan (2020); Gopura et al. (2015); Gull et al. (2020); Gupta et al. (2020); Jacobsen et al. (2004); Kapsalyamov et al. (2020); Massardi et al. (2022); Monica et al. (2021); Plaza et al. (2021); Schnieders and Stone (2020); Sun et al. (2022); Tijjani et al. (2022); Toxiri et al. (2018); Viteckova et al. (2018); Young and Ferris (2017);

pHMI

Cenciarini and Dollar (2011); Chen et al. (2020); Chinello et al. (2016) Chiri et al. (2012); Del Sanchez-Villamañan et al. (2019); Fischer (1987); Giusino et al. (2020); Gopura et al. (2015); Gupta et al. (2020); Huysamen et al. (2018a); Huysamen et al. (2018b); Kermavnar et al. (2018); Kermavnar et al. (2020);) Kim et al. (2022); Linnenberg et al. (2018); Mallat et al. (2019); Massardi et al. (2022); Monica et al. (2021); Pons (2008); Rodríguez-Fernández et al. (2021); Schiele and van der Helm (2006); Schiele (2009); Schnieders and Stone (2020); Sposito et al. (2019); Sun et al. (2022); Tijjani et al. (2022); Viteckova et al. (2018); Young and Ferris (2017);

UI

Chen et al. (2020); Fosch-Villaronga and Özcan (2020); Giusino et al. (2020); Knott and Bengler (2016); Monica et al. (2021); Moreno et al. (2022); Motti and Caine (2014); Plaza et al. (2021); Rodríguez-

Fernández et al. (2021); Tijjani et al. (2022); Viteckova et al. (2018); Young and Ferris (2017); ISO (2016); ISO (1999a);

C. General Design Principles

ID-Nr	General Design Principles	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
G.1	Good Usability (Exoskeleton must have a good usability for the designed main tasks including the workplaces individual restrictions)	Workplace analysis (main task description)	Standardized questionnaire (e.g., SUS, QUEAD)	D.9, D.15, P.1, C.1, C.2, C.4, S.4, U.1, U.5, U.8	Batavia & Hammer, 1990; Shore et al., 2018; Shore et al., 2020
G.2	Good User Experience (Additionally to a good usability, the user needs to have a good interaction with the product before and after the task it is designed for)	Workplace analysis (organizational structures) User Interview	Standardized questionnaire (e.g., UEQ)	D.5, D.6, D.14, P.8, C.3, C.9, S.9, U.9	Chen et al., 2020; Monica et al., 2021; Shore et al., 2022; Tijjani et al., 2022
G.3	Ease of use (The exoskeleton needs to be easy to use for the intended user group in every aspect)	User Interview	Standardized questionnaire (e.g., NASA TLX)	D.6, C.5, U.7	Shore et al., 2022; Shore et al., 2018
G.4	Positive aesthetic appeal	User Interview	Standardized questionnaire (e.g., AttrakDiff)	D.6	Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Gopura et al., 2015; Kapsalyamov et al., 2020; Monica et al., 2021; Schnieders & Stone, 2020; Shore et al., 2022; Shore et al., 2020
G.5	Low weight (The exoskeleton should be as light as possible and heavier components placed at the limbs should be avoided.)	National regulations (e.g., DGUV regulation 112-190) Company regulations User interview Asbeck et al. (2014)	Direct measurement (e.g., scales) Individualized questionnaire	D.4, D.10, D.17, P.13, S.9, U.4	Asbeck et al., 2014; Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Gopura et al., 2015; Gull et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Liang et al., 2022; Masia et al., 2018; Monica et al., 2021; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Shore et al., 2020; Tijjani et al., 2022; Young & Ferris, 2017
G.6	Compact size	Workplace analysis (workspace dimensions) Company regulations User interview Zeagler (2017)	Direct measurement (e.g., measuring tape, DHM) Individualized questionnaire	D.7, D.11, P.14	Chen et al., 2020; Gupta et al., 2020; Kapsalyamov et al., 2020; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Young & Ferris, 2017
G.7	Adequate use time (The technically possible time to use the exoskeleton (e.g., battery life) has to be adequate for the tasks and their durations over a shift or workday)	Workplace analysis (Shift and break times, rotation times, time-boxed use times)	Direct measurement (e.g., battery times with full load)	S.8	Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Schnieders & Stone, 2020; Viteckova et al., 2018
G.8	Transportable and storable (When the exoskeleton is not being used, it should be conveniently transportable and storable, for example in a locked, folded position or within a suitcase.)	Workplace analysis (organisational structures / availabilities)	Individualized questionnaire	G.5, G.6, D.4, D.11, U.4	Viteckova et al., 2018
G.9	Quick Setup (The setup procedure for the exoskeleton should be short and easy by the user themself, ensuring an optimal effort-to-use ratio for the user, thereby increasing the likelihood of users putting it on, even for short tasks.)	User Interview	Direct measurement (e.g., setup times for experienced/ unexperienced users) Individualized questionnaire	P.9, P.10, P.11	Fosch-Villaronga & Özcan, 2020; Gopura et al., 2015; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Sun et al., 2022; Viteckova et al., 2018; Young & Ferris, 2017
G.10	Safe State (If a malfunction occurs or the battery is running low, the system must transition into a safe state. This allows the user to exit safely, which may involve options like a gradual structure collapse, the activation of support braces, or the ability for the user to move freely even when the motors are not powered.)	DIN EN ISO 13482,	Direct measurement (yes/no)	D.18, C.12	Schnieders & Stone, 2020; Viteckova et al., 2018
G.11	Emergency Exit (If a medical emergency or workplace evacuation becomes necessary, the user or first responders should be able to remove the exoskeleton within a matter of seconds.)	DIN EN ISO 13482, DIN EN ISO 12100:2011 Company regulations	Direct measurement (e.g., take-off times for experienced/ unexperienced users)	P.11	Viteckova et al., 2018
G.12	Support rate (Workplace performance criteria must be met, such as achieving specific picking times, supporting designated loads for defined durations, covering particular walking distances within set time frames, etc.)	Workplace analysis (key performance indicators)	Direct measurement (e.g., cycle times) Key performance indicators	D.3	Schnieders & Stone, 2020
G.13	Low Discomfort	Fischer (1987); Sposito et al. (2019); Kermavnar et al. (2018)	Standardized questionnaire (e.g., PPT, PDT)	D.1, D.2, D.3, D.8, P.2, P.3, P.4, P.5, P.6, P.7, P.12, U.2	Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Gopura et al., 2015; Gupta et al., 2019; Monica et al., 2021; Young & Ferris, 2017

