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.

Keywords

Upper-limb exoskeleton, occupational exoskeleton, shoulder support, muscular activity reduction, in-the-field validation

1 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., 2018b, 2018a; Kim and Nussbaum, 2019; Maurice et al., 2020; Otten et al., 2018; Pacifico et al., 2020; Schmalz et al., 2019a; Schmalz et al., 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., 2019, 2018), 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, 2019; Gillette and Stephenson, 2018; 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.

2 Materials and Methods

2.1 The tested exoskeleton

The MATE (Muscular Aid Technology Exoskeleton, COMAU SpA, Grugliasco, Italy https://www.comau.com/EN/MATE, Figure 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 degrees). 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 features of the shoulder-support exoskeleton for the sake of completeness.

The device is made of four main components, i.e. two torque generator boxes, a physical human-machine interface, a kinematic chain of passive degrees of freedom, and a set of size adjustments. The two *torque generator boxes* (one for each arm) generate the assistive action to partially compensate for the arms' weight. The assistive action follows a biologically-inspired torque-versus-angle profile, designed to mimic the natural torque exerted by shoulder elevator muscles during shoulder flexion-extension movements. Hence, for all subjects, the maximum assistance plane is the horizontal plane defined by a shoulder elevation angle of 90 deg. (Figure 1b). The exoskeleton torque-versus-angle profile is gradual, continuous, and adjustable to seven discrete levels, with peak values ranging from 3.85 to 5.46 Nm. The *physical Human-*

Machine Interface (pHMI) connects the device to the human body at the waist, trunk, and arms and is responsible for transferring the physical load from the arms to the pelvis. Each torque generator box is connected to the frame through *a kinematic chain of passive degrees of freedom* (pDOFs), which allows the self-alignment of the robotic and human joint axes. Using a number of *size adjustment mechanisms* in its design, the exoskeleton can be adapted to fit users with a range of anatomical dimensions (height range: 1.54-1.92 m). The device weighs 4 kg.

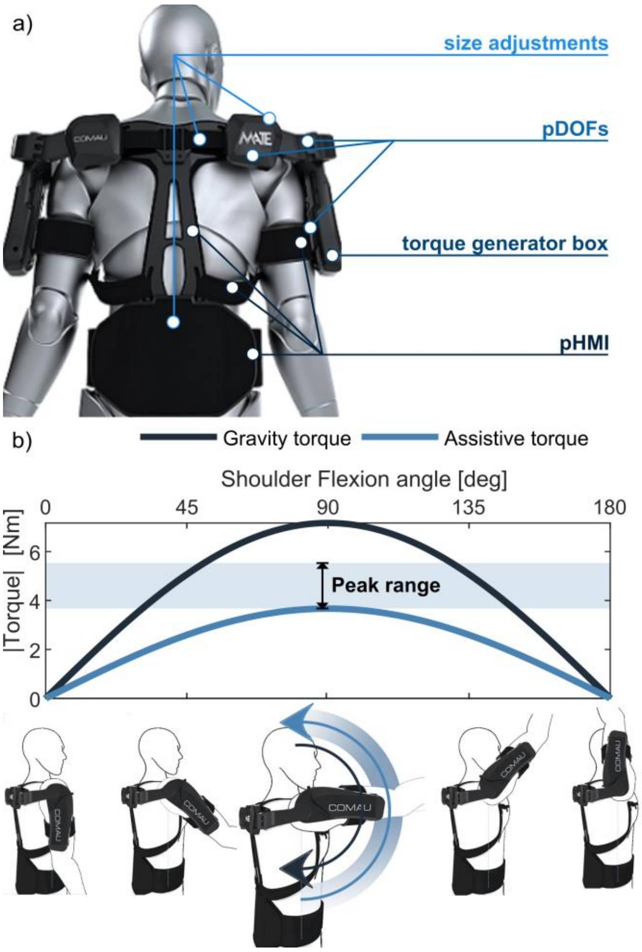

Figure 1: (a) The exoskeleton, back view. (b) The assistive action of the exoskeleton. The black and blue curves represent the estimated arm gravitational torque of a representative user, and the assistive torque, respectively. The assistive profile has been designed to match the shape of the biological gravitational angle–torque profile of the upper limbs, hence providing a smooth partial arm gravity compensation. The exoskeleton torque-versus-angle profile is gradual, continuous, and adjustable to seven discrete levels, with peak values ranging from 3.85 to 5.46 Nm (Peak range). For the sake of illustration, the arm gravitational torque in the figure has been calculated for an average male (weight: 70 kg, height: 170 m) (Snyder et al., 1975). Acronyms: *passive degrees of freedom* (pDOFs), *physical Human-Machine Interface (pHMI).* Single-column fitting image.

