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Exoskeletons for workers: A case series study in an enclosures production line

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Abstract

This case-series study aims to investigate the effects of a passive shoulder support exoskeleton on experienced workers during their regular work shifts in an enclosures production site. Experimental activities included three sessions, two of which were conducted *in-field* (namely, at two workstations of the painting line, where panels were mounted and dismounted from the line; each session involved three participants), and one session was carried out in a realistic *simulated* environment (namely, the workstations were recreated in a laboratory; this session involved four participants). The effect of the exoskeleton was evaluated through electromyographic activity and perceived effort. After *in-field* sessions, device usability and user acceptance were also assessed. Data were reported individually for each participant. Results showed that the use of the exoskeleton reduced the total shoulder muscular activity compared to normal working conditions, in all subjects and experimental sessions. Similarly, the use of the exoskeleton resulted in reductions of the perceived effort in the shoulder, arm, and lower back. Overall, participants indicated high usability and acceptance of the device. This case series invites larger validation studies, also in diverse operational contexts.

Introduction

Exoskeletons for industrial applications are expected to have a considerable market impact in the next few years. Tens-to-hundreds of thousands of units are projected to be deployed worldwide to support workers in their daily job routines and to enhance workplace safety and productivity (ABI research, 2019). Despite the growing interest in the field of wearable robotics for industrial applications, several barriers still need to be identified and faced to achieve widespread adoption of this technology. To this end, as highlighted by Howard et al. (2020), prospective interventional studies are necessary to evaluate the safety and efficacy of exoskeletons across various industry sectors.

Wearable technologies are expected to improve, in the long term, the working conditions of the operators and help prevent work-related musculoskeletal disorders particularly when other organizational measures are not feasible (Monica et al., 2020). In this framework, considering that shoulder syndromes account for one of the largest portions of work-related musculoskeletal disorders in Europe (EU-OSHA, 2019), several academic teams and companies have started designing occupational exoskeletons that can reduce the load on the shoulder girdle. Among all state-of-the-art devices and commercial solutions, passive spring-based actuation mechanisms have been preferred to powered actuation for most shoulder-support systems, due to their lower weight and lower overall complexity compared to their active counterparts (de Looze et al., 2016). Passive shoulder-support exoskeletons have been presented in a considerable number of experimental studies with the goal to investigate their effects on the users' biomechanics and experience.

Despite this growing body of literature, the majority of the studies of shoulder-support exoskeletons have been carried out in laboratory environments with naïve participants and stereotyped functional job activities within reconstructed workstations (Alabdulkarim and Nussbaum, 2019; Blanco et al., 2019; Huysamen et al., 2018a; Hyun et al., 2019; Kelson et al., 2019; Kim et al., 2018a, 2018b; Kim and Nussbaum, 2019; Maurice et al., 2020; Otten et al., 2018; Pacifico et al., 2020; Schmalz et al., 2019a, 2019b; Theurel et al., 2018). While laboratory tests have shown reduced muscular activity in performing target movements and represent the first step towards the technology validation (Maurice et al., 2020; McFarland and Fischer, 2019; Pacifico et al., 2020; Spada et al., 2018, 2019), the highly-limited variability of the experimental conditions may not fully represent the variety of movements executed in industrial environments (McFarland and Fischer, 2019).

The intrinsic variability of a real workstation often encompasses technical and non-technical issues that do not typically arise under experimental conditions. On the one hand, some degree of *task variability* arises from the manufacturing process flow, which requires the same line to produce different goods, according to the orders to fulfill or the planned volumes to stock. On the other hand, inherent *gesture variability* results from the execution of non-repetitive actions by the human operator, unrelated to the primary (highly repetitive) postures required by the workstation. Reproducing such an environment while preserving its complexity in a laboratory setting is challenging (Gillette and Stephenson, 2019). Additionally, as experienced workers are per se trained to perform the working activities at high biomechanical efficiency (Madeleine et al., 2003), carrying out tests on them present the possibility to realistically assess both the effect of the exoskeleton on muscular activity and the end-user perception of the technology (Spada et al., 2019). Such evaluations provide key elements that company decision-makers should carefully consider before adopting new technologies.