G.14	Mobility and Independence (Users need to be mobile and feel independent when wearing the exoskeleton)	User Interview	Individualized questionnaire	U.3	Chen et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Kapsalyamov et al., 2020; Liang et al., 2022; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Shore et al., 2022
G.15	Low Noise Emission	DIN EN ISO 9612 LärmVibrationsArbSchV	Direct measurement according to regulations	D.12	Shore et al., 2020; Viteckova et al., 2018
G.16	Low Vibrations	DIN EN ISO 5349 LärmVibrationsArbSchV	Direct measurement according to regulations	D.13	Monica et al., 2021
G.17	Safety (The exoskeleton must fulfill all the necessary regulations and certifications to be safe for use in the targeted workplace.)	DIN EN ISO 13482 DIN EN ISO 12100:2011 2014/35/EU	Direct measurement according to regulations	D.16, C.12	Fosch-Villaronga & Özcan, 2020; Giusino et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Motti & Caine, 2014; DIN EN ISO 13482; DIN EN ISO 12100:2011; 2014/35/EU
G.18	Compatibility with side tasks and tools	Workplace analysis (side tasks and tools)	Standardized questionnaire (e.g., SUS) Individualized questionnaire	D.2, D.3, D.8, D.9, C.2, C.3	Fosch-Villaronga & Özcan, 2020; Monica et al., 2021

D. Dynamics Design Principles

	Design principles Dynamics (Kinematics)	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
D.1	Sufficient anthropometric adaptation mechanisms (The kinematics need either manually adaptable or automatically adapting mechanism for the 5.-95. percentile of the target user group)	Anthropometric data bases (e.g., iSize, DIN 33402)	User observation in parcours Individualized questionnaire	G.13	Chiri et al., 2012; Gopura et al., 2015; Gull et al., 2020; A. Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Massardi et al., 2022; Monica et al., 2021; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Shore et al., 2022
D.2	High kinematic compatibility (The kinematics need to be compatible with the user's biomechanics during the whole movement, either through misalignment compensation or compliant structures or materials)	Motion capture 3D Scans	Biomechanical simulation Motion capture User observation in parcours Individualized questionnaire	G.13, G.18	Asbeck et al., 2014; Cenciarini & Dollar, 2011; Chen et al., 2020; Chiri et al., 2012; Gopura et al., 2015; Gull et al., 2020; Gupta et al., 2019; Jarrasse & Morel, 2011; Kapsalyamov et al., 2020; Klabunde & Weidner, 2018; Klepser & Morlock, 2020; Li et al., 2020; Liang et al., 2022; Mallat et al., 2019; Masia et al., 2018; Massardi et al., 2022; Näf et al., 2018; Plaza et al., 2021; Pons, 2008; Rodríguez-Fernández et al., 2021; Salis-Soglio, 2015; Sanchez-Villamañan et al., 2019; Schiele, 2009; Schnieders & Stone, 2020; Sposito et al., 2019; Sun et al., 2022; Young & Ferris, 2017; Zanotto et al., 2015
D.3	Full degrees of freedom (The entire range of movement and all the user's degrees of freedom must remain without any hindrance or awkward positions.)	Motion capture	Motion capture User observation in parcours Individualized questionnaire	G.13, G.12, G.18	Cenciarini & Dollar, 2011; Chen et al., 2020; Chiri et al., 2012; Fosch-Villaronga & Özcan, 2020; Gopura et al., 2015; Gull et al., 2020; Gupta et al., 2020; Liang et al., 2022; Monica et al., 2021; Plaza et al., 2021; Sposito et al., 2019; Tijjani et al., 2022; Toxiri et al., 2018; Viteckova et al., 2018; Young & Ferris, 2017
D.4	Lightweight mechanical structure (The whole kinematic structure must be as lightweight as possible either by lightweight materials or construction)	National regulations (e.g., DGUV regulation 112-190) Company regulations User interview Asbeck et al. (2014)	Direct measurement (e.g., scales) Individualized questionnaire	G.5	Asbeck et al., 2014; Chen et al., 2020; Kapsalyamov et al., 2020; Liang et al., 2022; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020
D.5	Low inertia (By putting heavy components as close to the body's center of gravity, the inertia of the system is perceived as low.)	User interview	Individualized questionnaire	G.2, C.6	Kapsalyamov et al., 2020; Liang et al., 2022; Masia et al., 2018; Plaza et al., 2021; Tijjani et al., 2022
D.6	Low complexity of the structure (A complex structure increases the setup time, makes it bulky and reduces the aesthetic appeal.)	User interview	Direct measurement (e.g., setup times for experienced/ unexperienced users) Individualized questionnaire	G.2, G.3, G.4, D.13	Rodríguez-Fernández et al., 2021; Schnieders & Stone, 2020; Toxiri et al., 2018; Young & Ferris, 2017
D.7	Correspond to the user's body awareness (If the exoskeleton increases the user's silhouette, it raises the risk of collisions with the environment. The kinematic structure must remain within specific regions of the user's body that align with their own body perception.)	Zeagler (2017)	Body scans User observation in parcours Individualized questionnaire	G.6, D.8	Zeagler, 2017