2.2 Study design

The study aimed to investigate the efficacy – through electromyographic and perception-related metrics, usability, and acceptance of the exoskeleton in real-work activities. Three experimental sessions were performed, of which two sessions were carried out *in-field* and one in a *simulated environment*. Participants could take part in one or more sessions according to their availability. Before starting the experiments, the participants were helped to don the exoskeleton by the experimenters, according to the donning procedures described in the user manual. Then, the experimenter set the assistance level, following the procedure described in Pacifico et al., 2020. According to these procedures, the recommended assistance level of the exoskeleton compensated at least 50% of the maximum gravitational torque of the user's arm, computed at the shoulder joint center (SJC) based on the height and weight of the user (using to the model estimated by De Leva, 1996). It was possible to slightly increase the level of assistance according to the user's preferences. Hence, the variability in the percentage of the assistive torque (from 50% to 70%) was due to the discretization of the assistance levels available for the exoskeleton and the preferences of the users. The assistance level set for each participant is described in

	Experimental session	*Height* (m)	*Weight* (kg)	*Total UL Mass* (kg)	*Gravitational Torque at SJC** (Nm)	*Assistance provided* (%)	*Assistive torque at BJC** (Nm)	*Assistance level*
Op.1	*In-field – Mounting* *Simulated*	1.80	90	4.45	9.76	53	5.16	6
Op.2	*In-field – Mounting* *Simulated*	1.69	64	3.16	6.52	65	4.26	3
Op.3	*In-field – Mounting* *Simulated*	1.82	64	3.16	7.02	65	4.56	4
Op.4	*In-field – Dismounting*	1.75	80	3.95	8.43	58	4.86	5
Op.5	*In-field – Dismounting*	1.64	63	3.11	6.22	69	4.26	3
Op.6	*In-field – Dismounting*	1.86	80	3.95	8.96	54	4.86	5
Op.7	*Simulated*	1.70	65	3.21	6.66	69	4.56	4

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UL = upper limb SJC = shoulder joint center BJC = active box joint center Op.= operator

*Note that the gravitational torque has been estimated according to Zatsiorsky-Seluyanov's adjustments (De Leva, 1996), and assuming a shoulder and elbow flexion angle of 90 and 0 deg, respectively.

Table 1: Operators' participation in experimental sessions and criterium for the selection of the assistance level.

In all sessions, before the start of the experimental activities, the subjects performed a short familiarization exercise, lasting approximately 5 minutes, during which they were asked to perform the full range of working gestures with the device.

The *in-field* sessions were carried out at two workstations of the enclosures painting line, namely the *mounting* and *dismounting* stations (Figure 2a, supplementary materials "Movie.mp4"). At the *mounting* station, the task consisted of mounting the cabinet panels on hooks hung on a mobile conveyor rack that transports the panels along the painting line. At the *dismounting* station, the task consisted of dismounting the panels from the hooks at the end of the painting line. The height of the rack is the same both at the mounting and dismounting stations and it measures about 260 cm. Subjects manipulated cabinet panels in batches, according to order and pace (i.e., on average, 4-5 panels per minute) required from the production plan of the day. In each batch, there were 30-40 panels of equal sizes and dimensions, whereas between different batches, panel weights, heights, and widths varied in the range of 10-25 kg, 100-200 cm, and 50-100 cm, respectively. Tests at the *mounting* station were carried out on three consecutive days, while tests at the *dismounting* station were carried out on a single day.

In-field tests used an alternating treatment design (A-B-A). The participant started performing his regular job activity for about 30 minutes without wearing the exoskeleton (NOEXO condition), for about one hour while wearing the exoskeleton (EXO condition), and then again for about 30 minutes without the exoskeleton (NOEXO condition). The duration of each condition was slightly adjusted to guarantee that, between the two different conditions (i.e. NOEXO-to-EXO and EXO-to-NOEXO transitions), the participants manipulated panels from the same batch (i.e. with the same height, weight, and width). In this way, EMG signals acquired in EXO and NOEXO conditions could be compared. Each session lasted roughly 3 hours – about 40% of a typical 8-hour shift duration (including rest periods).

The *simulated* session was conducted in a restricted area close to the shop floor, where a simulated environment was designed to recreate the workstations of the painting area (Figure 2b, supplementary materials "Movie.mp4"). The room was equipped with a rack, installed at the same height as the one of the production line (i.e. 260 cm), and a cart, for collecting the panels. Within the *simulated* session, the participants were requested to perform three isolated tasks that are typically performed within the painting area. The tasks consisted of *hanging* the hooks on the rack, *mounting* the panels on the hooks, and *dismounting* the panels from the hooks. Following Hogg et al., 2010, the tasks were repeated 30 times in both NOEXO and EXO conditions. The *mounting* and *dismounting* tasks were arranged in circuit and consisted of the following sequence of actions: (i) picking up a cabinet piece from the cart, (ii) carrying the piece below the rack, (iii) mounting the piece on the hooks, (iv) resting, (v) dismounting the cabinet from the hooks, (vi) carrying the piece to the cart, (vii) placing the piece into the cart, and (viii) resting. In both *mounting* and *dismounting* tasks, operators used one foot to support the cabinet piece, as they usually do in regular job tasks, and handled a cabinet piece whose weight, height, and width were, respectively, 11.67 kg, 199.5 cm and 46.5 cm. The hook *hanging* task consisted of hanging a set of six hooks on the rack and resting. In the *simulated* session, the control condition (NOEXO) was always performed first. This session lasted roughly 3 hours.