In recent years, a few studies have investigated the effects of passive shoulder-support exoskeletons in real industrial scenarios. The Levitate™ exoskeleton has been tested by workers in tasks of heavy equipment and automotive assembly lines (Gillette and Stephenson, 2018, 2019; Iranzo et al., 2020) and by workers performing stocking tasks in various conditions (Marino, 2019). Also, the prototype versions of SkelEx™, EksoVest™, and the shoulder-support exoskeleton commercialized by the Crimson Dynamics have been tested in assembly tasks in the automotive industry (Hefferle et al., 2020; Smets, 2019).

The purpose of this work was to assess a commercial passive shoulder-support exoskeleton in an industrial manufacturing workplace with experienced operators performing repetitive job-related activities. In particular, the work was conducted in an enclosure production site for power distribution, where the painting area is divided into workstations for panel *mounting*, *dismounting*, and *hook-hanging*. Three experimental sessions were performed, of which two sessions were carried out *in-field* at the panel mounting and dismounting workstations, and one was carried out in a *simulated environment*. The *in-field* sessions included tests in the operational scenario, and thus involved the natural complexity and variability of the working gesture. Tests in the *simulated* environment, where the higher repeatability of the tasks entailed a minimization of the *gesture variability*, were designed to provide a reference for comparison to laboratory studies from the state of the art, as well as to the outcomes of the *in-field* session.

Section snippets

The tested exoskeleton

The MATE (Muscular Aid Technology Exoskeleton, COMAU SpA, Grugliasco, Italy https://www.comau.com/EN/MATE↗, Fig. 1a) (Colombina et al., 2018) has been developed to assist operators in overhead manipulation tasks and repetitive upper-limb movements involving relatively high shoulder elevation angles (i.e., greater than 80°). A prototype version of the exoskeleton has been presented and validated with healthy young subjects in a laboratory study (Pacifico et al., 2020). Here, we recap the main…

In-field session – mounting task

The results of the *in-field mounting* task are shown in Fig. 3 for the three participants, namely Op.1, 2, and 3. For all participants the TiEMG index was reduced by, respectively, 24%, 14%, and 15% compared to the NOEXO condition (Fig. 3a). Considering the single muscles (Fig. 3b), the completion of the task without the exoskeleton entailed the largest activation of the AD, MD, and UT muscles, and the use of the exoskeleton led to reductions of these muscles ranging between 8% and 36%.…

Discussion

The growing market of exoskeletons for industrial applications has raised several expectations about their potential, especially as tools to help companies improve productivity by reducing the physical strain of workers. However, together with positive expectations, the adoption of any new technology must be accompanied by a thorough assessment of the risks and potential side effects that may accompany its use. The need to carry out comprehensive assessment processes has been highlighted by…

Conclusions

This work provides a preliminary evaluation of the efficacy, usability, and acceptance of an upper-limb spring-loaded exoskeleton in a relevant operational environment, through a series of cases in which the exoskeleton was tested *in-field* and in a *simulated* environment. This case-series study, including electromyographic and perception-related (LPE, Usability, and Acceptance) metrics, gathered from a team of experienced worker subjects, suggests that industrial upper-limb exoskeletons can…

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: A. Parri, F. Giovacchini, N. Vitiello, and S. Crea have interests in the spin-off company (IUVO S.r.l.). IUVO S.r.l. has developed the MATE technology. The IP protecting the MATE technology is owned by IUVO S.r.l. (Pontedera, Italy) and licensed to COMAU S.p.A. (Grugliasco, Italy) for commercial purposes in the industrial market. F. S. Violante, F. Molteni, N.…

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