	Design Principles Dynamics (Actuation)	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
D.8	Compliant Actuation (The whole actuation system must behave in the same way as the user's joints and limbs during motion by exhibiting a certain flexibility in their movement)	Motion capture 3D Scans	Biomechanical simulation Motion capture User observation in parcours Individualized questionnaire	D.7, G.13, G.18, C.8	Chen et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022; Toxiri et al., 2018; Young & Ferris, 2017
D.9	Appropriate assistive forces (The power of the action system should be suited to the task: not excessively strong to allow user override and not too weak to achieve the desired musculoskeletal relief.)	Workplace analysis (e.g., handled loads)	Single point pressure magnitude Standardized questionnaire (PDT, PTT) Individualized questionnaire	G.1, G.18, C.7	Cenciarini & Dollar, 2011; Gupta et al., 2019; Liang et al., 2022; Moreno et al., 2022
D.10	Good power to weight ratio (An actuation system should be chosen that has a high power density, to achieve minimal weight for the needed power)	National regulations (e.g., DGUV regulation 112-190) Company regulations User interview Asbeck et al. (2014)	Direct measurement (e.g., scales) Individualized questionnaire	G.5	Chen et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022; Young & Ferris, 2017
D.11	Compact size (The actuation system in total must have a minimal construction space and not be too expansive)	Zeagler (2017)	Direct measurement (e.g., measuring tape, DHM) Individualized questionnaire	G.6	Chen et al., 2020; Gopura et al., 2015; Gupta et al., 2020; S. Gupta et al., 2019; Kapsalyamov et al., 2020; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022; Young & Ferris, 2017
D.12	Low noise emission	DIN EN ISO 9612; LärmVibrationsArbSchV	Direct measurement according to regulations	G.15	Tijjani et al., 2022; Young & Ferris, 2017
D.13	Low inertia by variable stiffness or damping (Inertia impacts the user's perception of performance. This can be mitigated through mechanisms designed to vary stiffness or locking mechanisms, as well as by applying damping to mitigate the effects of forces exerted on the human body by the actuators.)	User lab study (preliminary tests for accepteble inertia)	Individualized questionnaire	G.16, D.6, C.6	Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Liang et al., 2022; Masia et al., 2018; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022
D.14	High control bandwidth (Fast motor response (e.g., speed, position, frequencies) to changing input signals by the control)	Workplace analysis (pace of tasks and changes) User lab study (acceptable reaction times for the system)	Direct measurement (e.g., cycle time changes) Individualized questionnaire	G.2	Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022; Young & Ferris, 2017
D.15	Accurate torque delivery (The actuation must offer repeatablility and predictable accuracy)	Motion capture Analytical methods Biomechanic simulations	Direct measurement (e.g., torque delivery)	G.1	Chen et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Tijjani et al., 2022; Young & Ferris, 2017
D.16	Robust to environment (Actuation must be robust against factors like pressure, electromagnetic fields, weather, dust, and humidity)	Workplace analysis (environmental factors)	Direct measurement (e.g., torque delivery)	G.17	Kapsalyamov et al., 2020; Tijjani et al., 2022
D.17	Low energy consumption (Actuation is efficient when in full load but also has low energy consumption when not active or in transparent mode. This can be achieved with magnetic brakes or elastic components for short-term storage. For example, hydraulics need energy to stay in one position.)	Workplace analysis (load cycle times)	Direct measurement (e.g., battery usage)	G.5	Asbeck et al., 2014; Kapsalyamov et al., 2020; Liang et al., 2022; Schnieders & Stone, 2020
D.18	Transparent and backdriveable (User still has full range of motion when actuation system is not powered, and it has low impedance behavior when not powered)		Individualized questionnaire	G.10	Asbeck et al., 2014; Gopura et al., 2015; Gupta et al., 2019; Sanchez-Villamañan et al., 2019; Tijjani et al., 2022