Inclusion criteria for recruitment of subjects included: the absence of any physical restrictions in performing the job tasks at the time of recruitment and the absence of skin wounds on the body parts in contact with the exoskeleton's pHMI. Before taking part in the experiment, all volunteers were informed about the goals of the study and signed a written informed consent form. The measurements were performed following the declaration of Helsinki. The Institutional Review Board of Scuola Superiore Sant'Anna approved the study (study n. 1 of the year 2020). Participants were employees in the cabinet production line and were usually assigned to the *mounting* or *dismounting* workstations of the cabinet painting area. They had no previous experience with the use of the exoskeleton and could decide to take part in one or more experimental sessions, according to their availability. In total seven operators took part in the experiments (7 males; age: 40 ± 14 years); three operators participated in the *in-field mounting* session (Op.1, 2, 3), three operators took part in the *in-field dismounting* session (Op.4, 5, 6), and four operators participated in the *simulated* session (Op.1, 2, 3, 7).

	Experimental session	*Height (m)*	*Weight (kg)*	*Total UL Mass (kg)*	*Gravitational Torque at SJC* (Nm)*	*Assistance provided (%)*	*Assistive torque at BJC* (Nm)*	*Assistance level*
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reports the participant's anthropometric characteristics and their participation in the experimental sessions.

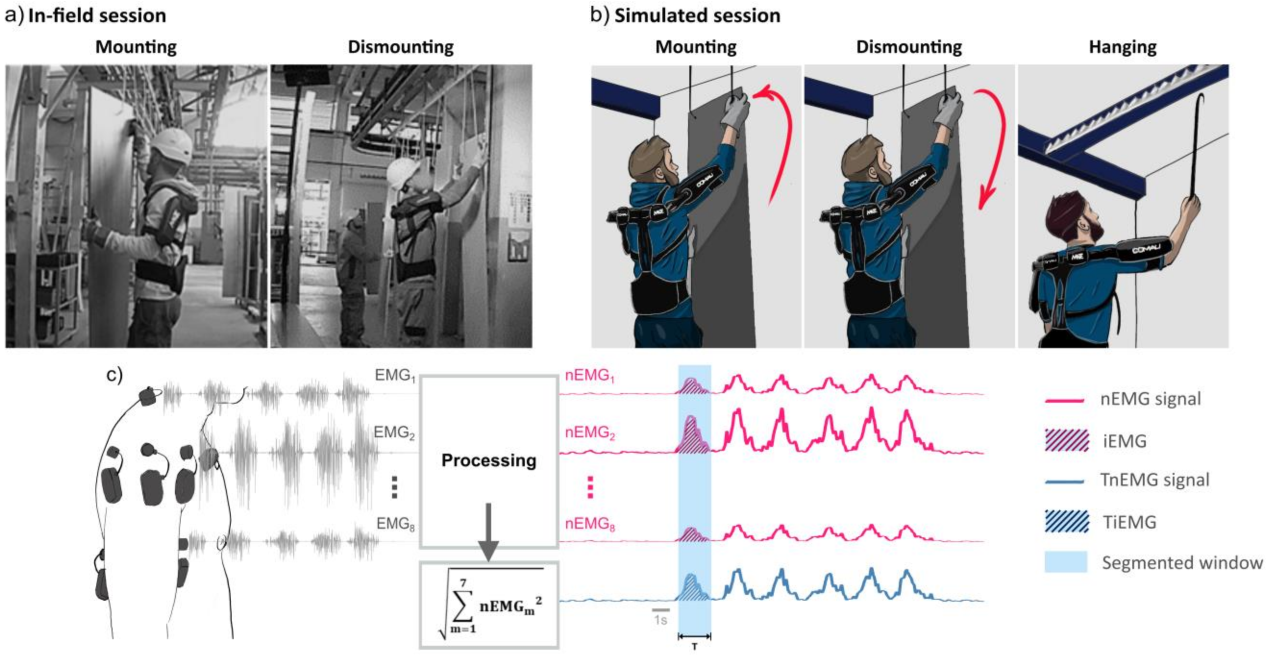

Figure 2: Illustration of participants during *in-field* (a) and *simulated* (b) sessions. In the *in-field* session, the exoskeleton was tested in the *mounting* and *dismounting* station. The *simulated session* included three tasks: the *mounting*, *dismounting* tasks, and the *hanging* task. c) Off-line processing scheme of EMG signals. Signals from 8 muscles were acquired, namely: anterior deltoid (AD), medial deltoid (MD), upper trapezius (UT), pectoralis major (PM), biceps brachii long head (BB), triceps brachii long head (TB), posterior deltoid (PD), erector spinae longissimus (ES). Raw EMG signals (EMG_i, i=1…7, gray signals), acquired at 1000 Hz were

processed, normalized for the MVC (nEMG $_i$, i=1…7, pink signals), and were all combined to obtain the TnEMG signal (blue signal). nEMG and TnEMG signals were segmented, integrated, and normalized for the task duration (*T*) to obtain the iEMG and TiEMG indices. Double-column fitting image.

