Usability of exosystems: A review

Poster · September 2019

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ABSTRACT

One major issue when designing exoskeletons is the lack of requirements, guidelines and performance analysis tools. Specifically, there is the need to address the usability and the practical value of exoskeleton technologies. Furthermore, recent literature highlights the importance of better exploring the human-exosystem interaction to improve human safety and performance. The present study is part of the H2020 EU-project EUROBENCH which aims to create the first benchmarking framework for bipedal locomotion robotic systems in Europe. The framework will allow companies and researchers to test the performance of robots and exosystems at any stage of development. A literature review has been conducted to shed light on usability evaluation methods. Most of the studies used surveys (e.g., SUS, local discomfort heatmap) and physiological and task-related measures. Four main challenges regarding the usability of exoskeletons are identified: adjustability of the exoskeleton to the user body, safety issues, user control interfaces, and social aspects of wearing an exoskeleton. Exoskeletons change greatly depending on the task the exoskeleton is designed to help. An industrial exoskeleton has a different design from one used for medical rehabilitation use. Future standards will need to cover all types and industries.

CCS CONCEPTS

• User characteristics • Interaction device

KEYWORDS

Exoskeletons, Usability, Wearable robots, Evaluation methods, Objective evaluation, Human-robot interaction, Pilot Attachment System, Safety

1 Introduction

Exoskeletons can be classified as passive or active (i.e., powered) [1] and they can be distinguished by the body part or level of support such as lower-limbs or upper-limbs [2]. Powered exoskeletons are defined as wearable physical robots which are designed to improve user's performance and restore, enhance or provide new human perceptual, cognitive, or physical abilities [3]. These wearable robots are used in different sectors of application, such as: military [4], like PowerWalk™ by Bionic Power Inc.; industry [5], like Ekso Works™ by Ekso Bionics; and medical [6], like Ekso GT™ by Ekso Bionics, HAL® by CYBERDYNE and Indego® by Parker Hannifin Corp. To date, consumer exoskeletons available on the market constitute a huge minority.

Although exoskeletons have been successfully implemented in several fields, limitations in their usability often prevent from a widespread adoption of such devices in daily life [7]. Their success is highly dependent on user acceptance, which in turn is determined by the subjective intention-to-use, as well as by the perception of usability and comfort [8]. According to Earthy, Jones and Bevan [9], usability can be considered as "quality in use" and defined as "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context [...]" (ISO 9241-210:2009).

The lack of guidelines for rigorous evaluation of exoskeletons, their design requirements and tools for performance analysis have been identified as key issues [12; 13]. There is a need to define standards, as they provide a baseline set of design and performance criteria that are useful to compare different exoskeleton products and to quantify the importance of design features concerning operational application scenarios. Critical design requirements are provided by the standard ISO 13482:2014 and JIS B 8456-1 to ensure the user's safety as a mandatory condition for exoskeletons usability. The guidelines for the inherent safe design, protective measures and information for the use of non-medical personal care robots [11] can be extended to the wearable exosystem domain. Lack of product standards and certifications have been described as barriers to adoption of exoskeleton technologies in industry practice. While exoskeletons are not considered a traditional form of personal protective equipment (PPE), they are similarly wearable, and much of the interest in their application in the industrial/workplace domain is motivated by injury prevention. ASTM F48 stands that standards and certifications for exoskeletons in their manufacture, deployment, and use would enhance their adoption and effective application in the workplace [12].

Usability can be assessed using various methods. Each method has benefits and drawbacks related to ease of conducting the study, predictive power and generalisability. No single approach will answer all questions because each approach can identify only a subset of usability problems. Therefore, it is reasonable to assert that a combination of different techniques will complement each other. Evaluation methods vary and may be conducted solely by experts or involve end users. Expert reviews, such as heuristic evaluation, involve usability specialists who systematically inspect the technology and then identify best practice design violations. Experts may build cognitive models to predict the time and steps needed to complete specific tasks. End users may participate in usability testing in which they are given tasks to complete and their performance is evaluated. Surveys are another method to assess the usability of a product in development. Surveys measure user satisfaction, perceptions and evaluations; they have the advantages of being inexpensive to administer, the results quickly procured, and provide insight into the user experience with the product. Also, open-ended survey questions provide deeper insight into various usability concerns.