E. pHMI Design Principles

P	Design Principles pHMI	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
P.1	Efficient transfer of assistive forces (The assisting forces need to be transferred efficiently perpendicular to the contact surface)	Analytical methods Simulation	Single point pressure magnitude Individualized questionnaire	G.1	Chiri et al., 2012; Giusino et al., 2020; Gopura et al., 2015; Gupta et al., 2020; Tjasa Kermavnar et al., 2020; Tjaša Kermavnar et al., 2018; Kim et al., 2022; Linnenberg et al., 2018; Massardi et al., 2022; Schiele, 2009; Sposito et al., 2019; Young & Ferris, 2017
P.2	Suitable anthropometric lengths (The dimensions of the pHMI have to be suitable or adaptable for the 5.-95. percentile of the target user group and still transfer the necessary forces efficiently)	Anthropometric data bases (e.g., iSize, DIN 33402)	User observation in parcours Individualized questionnaire	G.13	Linnenberg et al., 2018
P.3	Suitable anthropometric circumference (If limbs are enclosed by the pHMI, the circumference has to be suitable or adaptable for the 5.-95. percentile of the target user group and still transfer the necessary forces efficiently and in the intended direction)	Anthropometric data bases (e.g., iSize, DIN 33402)	User observation in parcours Individualized questionnaire	G.13	Linnenberg et al., 2018; Massardi et al., 2022; Young & Ferris, 2017
P.4	Suitable for changing volumes of limbs (The changing volume must be accounted for, e.g., over lager muscle groups or the stomach.)	Klepser & Morlock, 2020; Anthropometric data bases (e.g., iSize, DIN 33402)	User observation in parcours Individualized questionnaire	G.13	Linnenberg et al., 2018
P.5	Accounting for elongation (The pHMI must adapt to the elongation or shortening of measurements around joints during movement without slippage and still transfer the necessary forces efficiently.)	Klepser & Morlock, 2020; Salis-Soglio, 2015 Anthropometric data bases (e.g., iSize, DIN 33402)	User observation in parcours Individualized questionnaire	G.13	Gupta et al., 2019; Klabunde & Weidner, 2018; Klepser & Morlock, 2020; Salis-Soglio, 2015; Matteo Sposito et al., 2020
P.6	Compliant design (The pHMI must account for inherent non-linear viscoelastic properties of human soft tissues (e.g., tendons, ligaments, skin) with mechanical degrees of freedom or biocompatible materials)	User lab studies (elasticity at the contact points)	3D Scans Direct measurement (e.g., position change on the limb) Individualized questionnaire	G.13	Sanchez-Villamañan et al., 2019
P.7	Thermal comfort (The thermal conditions at the pHMI must stay in comfortable parameters even with hot outside temperatures and high physical activity)	DIN EN ISO 22523	Direct measurement (e.g., thermomenter, hygrometer) Individualized questionnaire	G.13	Cenciarini and Dollar, 2011; DIN EN ISO 22523
P.8	Hygiene concept (Components of the pHMI with direct skin contact need to be washable or disinfectable, or used individualized.)	Workplace regulations	User interview Direct measurement (yes/no)	G.2	Sanchez-Villamañan et al., 2019;
P.9	Easy and quick fastening (The setup procedure for the pHMI should be short and easy by the user themself, ensuring an optimal effort-to-use ratio for the user, thereby increasing the likelihood of users putting it on, even for short tasks.)	User interview	Direct measurement (e.g., setup times for experienced/ unexperienced users) Individualized questionnaire	G.9	Gopura et al., 2015; Rodríguez-Fernández et al., 2021; Sanchez-Villamañan et al., 2019; Schnieders & Stone, 2020; Viteckova et al., 2018
P.10	Fastening with one hand (At the arms the pHMI must be operable effortlessly with just one hand by the user themself)	User interview	Direct measurement (e.g., setup times for experienced/ unexperienced users) Individualized questionnaire	G.9	Gopura et al., 2015
P.11	Pressure within comfort	Fischer, 1987; Kermavnar et al., 2018;	Single point pressure magnitude Standardized questionnaire (PDT, PTT) Individualized questionnaire	G.9, G.11	Fischer, 1987; Huysamen, Bosch, et al., 2018; Huysamen, Looze, et al., 2018; Massardi et al., 2022; Schiele, 2009; Schnieders & Stone, 2020; Matteo Sposito et al., 2020; Sun et al., 2022; Tijjani et al., 2022; Young & Ferris, 2017
P.12	No chafing, shear, or radial forces	Chinello et al., 2016	Direct measurement (e.g., lateral forces at pHMI)	G.13	Chinello et al., 2016; Chen et al., 2020; Gupta et al., 2020; Tjasa Kermavnar et al., 2020; Mallat et al., 2019; Massardi et al., 2022; Schiele, 2009; Schnieders & Stone, 2020
P.13	Lightweight (Especially in the limbs, lightweight components are essential due to the heightened perception of inertia and the increased metabolic costs as they are placed further out.)	National regulations (e.g., DGUV regulation 112-190) Company regulations User interview	Direct measurement (e.g., scales) Individualized questionnaire	G.5	Kapsalyamov et al., 2020; Liang et al., 2022; Plaza et al., 2021
P.14	Correspond to the user's body awareness (If the exoskeleton increases the user's silhouette, it raises the risk of collisions with the environment. The kinematic structure must remain within specific regions of the user's body that align with their own body perception.)	Zeagler (2017)	Body scans User observation in parcours Individualized questionnaire	G.6	Zeagler, 2017