2.3 **Collected data**

Before taking part in the experimental activities, participants were equipped with surface electrodes under their regular working clothes. The electromyographic measurement system was the BTS FREE EMG 1000 (BTS Bioengineering, Milan, Italy). Surface electrodes (Ag-AgCl electrodes, Eurotrode® 36mm) were placed unilaterally on the dominant arm, on the following muscles: anterior deltoid (AD), medial deltoid (MD), upper trapezius (UT), pectoralis major (PM), biceps brachii long head (BB), triceps brachii long head (TB), posterior deltoid (PD). To assess the physiological strain of the back, an additional probe was placed on the erector spinae longissimus muscle (ES). Electrodes were placed following the SENIAM recommendations (Hermens et al., 1999) and secured to the user's skin using medical tape. In this phase, care was taken to avoid contact between the probes and the exoskeleton structures. The maximum voluntary contraction (MVC) of each muscle was acquired at the start of the protocol for signal normalization. MVC tests consisted of isometric exercises at different flexion, abduction, and trunk extension angles, as suggested in (Brooke, 1996; Watt and Grove, 1993). MVCs were repeated three times for each muscle, with each contraction held for 5 s, with positive verbal encouragement from the experimenter. Moreover, a twin-axis Electrogoniometer (EGN) SG150 (Biometrics Ltd, Newport, UK) was placed on the shoulder joint and collected synchronously with electromyographic signals (EMG) by the BTS FREE EMG 1000.

The Local Perceived Exertion (LPE) test, an ad-hoc usability questionnaire, and the Technology Acceptance Model (TAM) (Venkatesh and Davis, 2000) were used to assess the perceived efficacy, usability, and acceptance of the device. The LPE test evaluated the perceived effort in three specific anatomical areas –shoulder, arm, and lower back – in each experimental condition (i.e., NOEXO and EXO), using the Borg CR10 scale (Borg, 1998). In the *in-field* session, the LPE test, the usability and acceptance questionnaires were administered at the end of the performed working task (*mounting* or *dismounting* depending on which working station the participant was assigned to), whereas, in the *simulated* session, operators assigned a single LPE score related to all the three tasks.

The ad-hoc usability questionnaire used for the experiment is an extension of the System Usability Scale (SUS) (Brooke, 1996) on a 7-points Likert scale, as proposed by Finstad in 2010 (Finstad, 2010). The TAM consisted of questions on a 7-point Likert scale and, in this study, it was formulated with 8 constructs*: the intention to use, the perceived usefulness, the perceived ease of use, the voluntariness, the image, the job relevance, the output quality, and the result demonstrability,* which have been described by Agarwal and Prasad in (Agarwal and Prasad, 1997) and Venkatesh and Davis in (Venkatesh and Davis, 2000). For the sake of clarity, hereafter a short definition of the constructs is reported. The *intention to use* is the intention to use the innovation in the future. The *perceived usefulness* is “the extent to which a person believes that using the system will be free of effort”. The *perceived ease of use* is “the extent to which a person believes that using the system will be free of effort". The *voluntariness* is "the extent to which potential adopters perceive the adoption decision to be non-mandatory". The *image* "captures the perception that using an innovation will contribute to enhancing the social status of a potential adopter". J*ob relevance* is the "individual's perception regarding the degree to which the target system applies to his or her job". The *output quality* takes into consideration how well the user performs the job task with the target system. The result demonstrability is the tangibility of the results of using the device.

During the execution of the experiments, the operators were invited to provide qualitative observations related to their experience with the use of the exoskeleton (e.g. possible advantages and disadvantages), and on their intention to use the device in their work shift. Free comments were noted by the experimenters.

Audio-video footage was captured throughout the whole experimentation.

2.4 Data processing

Raw EMG signals were recorded at 1 kHz. Data were stored and processed offline using a custom Matlab routine (2019b, Natick, Massachusetts: The MathWorks Inc). Raw data were band-pass filtered (zero-lag 2nd order Butterworth, filter range: 20-450 Hz (Hermens et al., 1999)) to remove movement artifacts and high-frequency noise. A notch filter (zero-lag 2nd order IIR notch filter at 50 Hz) was applied to filtered signals to remove the AC interference. EMG signals were rectified and low-pass filtered using a 100 ms moving average. EMG envelopes were normalized (nEMGs) using the maximum values extracted from MVC signals. Then, the total nEMG (TnEMG) signal was extracted by combining the nEMG signals of the seven muscles involved in the shoulder movements (namely, AD, MD, UT, PM, BB, TB, and PD) , using (1), according to the method described in (Lee et al., 2004):

$$\mathrm{TnEMG}\ (\mathrm{t}) = \sqrt{\sum_{\mathrm{m}=1}^{7} \mathrm{nEMG_m}\ (\mathrm{t})^2}; \tag{1}$$

, where t is the tth sample, and m is the mth muscle. The nEMG and the TnEMG were manually segmented into single gestures, which were considered as representative of each task.

