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Comprehensive development, implementation and evaluation of industrial exoskeletons

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Abstract: The article describes the designers' perspectives for development and implementation of industrial exoskeletons. Findings are based on the research and own development of commercial available exoskeletons. The authors describe and emphasize the importance of a user centered design and implementation process.

Keywords: assistive device; biomechanics; exoskeleton; orthopaedic technology; overhead work; PAEXO.

Introduction

The idea of devices that can assist the human body has motivated engineers and inventors for centuries. A passive spring body brace invented in 1890, which supports a person upper body in a stooping position (Figure 1, left) has inspired more functional and sophisticated devices that can support a variety of human movements (Figure 1, right). In general, these devices are well known and discussed in the literature under the term 'exoskeletons'. An exoskeleton is a mechanical or mechatronic device attached closely to the body, is anthropomorphic and provides physical assistance to its user through assistive torques or structural support [2]. These devices can be divided into active and passive exoskeletons. Active exoskeletons aim to increase user performance on a given task by supplying additional energy, while passive systems, store mechanical energy from the user's movement into spring elements, and typically release it in a controlled manner when needed. The main drivers and applications of exoskeletons are in the field of medical technology, where they are mainly known as orthoses and are intended for the rehabilitation of patients. In military applications and more recently in the industrial sector, these devices are known as 'industrial exoskeleton'. Exoskeletons are very diverse in their technical and functional design, which is

closely dependent on their application domain. Besides the distinction between active and passive systems, further characterizations of these assistance systems have been established [2, 4].

Industrial exoskeletons

Work-related musculoskeletal disorders (WMSDs) are the most common cause of the inability to work, resulting in significant costs for companies and healthcare systems. According to the Federal Institute for Occupational Safety and Health, the cost of lost production due to musculoskeletal disorders was 17.2 billion € in 2016 for Germany alone [5]. Despite the trend in industrial robotics and automation in the industry over the last decade, many workers are still exposed to physical workloads, and WMSDs are still prevalent in production [4]. Based on these facts, industrial exoskeletons have become highly interesting in the occupational field to support workers performing physically demanding tasks. A major advantage of industrial exoskeletons is that the human dexterity, agility and adaptability are preserved in the production process since the exoskeleton is tightly coupled to the body. So far, no industrial robots have been able to reproduce the necessary flexibility and uniqueness of human movements and perception in production. In addition, only limited modifications of the workplace are needed [4]. The development, therefore, has become very dynamic. As of 2019, there were 62 industrial exoskeletons worldwide that are either commercially available or in the process of being under research and development [6].

Comprehensive development of industrial exoskeletons

A user-oriented design process focuses on the users and stakeholders needs in each phase of the design process (Figure 2). The user-oriented design process should be based on an interdisciplinary approach, that takes into account a large number of stakeholders, besides the user (Figure 2, Stakeholder). This approach can be achieved by conducting joint workshops or interviewing the stakeholders. Focus on an in-depth analysis of the user context

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Figure 1: Exoskeleton evolution, spring body brace from 1890 (left) [1], active exoskeleton for gait support from 2018 (right) [3].

and what they try to accomplish should be the starting point of the development. Market research concepts such as the ‘jobs to be done’ [7] (Figure 2, (1)) can be used to quantify user needs and define the design challenge from a clear perspective of the customer. After developing a rough understanding of the general conditions and ergonomic problems, the next step is to define detailed requirements (Figure 2, (2)). One possibility to do this is through ergonomic and biomechanical analyses, e.g. rebuilding the working situation in a lab. Simulation tools can also enable already to examine some of the defined requirements systematically and generate different design concepts. This makes it possible to analyse detailed aspects of the device, such as the optimal force support curve [8] or the biomechanical effects on the body [9]. During the prototyping phase (Figure 2, (3)), it is essential to understand the acceptance of the proposed technical solutions from the user perspective. Field tests and comfort tests can help to adapt the exoskeleton iteratively to the needs and conditions in a real context based on the user feedback. User acceptance is an important aspect and a key factor of a later successful application and should be investigated during the prototyping. In any case, objective and subjective scientific evaluations should be carried out to determine the transition from the prototyping to the product (Figure 2, (3–4)).