F. Control Design Principles

C	Design Principles Control	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
C.1	High accuracy in following trajectories for the target task (High accuracy includes real-time performance, low latency, velocities and accelerations of natural motion, fast decisions for safety, reliable movement estimation, controllability, and reversibility)	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	G.1, S.1, S.2, S.3	Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Gupta et al., 2020; Gupta et al., 2019; Kapsalyamov et al., 2020; Kumar et al., 2019; Massardi et al., 2022; Monica et al., 2021; Plaza et al., 2021; Rodríguez-Fernández et al., 2021; Schnieders & Stone, 2020; Sun et al., 2022; Toxiri et al., 2018; Young & Ferris, 2017
C.2	Adapt in unstable situations, (This includes fast adaptation in unforeseen events, that are not part of the target task (e.g., stable in slippery terrain))	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	G.1, G.18	Fosch-Villaronga & Özcan, 2020; Gupta et al., 2020; Rodríguez-Fernández et al., 2021; Schnieders & Stone, 2020; Sun et al., 2022
C.3	Smooth switching between modes (The time of transitions between different states or modes must be as fast as possible and without perceivable interruptions for the user)	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	G.2, G.18	Fosch-Villaronga & Özcan, 2020; Kumar et al., 2019; Sun et al., 2022; Young & Ferris, 2017
C.4	Fault tolerance (Robust against short unforeseen adverse events from outside (e.g., collisions), but also from the user (e.g., tremors and sneezing).)	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	G.1, S.5, S.6, S.7	Fosch-Villaronga & Özcan, 2020; Kumar et al., 2019; Massardi et al., 2022; Monica et al., 2021; Rodríguez-Fernández et al., 2021; Schnieders & Stone, 2020; Sun et al., 2022
C.5	Simplicity (The control algorithm should be as simple as possible to reduce computing power and necessary hardware.)	Analytical methods Simulation	Simulation Test stands	G.3	Schnieders & Stone, 2020; Sun et al., 2022
C.6	Low impedance (Impedance relates to the perceived stiffness of the system. It enables interactive transmission of forces, lets the user feel less inertial forces, and allows the exoskeleton to follow the human's motions, "assist-as-needed".)	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	D.5, D.13	Chen et al., 2020; Kapsalyamov et al., 2020; Liang et al., 2022; Plaza et al., 2021; Schnieders & Stone, 2020; Sun et al., 2022; Tijjani et al., 2022; Toxiri et al., 2018; Zhang et al., 2021
C.7	Factor in compression of soft tissue (The control must account for inherent non-linear viscoelastic properties of human soft tissues (e.g., tendons, ligaments, skin))	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	D.9	Sun et al., 2022; Young & Ferris, 2017
C.8	Friction and inertia compensation (The control must account for the friction and the inertia of the exoskeleton)	Analytical methods Simulation	Simulation Test stands User observation in parcours Individualized questionnaire	D.8	Kumar et al., 2019;
C.9	Feedback signals from and to the user ("Human- in-the-loop": Feedback signals from the human user must be included, as well as feedback to the user)	Analytical methods Simulation	Simulation Direct measurement (yes/no)	G.2	Chen et al., 2020; Schnieders & Stone, 2020; Sun et al., 2022; Young & Ferris, 2017
C.10	Based on a hierarchical structure (A hierarchical structure in control is recommended to implement different levels of controllers (e.g., torque control, backlash compensation, impedance control))		Direct measurement (yes/no)		Chen et al., 2020; Dinh et al., 2017; Masia et al., 2018; Toxiri et al., 2018
C.11	Include distributed control (Enhances flexibility and scalability through adaptive strategies without a central controller, increasing responsiveness and adaptability to unforeseen events.)		Direct measurement (yes/no)		Gupta et al., 2019; Plaza et al., 2021
C.12	Safety protocols (The control implements protocols for safety-related events, (e.g., the safe state is entered, the kill switch is pressed))		Direct measurement (yes/no)	G.10, G.17	Chen et al., 2020; Fosch-Villaronga & Özcan, 2020; Gupta et al., 2020; Sun et al., 2022