Signals were segmented by visually inspecting the gesture pattern's projection in the EGN signal and identifying two consecutive local minima as the beginning and end of each gesture. Multimedia videos were used to double-check data when signals showed abnormal patterns and manual segmentation was unclear. Then, the time-normalized iEMG parameter was calculated using (2) and (3):

$$T\mathrm{iEMG_k} = \int_1^T \frac{\mathrm{TnEMG(t)}}{T}\,\mathrm{dt}; \tag{2}$$

$$\mathrm{iEMG}_{\mathrm{k,m}} = \int_{1}^{T} \frac{\mathrm{nEMG}_{\mathrm{m}}(\mathrm{t})}{T} \mathrm{dt}; \tag{3}$$

, where k is the kth cycle, m is the mth muscle, T is the duration of the cycle, TiEMG is the time-normalized integral of the TnEMG signal, and iEMG is the time-normalized integral of the nEMG signal. The iEMG is expressed as percentages of MVC (% MVC). The TiEMG is expressed as percentages of the root square sum of the total MVC for the recorded shoulder muscles (% total MVC).

The EGN signal excursions were computed in EXO and NOEXO conditions as the difference between the maximum and minimum values of the EGN signal in each cycle.

For each subject, iEMG and TiEMG parameters were averaged across the segmented gestures within conditions. The pairwise relative changes (%NOEXO) between the averaged iEMG, TiEMG, and LPE in the EXO and NOEXO condition were extracted. Since the *in-field mounting* task was performed on multiple days, for each subject the mean of the iEMG, TiEMG, LPE and percentage changes between NOEXO and EXO conditions were calculated between days. Global usability and acceptance indices were computed for each participant involved in the *in-field* session as the average score assigned to each item and then averaged between subjects to describe the usability and acceptability of the exoskeleton in the painting workstation. Scores related to the 8 constructs were computed by averaging scores assigned to the corresponding building items. Thoughout the paper, usability and acceptance indicators are expressed in percentage.

3 Results

3.1 In-field session – Mounting task

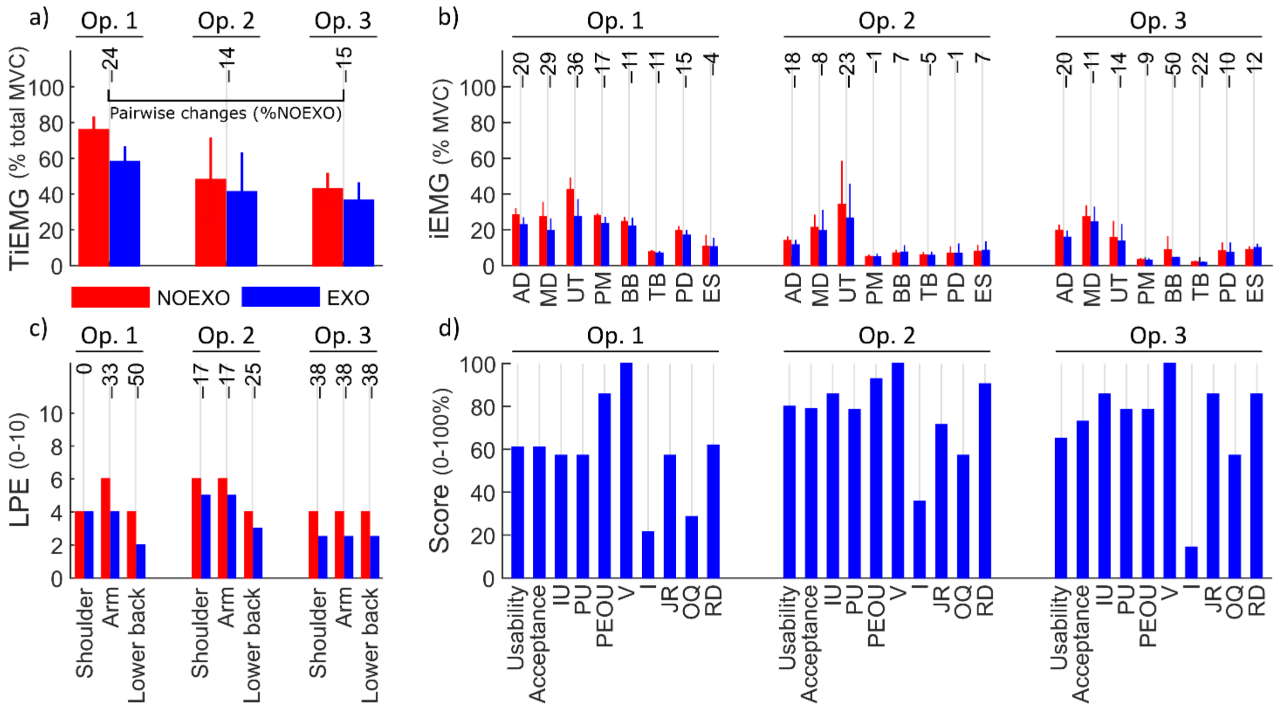

Figure 3: Results of the *in-field mounting* task for operators 1, 2, and 3: (a) the total iEMG index (TiEMG), (b) the iEMG index of the eight recorded muscles, (c) the LPE scores of the shoulder, arm, and lower back, (d) usability and acceptance (TAM scores). Bar and error lines delimit the between-gestures mean and standard deviation of the TiEMG and iEMG. Numbers above the bars quantify the pairwise relative changes between the averaged iEMG, TiEMG, and LPE in the EXO compared to the NOEXO condition (% NOEXO). Muscles acronyms: anterior deltoid (AD), medial deltoid (MD), upper trapezius (UT), pectoralis major (PM), biceps brachii long head (BB), triceps brachii long head (TB), posterior deltoid (PD), erector spinae longissimus (ES). TAM constructs acronyms: intention to use (IU), perceived usefulness (PU), perceived ease of use (PEOU), voluntariness (V), image (I), job relevance (JR), output quality (OQ), result demonstrability (RD). Double column fitting image.