Novel interdisciplinary approaches for the design and training of cyborg technologies, specifically upper body exoskeletons have been proposed [14], combining research methods from the arts with human robot interaction (HRI) research. The rationale for using ethnographic methods (e.g., video data and multimodal interaction analysis) within an HRI framework is to develop nuanced approaches for studying embodiment and techno corporeality in socially-situated contexts. This investigation has led to the development of new evaluation tools and frameworks for studying human-machine interaction, including human-centred assessments and custom virtual reality tools that allow for fine-grained analysis. Interdisciplinary approaches seem promising for studying the corporeal experience in human-machine interactions.

The present review is part of the larger overarching H2020 EU-project EUROBENCH (http://eurobench2020.eu) which aims to create the first benchmarking framework for bipedal locomotion robotic systems in Europe. The framework will allow companies and researchers to test the performance of robots and exosystems at any stage of development. Specifically, the sub-project STEPbySTEP will develop a modular reconfigurable staircase testbed for lower-limb exoskeletons benchmarking.

2 Rationale and Purpose

As the use of wearable robots has been increasing, assessing their usability has become of utmost importance for a successful implementation. To our knowledge, no comprehensive review drawing the state of the art on the topic has been published. Hence, the purpose of the present work is twofold: firstly, to detect and identify the different evaluation measures that are currently used to assess exoskeletons usability; and secondly, to summarise the available evidence on the relationship between the system characteristics and usability.

3 Method

A literature search was performed. The eligibility criteria were the following: 1) the words "exoskeleton" and "usability" had to be included in the article title, abstract or keywords; 2) the article had to be published in the 10-year period comprised between 2009 and 2019; 3) a peer-reviewed scientific article (reviews were excluded); 4) written in English; 5) an empirical study; 6) measuring the usability of exoskeletons. The search was conducted via the Web of Science and Scopus bibliographical databases. The search in Scopus yielded 50 results, whereas 41 were retrieved from Web of Science. Out of this total of 91 results, 32 items were removed as being duplicates. Also, 27 articles were excluded as they were considered not relevant during the full-text screening. The final sample of eligible studies consisted of 32 papers ranging from 2011 to 2019, which were ultimately reviewed to the aim of the present study.

4 Results

Results show that the methods adopted for assessing the usability of exoskeletons are subjective and objective (Table 1).

Subjective methods are defined as those methods attempting to systematise and quantify the use of subjective beliefs and opinions [15]. These include quantitative measures such as the System Usability Scale [16; 17; 18; 19; 20; 21; 22; 23; 24], and qualitative measures such as focus-groups [25; 26] and semi-structured interviews [25; 26; 27].

Objective methods include physiological measures, observational measures and technical measures. Physiological measures are mainly electromyography (EMG) and the range of motions measurement [20; 28]. Observational measures are aimed at measuring user performance such as time spent for donning, setup and doffing the exoskeleton [29; 30; 31; 32]. Technical measures include battery autonomy and torque control performance [29; 33].

It should be noticed that not all the measures are designed to proximally address usability as a dimension. For instance, EMG is first of all a metric for perceived musculoskeletal effort, as well as time spent for donning the exoskeleton is a metric for how much time the user needs to wear it. However, an exoskeleton requiring too much musculoskeletal effort or too much time for being donned, is unlikely to be rated as very usable by its user. Therefore, all the retrieved measures are arguably likely to lead to usability, which is the reason why they were included in the current review.

Shore et al. [10] proposed and performs initial testing with Exoscore, a design evaluation tool to assess factors related to acceptance of exoskeleton by older adults, during the technology development and testing phases. They applied the three-phase Exoscore tool during testing with 11 older adults. Feasibility and face validity of applying the design evaluation tool during user testing of a prototype soft lower limb exoskeleton was good. The Exoscore method can be part of an iterative design evaluation process when assessing technology acceptance of exoskeletons by older adults.

Four main challenges regarding the usability of exoskeletons have been identified. The first challenge concerns the adjustability of the exoskeleton to the user body. Even users with similar body dimensions can require a unique fit for optimal system operation. The misalignment between the body and exoskeleton joints can decrease the ease of use and increase the perceived discomfort.

The second challenge is about safety when facing hazards such as pinch, trip, and snag. If the user experiences some degree of discomfort, or even gets injured, the system should be easily removable so that it does not interfere with the user receiving immediate medical care.