G. Sensors Design Principles

S	Design Principles Sensors	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
S.1	Reliable detection of the state of the exoskeleton (Proprioceptive sensors and potentially additional sensors are required to capture the exoskeleton's present condition, its planned path, and to provide feedback.)		Test stands Data sensitivity and robustness of detection	C.1	Fosch-Villaronga & Özcan, 2020; Gull et al., 2020; Kapsalyamov et al., 2020; Tijjani et al., 2022; Young & Ferris, 2017
S.2	Reliable detection of the state of the user: (Intention detection as the basis for trajectory planning, as well as the detection of the current body posture, must be included)		Data sensitivity and robustness of detection	C.1	Chen et al., 2020; Gopura et al., 2015; Gull et al., 2020; Gupta et al., 2020; Kapsalyamov et al., 2020; Massardi et al., 2022; Plaza et al., 2021; Sun et al., 2022; Tijjani et al., 2022; Viteckova et al., 2018; Young & Ferris, 2017
S.3	Reliable detection of the influence of the environment: (Detection of environmental factors are necessary (e.g., the payload, ground contact, collisions, environmental factors for motion prediction))		Data sensitivity and robustness of detection	C.1	Gull et al., 2020; Monica et al., 2021; Tricomi et al., 2023; Young & Ferris, 2017
S.4	High usability for sensor setup (In industrial settings, tasks regarding the sensors (e.g., placing them on the body, calibration) have to be doable for the target user group with most likely with no to little training)		Direct measurement (e.g., setup times for experienced/ unexperienced users) Individualized questionnaire	G.1	Gopura et al., 2015; Jacobsen et al., 2004; Schnieders & Stone, 2020; Sun et al., 2022; Viteckova et al., 2018; Young & Ferris, 2017
S.5	Inter- and intrasubject variation (Especially biosignals change between different users, but also change during the day for the same user.)		Direct measurement (difference between different and the same users)	C.4	Massardi et al., 2022; Young & Ferris, 2017
S.6	Robust against environmental influence, (e.g., electromagnetic fields, dust, collisions, human error)		Data sensitivity and robustness of detection	C.4	Viteckova et al., 2018
S.7	Valid, reliable, objective sensor data (Used sensors must be stable over time, have low data noise, measure as intended, deliver consistent values, and allow objective interpretation.)		Direct measurement (yes/no)	C.4	Massardi et al., 2022; Sun et al., 2022; Young & Ferris, 2017
S.8	Long wearability (E.g., sensors with direct skin contact must be robust against sweat, or sensors around joints have to be robust against tearing)		Direct measurement (Data sensitivity and robustness of detection over time)	G.7	Sanchez-Villamañan et al., 2019
S.9	Low obtrusiveness (If the sensors are too bulky, it raises the risk of collisions with the environment or other body parts. The structure must remain within specific regions of the user's body that align with their own body perception.)	Zeagler (2017)	Body scans DHM User observation in parcours Individualized questionnaire	G.2, G.5	Toxiri et al., 2018; Zeagler, 2017

H. User Interface Design Principles

U	Design Principles UI	Requirements synthesis	Requirement Achievement Test	Dependency	Sources
U.1	High usability (The UI must have a high usability on its own and include bidirectional information exchange between the user and the exoskeleton)		Standardized questionnaire (e.g., SUS, QUEAD)	G.1	Monica et al., 2021; Rodríguez-Fernández et al., 2021; Tijjani et al., 2022; Viteckova et al., 2018; Young & Ferris, 2017
U.2	High compliance (The UI must be easy to use and react according to the user's mental model.)		Individualized questionnaire	G.13	Giusino et al., 2020; Tijjani et al., 2022; ISO 6385:2016; ISO 9355-1:1999
U.3	No restriction of natural motion (If the UI is too bulky, it raises the risk of collisions with the environment or other body parts. The structure must remain within specific regions of the user's body that align with their own body perception.)	Zeagler (2017)	Body scans DHM User observation in parcours Individualized questionnaire	G.14	Giusino et al., 2020; Zeagler, 2017
U.4	Lightweight (Especially in the limbs, lightweight components are essential due to the heightened perception of inertia and the increased metabolic costs as they are placed further out.)	National regulations (e.g., DGUV regulation 112-190) Company regulations User interview	Direct measurement (e.g., scales) Individualized questionnaire	G.5	Rodríguez-Fernández et al., 2021; Tijjani et al., 2022
U.5	Offer adaptability to the specific task and the user	Workplace analysis (types of tasks and loads)	Individualized questionnaire	G.1	Chen et al., 2020; Moreno et al., 2022; Plaza et al., 2021
U.6	Availability of a monitor interface (An interface must be included not for users but for developers and maintenance personnel.)		Direct measurement (yes/no)		Moreno et al., 2022
U.7	Unambiguous (The information displayed by the UI must be clear and straightforward for the target user group.)	User Interview	Individualized questionnaire	G.3	Chen et al., 2020; Giusino et al., 2020
U.8	Noticeable during the task (In industrial environments, the user's attention is not on exoskeleton usage. Environmental factors like noise make it harder to notice sounds. For safety-critical information, a multimodal feedback system may be necessary.)	Workplace analysis (types of tasks and environmental factors)	Individualized questionnaire	G.1	Giusino et al., 2020; ISO 6385:2016; ISO 9355-1:1999
U.9	Not add mental load and low distraction during tasks	Workplace analysis (types of tasks)	Standardized questionnaire (e.g., NASA TLX)	G.2	Giusino et al., 2020; ISO 6385:2016; ISO 9355-1:1999; ISO 9355-3:1999
U.10	Reachable (Inputs of the UI must be reachable, especially for safety-related inputs, e.g., kill switch, activation, and deactivation of assistance)	ISO 9355	User observation in parcours Individualized questionnaire		Fosch-Villaronga and Özcan, 2020; ISO 6385:2016; ISO 9355-1:1999
U.11	Visible	ISO 9355 DIN EN ISO 15008	User observation in parcours Individualized questionnaire		ISO 6385:2016; ISO 9355-1:1999
U.12	Accommodation size	ISO 9355 DIN EN ISO 15008	User observation in parcours Individualized questionnaire		ISO 6385:2016; ISO 9355-1:1999
U.13	Safety (Designed to prevent misuse and implement kill switch features=)	ISO 9355	User observation in parcours Individualized questionnaire		Giusino et al., 2020; ISO 6385:2016; ISO 9355-1:1999
U.14	Grouped according to function and frequency of use	ISO 9355	User observation in parcours Individualized questionnaire		ISO 6385:2016; ISO 9355-1:1999
U.15	Suitable for operating body part	ISO 9355	User observation in parcours Individualized questionnaire		ISO 9355-3:1999