The results of the *in-field mounting* task are shown in Figure 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 (Figure 3a). Considering the single muscles (Figure 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%. Reductions were observed also in the PM and PD muscles. The exoskeleton condition produced a more variable behavior in BB, TB, and ES. Indeed, for Op.3, results showed a reduction of the BB and TB muscles, by, respectively, 50% and 22%, and increased activity of the ES by 12%, but minimal changes were observed in these three muscles for Op.1 and 2.

All the operators reported a reduced LPE score in the EXO compared to the NOEXO condition except for Op.1 who did not perceive changes in the shoulder between the two experimental conditions (Figure 3c).

Global usability, global acceptance and results from the TAM analysis are shown in Figure 3d. The global usability score resulted equal to 61%, 80%, 65% and the global acceptance score equal to 61%, 79%, 73%, respectively. The analysis of eight TAM constructs indicated that the three participants achieved the highest score in *perceived ease of use*, *voluntariness*, and *result demonstrability* (from 86% to 100%). The score for the *intention to use* construct was equal to 86% for Op.2 and 3 and to 56% for Op.1. The operators gave the lowest scores to the *image* construct (from 14% to 36%).

Regarding the free comments, two operators expressed their intention to use the device under specific production assignments while one operator considered the use of the device as sustainable for the entire work shift. All the operators highlighted that, when picking pieces from the cart, the device may interfere with the cart and thus be uncomfortable.