The third challenge refers to the user control interface. This interface is generally easily accessible and protected from accidental actuation. As a general user-centred design principle, the interfaces should be intuitive so that cognitive, perceptual, and physical effort associated with operating the system can be minimised. A stop-switch to promptly turn off the system is often suggested as a feature to ensure user safety in case of system malfunction.

An interesting study [36] showed that an overall increase in comfort and user experience can be achieved by realising a user-centred redesign of the physical interface system. Authors used qualitative usability evaluations, needs assessments, and re-design the Pilot Attachment System (PAS) and this favourably impacted the device and its intended application. Integrating the target population into each stage of assistive technology development could help overcoming acceptance limitations and to more significantly improve the quality of life of people living with functional disabilities. Usability of control interfaces should be enhanced by taking into account both users and external operators.

Finally, the fourth challenge entails the consideration of the psychosocial aspects which might be related to wearing an exoskeleton. Exoskeletons, as well as many other robotic prosthetics, might prime social stigma towards the lack of physical abilities [34], and might be regarded as not appropriate due to the manner in which society perceives and judges their users. Thus, negative social perception might indirectly affect the usability perception of such wearable devices. Although the present review has not yielded unequivocal results about this issue, we consider stigmatisation as a major social factor potentially affecting usability through the reduction of the system acceptance and willingness to use. However, as far as we know, an opposite phenomenon might occur that a spinal-injured wheelchair patient will feel relieved from the social stigma constituted by the wheelchair itself when shifting to an exoskeleton-based rehabilitation therapy. These scenarios should need to be empirically tested.

5 Discussion and Conclusions

As long as exoskeletons remain confined within controlled environments such as military, industry and medical settings, some potentially negative effects coming from the highlighted usability challenges can be contained. However, future research about exosystems design should address such challenges in order to break down the barriers that may hinder the widespread uptake and daily-life use of exoskeletons. This should be done in light of the many benefits that these technologies can bring to their users.
Recently, scientists from the Wyss Institute at Harvard University and the University of Nebraska Omaha developed a portable lightweight exosuit weighing five kilograms specifically targeting hip extension movements, during both walking and running [37]. The exosuit has a mobile actuation system at the back of the suit, controlled by an algorithm that can correctly gauge whether the user is walking or running. It then adapts its usability to suit the correct movements. Their study demonstrates that it is possible to have a portable wearable robot assisting more than just a single activity, helping to pave the way for these systems to become ubiquitous in our lives. The exosuits can be applied to a range of applications, including assisting those with gait impairments, industry workers at risk of injury performing physically strenuous tasks, or recreational weekend athletes.

Our findings show that a combination of different techniques that complement one another is necessary to adequately evaluate usability in exoskeletons. Although user testing methods seem to detect more and different usability problems than the interview and survey methods, no single method can be successful at capturing all usability problems. Surveys, questionnaires and interviews provide a window on the user experience, which is fundamental for designing safe, usable and strongly performing technologies based on avoidance of misuse. On the other hand, task and behavioural related methods can limit the self-report bias [35], but still the data they generate needs to be interpreted through a basically inferential process.

To conclude, exoskeletons change greatly depending on the task the exoskeleton is designed to help. An industrial exoskeleton has a different design from one used for medical rehabilitation use. Future standards will need to cover all types and industries. The three major sectors currently using exoskeletons are industrial, medical rehabilitation, and defence. Users in these areas will benefit most from novel metrics and standards, as will exoskeleton manufacturers and regulatory bodies. This knowledge will inform the future development of a benchmarking framework and protocol for the evaluation of wearable exosystems grounded on Human Factors and Ergonomics metrics.

ACKNOWLEDGEMENTS
This project has received funding from the European Union's Horizon 2020 research and innovation programme, via an Open Call issued and executed under Project EUROBENCH (grant agreement Nº 779963)".
http://eurobench2020.eu

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Usability of Exosystems: A Review

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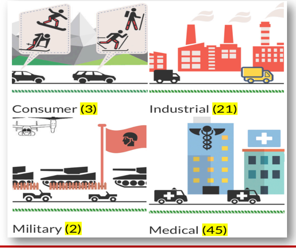
Introduction

Exoskeletons are wearable robotic systems designed to improve user performance and restore, enhance or provide new perceptual, cognitive or physical abilities to humans.