I. Case Study 1: Expert interview

Guideline Questions Expert Interview

1. Can you think of possible use cases within the company where this exoskeleton could be suitable? If yes, which ones?

2. How well do you assess the usability of this system? (Support area, support level)

3. Also, consider any potential side tasks:

4. Do you think all the required degrees of freedom for movement are allowed by this system?

5. Do you find the weight of the system, just under 5 kg, acceptable for supporting 10 kg?

6. What is positive about this design?

7. What could potentially turn out to be a disadvantage?

8. Do you think this system would gain better acceptance among employees compared to other systems you have tested within the company?

9. Can you think of possible future stumbling blocks or general factors to be considered in further development?

J. Case Study 1: Exoskeleton presentation

Soft cable-driven elbow exoskeleton

Exoskeletons for sustainable work

In Germany….

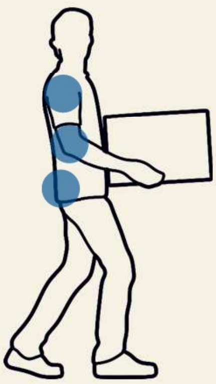
5.5 million people work in physically demanding jobs in production and logistics

Around 20% suffer from musculoskeletal diseases (e.g., arthrosis)

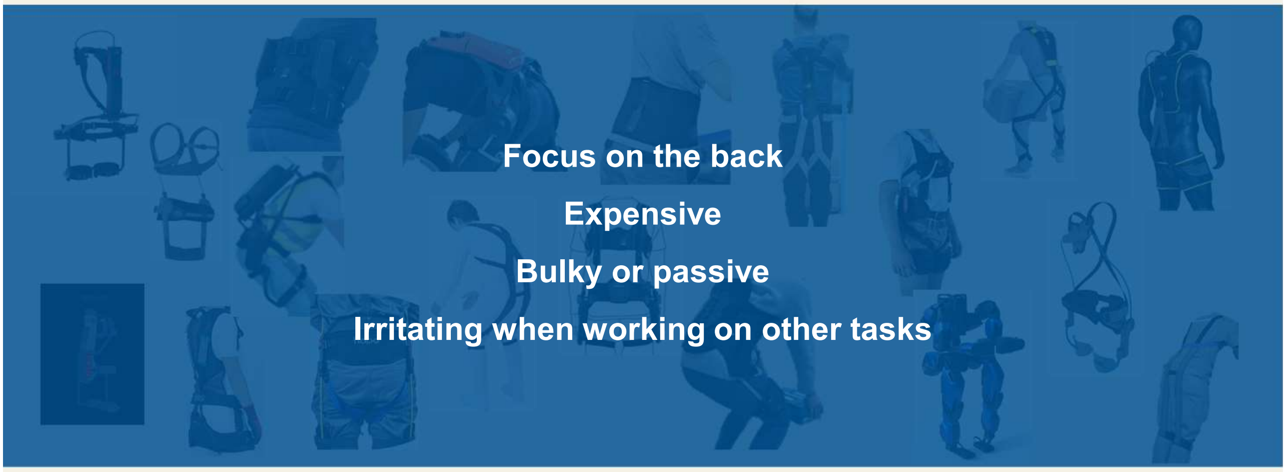
Loss of productivity and workforce

Rising numbers with aging society

Most needed bodyparts for lifting and carrying are…



Exoskeleton market for lifting tasks:



What the market is missing

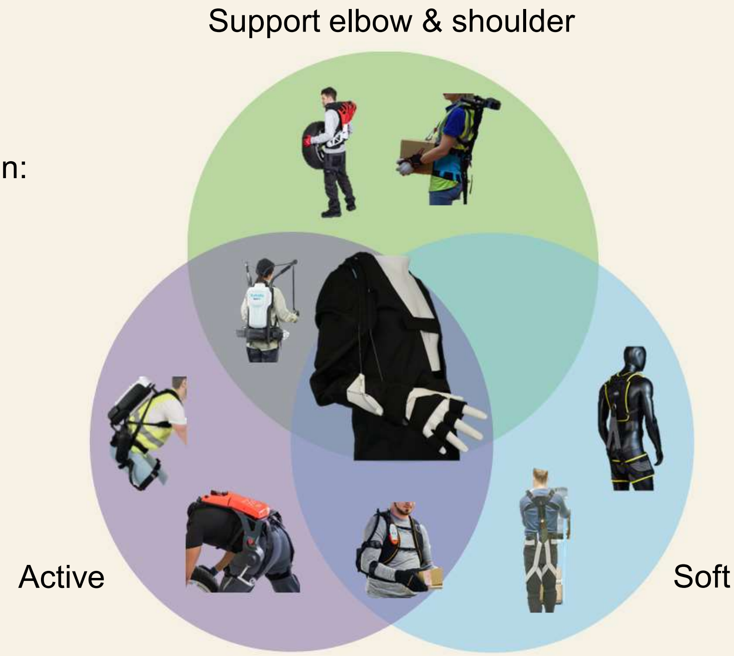
An exoskeleton, that allows **FULL RANGE OF MOVEMENT**