3.1 In-field session – Dismounting task

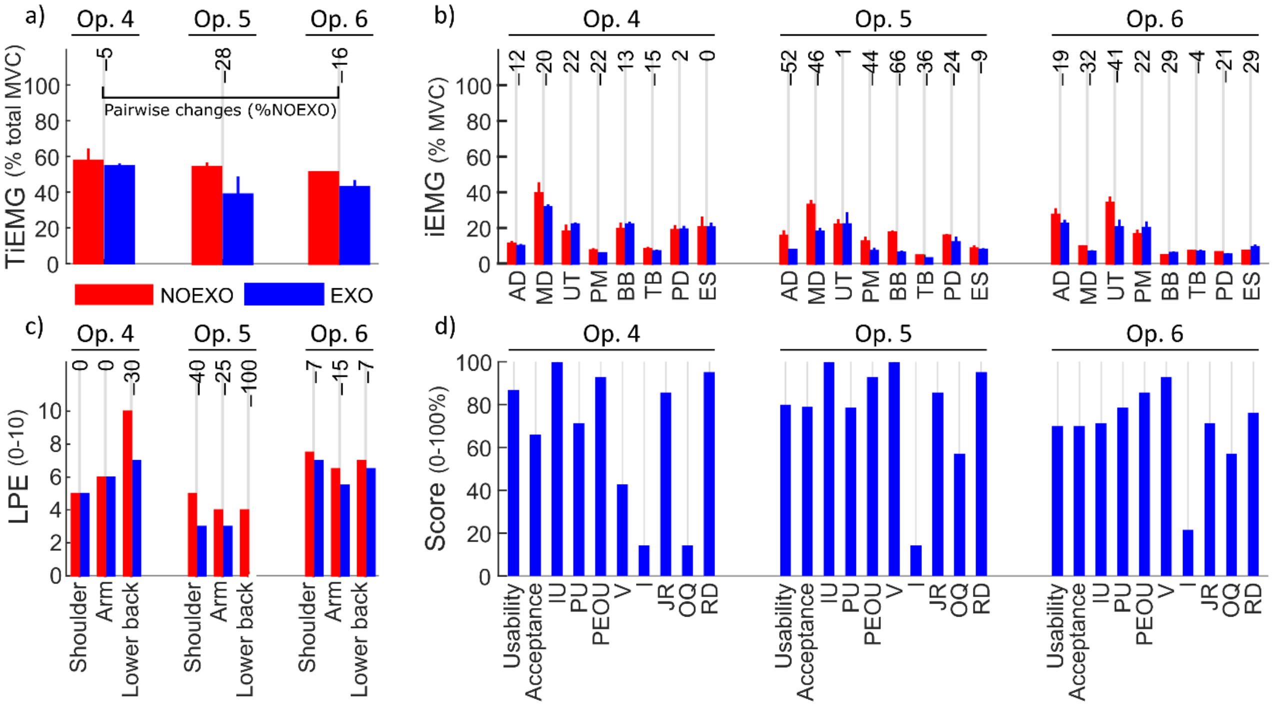

Figure 4: Results of the *in-field dismounting* task for operators 4, 5, and 6: (a) the total iEMG index (TiEMG), (b) the iEMG index of the eight recorded muscles, (c) the LPE scores of the shoulder, arm, and lower back, (d) usability and acceptance (TAM scores). Bar and error lines delimit the between-gestures mean and standard deviation of the TiEMG and iEMG. Numbers above the bars quantify the pairwise relative changes between the averaged iEMG, TiEMG, and LPE in the EXO compared to the NOEXO condition (% NOEXO). Muscles acronyms: anterior deltoid (AD), medial deltoid (MD), upper trapezius (UT), pectoralis major (PM), biceps brachii long head (BB), triceps brachii long head (TB), posterior deltoid (PD), erector spinae longissimus (ES). TAM constructs acronyms: intention to use (IU), perceived usefulness (PU), perceived ease of use (PEOU), voluntariness (V), image (I), job relevance (JR), output quality (OQ), result demonstrability (RD). Double column fitting image.

The results of the *in-field dismounting* task are shown in Figure 4 for the three participants, namely Op.4, 5, and 6. The operators reduced the TiEMG index in the EXO condition, by 5%, 26%, and 16%, respectively (Figure 4a). Considering the single muscles, the execution of the task produced the greatest engagement of the MD muscle for Op.4 and 5, and the AD and UT muscles for Op.6 (Figure 4b). For these muscles, the use of the exoskeleton led to reduced activity compared to the NOEXO condition. Overall, the

AD, MD, and TB muscles were reduced in all operators, whereas a more variable effect was found on the other muscles. Concerning the UT muscle, the exoskeleton led to increased activity for Op.4 and 5, respectively of 22% and 1%, and reduced activity of 41% for Op.6. Concerning the PM muscle, results showed reduced activity for Op.4 and 5 and increased activity for Op.6. Increased values or no changes were found in the iEMG of BB and ES in the EXO condition for Op.4 and 6, whereas a reduction of the same indices was observed for Op.5. The iEMG index of PD was slightly increased in Op.4 and decreased in Op.5 and 6.

All the operators reported reduced LPE scores in the EXO compared to the NOEXO condition except for Op.4 who did not perceive changes in the shoulder and arm. Op.4 and 5 reported a lower perceived exertion due to the use of the exoskeleton in the lower back LPE score, equal to 30% and 100%, respectively (Figure 4c).

The global usability score resulted equal to 87%, 80%, 70%, and the global acceptance score resulted equal to 66%, 79%, 70%, respectively (Figure 4d). Concerning the TAM constructs, Op.4 and 5 gave the highest scores relative to the *intention to use* (100%). The *voluntariness* was among the best-rated construct for Op.5 and 6 and among the lowest-rated construct for Op.4. All operators gave the lowest score to the *image* construct (from 14% to 21%).

Regarding the free comments, all operators expressed their intention to use the device for part of the work shift, under specific production assignments. All the operators highlighted that, when picking pieces from the cart, the device may interfere with the cart and thus be uncomfortable.

3.2 Simulated session

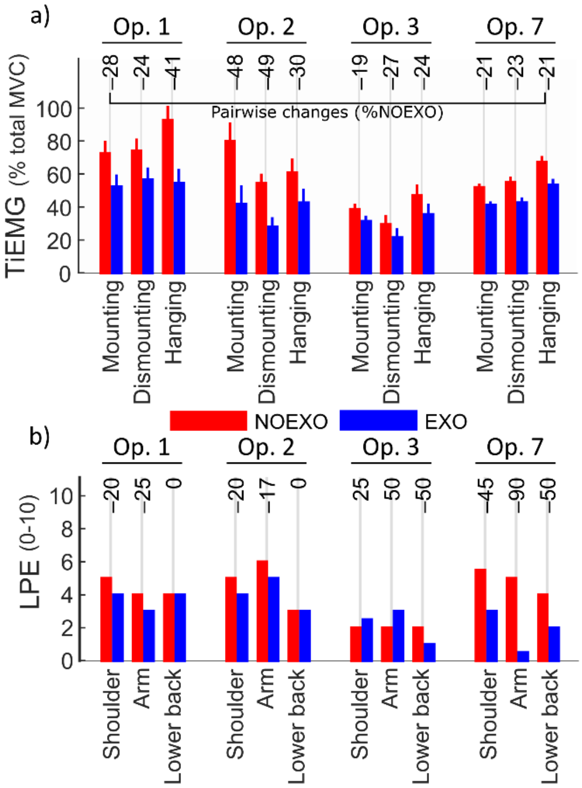

Figure 5: Results of the *simulated* session for operators 1, 2, 3, and 7: (a) the total iEMG index (TiEMG), (b) the LPE scores of the shoulder, arm, and lower back. Bar and error lines delimit the between-gestures mean and standard deviation of the TiEMG. Numbers above the bars quantify the pairwise relative changes between the averaged TiEMG and LPE in the EXO compared to the NOEXO condition (% NOEXO). Single-column fitting image.