Exoskeletons can be classified based on:

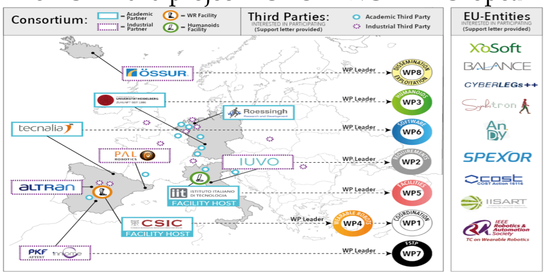
- Power source: passive vs. active exoskeletons;
- Body part: lower-limb vs. upper-limb exoskeletons.

Fields of Application (N market-available products)



The EUROBENCH Project

The EU-H2020 project EUROBENCH – EUropean RObotic framework for bipedal locomotion BENCHmarking (http://eurobench2020.eu) aims to create the first European ecosystem for the assessment of robots for bipedal locomotion. The ecosystem will be composed of two main parts:

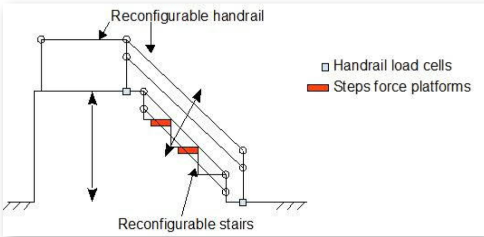


- A **methodological framework**, translating experimental protocols and processing algorithms into a software suite allowing researchers and developers, both academic or industrial, to apply benchmarking procedures to a wide range of robotic platforms and laboratory conditions;
- An **experimental framework**, composed of two testing facilities, one for humanoids (Italy) and one for wearable robots (Spain), including all testing devices needed to test bipedal systems.

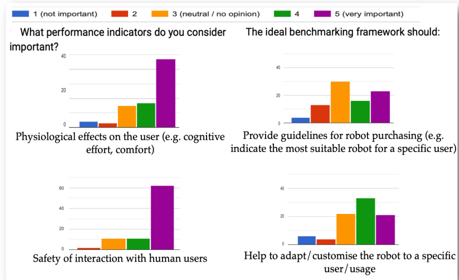
The STEPbySTEP Sub-Project

The EUROBENCH sub-project STEPbySTEP – Systematic Test of Exoskeleton Products by a Stairs-based Testbed Evaluation Protocol – aims to develop a UX-based benchmarking protocol for rehabilitation-assistive lower-limb exoskeletons in a stairs-based use-case.

Use case



Results from survey on benchmarking wearable robots and humanoids with 86 experts



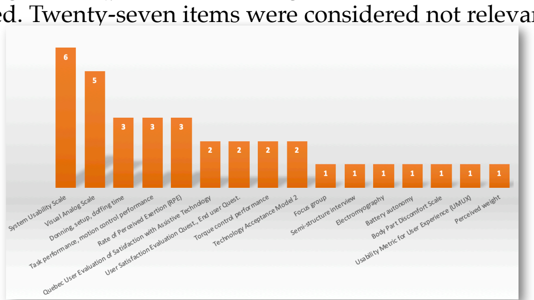
Purpose of the Review

Objectives of the study were to: 1) identify the evaluation measures currently used to assess exoskeletons usability; 2) summarise major issues concerning system characteristics and usability.

Method

Eligibility criteria: "exoskeleton" and "usability" included in title, abstract or keywords; article published between 2009 and 2019; peer-reviewed; English; empirical; measuring exoskeletons' usability. Scopus yielded 50 results, Web of Science 41. Thirty-two duplicate items were removed. Twenty-seven items were considered not relevant after full-text screening. Final sample: 32 papers (2011-2019).

Results



Usability is higher when…

- Exoskeletons are adjustable to the user body and ensure unique fit for optimal system operation.
- Exoskeletons are safely removable when the user faces hazards such as pinch, trip, and snag.
- User and operator control interfaces are intuitive, easily accessible and protected from accidental actuation.

Conclusions

- Combining different techniques is necessary to adequately evaluate exoskeletons' usability.
- Psychosocial stigma towards lack of physical abilities might hinder acceptance and perceptions of usability.
- The retrieved knowledge will inform an assessment protocol grounded on Human Factors metrics.
- The methodology will be validated in three medical neuromotor rehabilitation settings of Emilia-Romagna Region, Northern Italy, by sampling spinal-injured patients using Ekso GT™ by Ekso Bionics, HAL® by CYBERDYNE and Indego® by Parker Hannifin Corp.

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