Industrial implementation and application

From the industrial application perspective, the challenge is to select suitable exoskeletons and to manage stakeholders’ expectations and interests. The lack of standards leads to hurdles and uncertainty during the decision-making process and deployment phase of industrial exoskeletons.

Because of the novelty, the responsibilities are often unclear, or there is an overlapping of accountabilities, which are not only country-specific but also interpreted differently in the production industries. For example, exoskeletons are not considered as a traditional form of personal protective equipment (PPE) [10], although the interaction between exoskeletons and PPE (Figure 3) is already a reality. In Germany, for example, there are already first drafts for the assessment of occupational safety by the employer following the labour protection law [11]. It is crucial that regulatory requirements, mainly driven by the stakeholders (Figure 2), have to be considered by developers of industrial exoskeletons. User acceptance is another essential aspect that needs to be taken in to account.

The industrial exoskeletons main acceptance factors can be separated into physical aspects (e.g. safety, comfort), occupational aspects (e.g. safety in the context of work, flexibility with different work, quality standards), cognitive aspects (e.g. usability, ease of use, optical design) and affective aspects (e.g. positive connotation, sense giving) [12].

Large parts of these aspects already play a significant role in the development of the industrial exoskeleton, since they can be seldom influenced afterwards. However, it should be emphasised once again that acceptance also clearly depends on social aspects. Thus, there should be responsible support during the introduction of these devices to workers. The accumulation of several aspects may promote the users’ rejection because of lack of information and supervision during the introduction of such a new technology [13].

Evaluation and effectiveness

From the perspective of the developers, it is recommended to include scientific evaluation of objective and subjective

Figure 2: User centred design and implementation process with important stakeholder in the field of industrial exoskeletons.

Figure 3: Use of upper extremity exoskeleton with personal protective equipment; breathing mask, protective suit and gloves (PAEXO, Ottobock SE & Co. KGaA, Duderstadt, Germany).

effects of the exoskeleton into the design process. During the development of an upper extremity exoskeleton (Figure 3) the assessment of physical, physiological, and psychological aspects [14] gave valuable feedback to the exoskeleton designers. There is already a large number of scientific studies in the field of industrial exoskeletons that considers assessment during early design stages, e.g. from the biomechanical and design simulations [15, 16].

However, in many cases, results can be hardly transferred to other studies or exoskeletons due to the large variety of evaluation methods and the heterogeneous exoskeletal systems. The ongoing debate in the research community also deals intensively with the interaction with the workplace environment and how a meaningful assessment can be made, mainly because of the challenge of the wide variety of industrial applications scenarios. First conclusions can already be drawn from the results of laboratory studies. In the case of the developed upper extremity exoskeleton (Figure 3) it demonstrates biomechanical and metabolic benefits of supporting overhead work activities and potentially reducing WMSDs [14]. Further research is needed into the effects on workers' health, especially that WMSD are a complex issue, long-term studies and observations under best possible controlled conditions must show how the benefits of industrial exoskeletons affect the pathogenesis of WMSD [17].

Conclusion

In this paper, we have outlined insights into the development of industrial exoskeletons, their implementation in an industrial application domain, the effects and evaluation methods and current challenges.

For the development of industrial exoskeletons, we emphasize from the proposed user-centered design and implementation process the importance of:

- Responsible development, taking into account the latest scientific methods and findings
- Make acceptance criteria to a significant development goal
- Consider ergonomic and biomechanical aspects
- Use of simulation in the early design phase, e.g. to optimize specifications and ergonomic impact
- Use design rules from orthopedics and their fundamentals on human-machine interfaces
- Involving users and stakeholders in all design phases
- Lab and field studies that evaluate subjective and objective effects
- Establish carefully arranged guidelines for industrial implementation and communication together with users

As the next step, the advent of semi-active exoskeletons in the industrial field will most certainly stimulate the development of medical exoskeletons and assistive technologies as well and open up new exciting possibilities in the whole exoskeleton world.

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