An **ACTIVE** exoskeleton

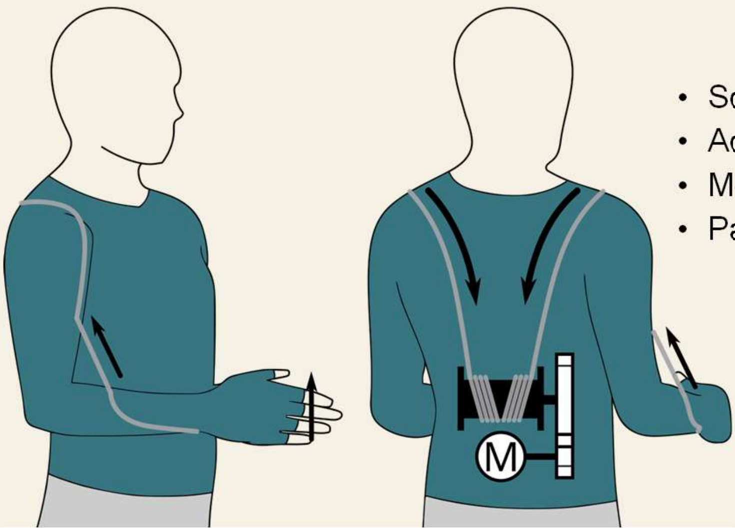
An exoskeleton that supports **ELBOW AND SHOULDER** for lifting and carrying

We deliver a
unique solution:

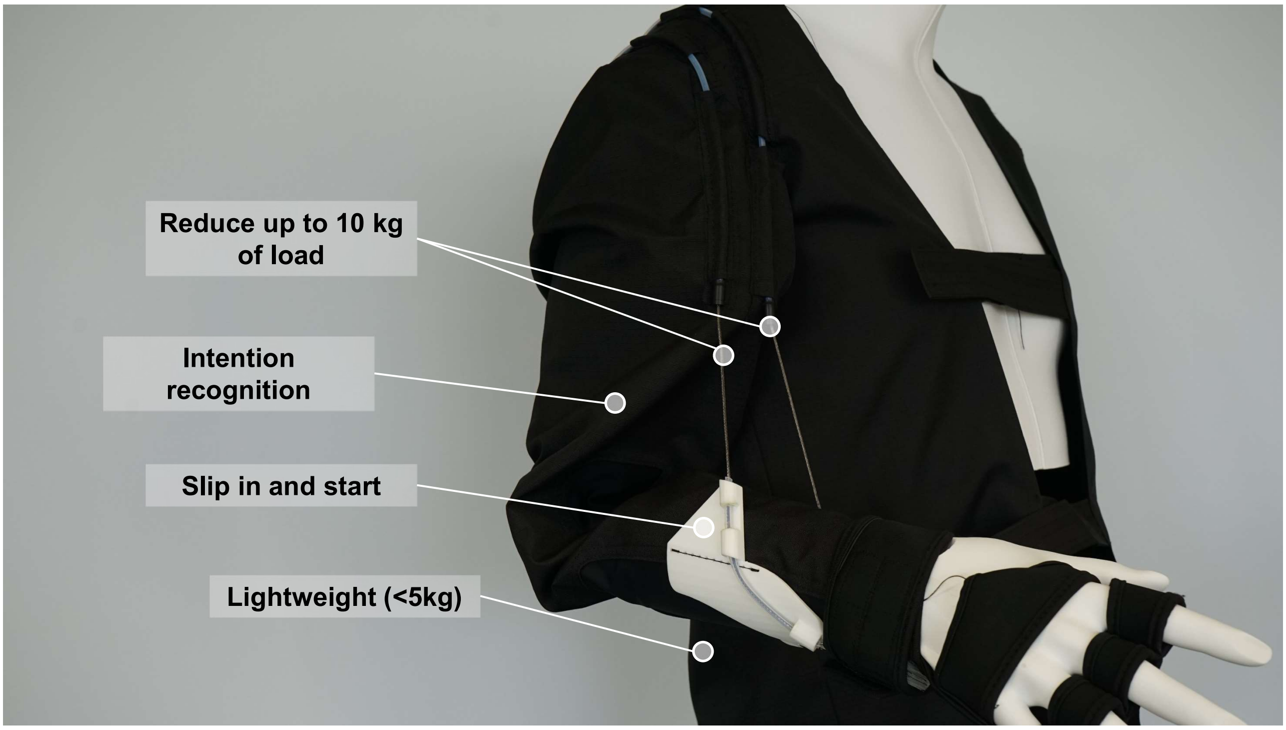
Hawk.L



Hawk.L - The human-centered exoskeleton



- Soft textile base
- Adaptable to every body type
- Motors on back support elbows
- Passive lower back support


Reduce up to 10 kg of load
Intention recognition
Slip in and start
Lightweight (<5kg)

Questions?