The results of the *simulated* session are shown in Figure 5 for the four participants, namely Op.1, 2, 3, 7. For all the operators, the TiEMG index was lower in EXO than in NOEXO condition, with reductions ranging from 19 to 49% (Figure 5a). EMG results from individual muscles are reported in the supplementary materials (“Fig. S. 1”). The use of the exoskeleton reduced the EMG activity of AD, MD, UT, and PM in all subjects and all tasks, with reductions ranging from 6% to 61% of NOEXO. The only exception was found for UT in Op.3, whose iEMG index was 14% higher in EXO than in NOEXO condition in the *mounting* task. Also, the TB and PD muscles showed reduced iEMG index in the EXO condition (from 4% to 59% of NOEXO). A more variable behavior was observed for the BB and ES muscles.

The execution of the *simulated mounting*, *dismounting*, and *hanging* tasks resulted in lower LPE scores when using the exoskeleton, in the shoulder and the arm, for Op.1, 2, 7 (variations ranging between 17% and 90% of NOEXO). Op.3 reported an increased perceived exertion in the shoulder and arm by 25% and 50% of NOEXO, respectively. Referring to the effect of the exoskeleton on the lower back, Op.3 and 7 indicated halved LPE scores with respect to the NOEXO condition, while Op.1 and 2 did not perceive changes between the two experimental conditions.

The EGN data inspection, performed considering all the subjects and the tasks of the *simulated* session, showed that the difference between median EGN signal excursions in EXO and NOEXO conditions is confined within a range of -11 and 16 degrees.

4 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 Howard and colleagues in a recent commentary (Howard et al., 2020). The authors highlighted the importance of designing test methods that include laboratory and in-the-field testing, and involving end-users in the evaluation process with the final goal to highlight the potential as well as risks related to the use of any new technology. In a previous study, a prototype version of the exoskeleton was tested in-lab with healthy young subjects, providing evidence of its efficacy in reducing muscular activity, as well as the quality of human-robot kinematic coupling (Pacifico et al, 2020). This case-series study with experienced workers aimed at assessing the exoskeletons' effects in an operational scenario.

The *mounting* and *dismounting* tasks described in this study are very common in industrial manufacturing environments, especially in those plants where goods are required to be moved across different production lines. Such workstations are typically characterized by a high upper-limb ergonomic risk factor, due to the repetitive and overhead nature of the *mounting* and *dismounting* tasks. Exoskeletons can present viable tools to reduce the workers' strain in these tasks and therefore need to be carefully evaluated from a user-centered perspective. Although the limited number of subjects in this study could be considered a limitation from a generalization perspective, detailed case-series studies of this type are paramount to verify the short-term efficacy, thus the potential long-term benefits of such technologies, before investing in larger-scale studies involving multiple plants and larger cohorts.

4.1 Electromyographic assessment

The results of the *simulated* session showed a lower total shoulder muscle activity in the EXO condition compared to the NOEXO condition, for all subjects. In line with the global reduction, individual muscle activity showed reduced activations in both agonist (AD, MD, UT) and antagonist muscles (PD and TB). Similar qualitative trends in agonist and antagonist muscles were observed in the *in-field* session. The results of this study are in line with those previously observed by Pacifico et al. (2020) in a laboratory setting with a prototype version of the exoskeleton, with particular regard to overhead manipulation tasks. Indeed, the findings of these studies indicate that the exoskeleton can reduce the muscular activity on both movement-agonist and antagonist muscle groups. Regarding the trends in agonist muscle activity, other field studies have confirmed the reduction of the AD (Gillette and Stephenson, 2017, 2019; Iranzo et al., 2020) and UT (Iranzo et al., 2020) muscle activity when using the exoskeleton during tasks involved in the automotive manufacturing sector.

As far the trends in antagonist muscles are concerned, the present study results are consistent with those reported in previous works by Schmalz et al. (Schmalz et al., 2019a; Schmalz et al., 2019b), which observed decreased activity of the PD in dynamic overhead manipulation tasks performed at a slow pace. Three previous studies have shown trends of increased TB activity. Of these, one study (Theurel et al., 2018) was conducted with the EXHAUSS exoskeleton during simulated lifting and stacking tasks. The study by Van Engelhoven et al. (Van Engelhoven et al., 2019) was conducted with the ShoulderX in overhead screwing tasks and reported significant increases in TB activity (+3-7% MVC) associated with increasing levels of assistive torque (10-15 Nm). Here the authors attributed the increased antagonistic muscle activity to the high assistive torque level. A third study by Alabdulkarim & Nussbaum (Alabdulkarim and Nussbaum, 2019) analyzed the between-gender effects of a shoulder-support exoskeleton during simulated overhead drilling tasks. This evidence suggests that when dealing with exoskeleton technologies, adequate training or usage time is paramount to allow users to familiarize themselves and adapt to the device, as this aspect can be critical to reducing the antagonist muscle activity.

Reduced iEMG indices of agonist and antagonist muscles resulting from the use of shoulder support exoskeletons have been documented by other studies confirming that similar exoskeleton technologies can have beneficial impacts on their end-users (Hyun et al., 2019; Kelson et al., 2019; Kim et al., 2018a; Kim and Nussbaum, 2019; Maurice et al., 2020; Otten et al., 2018; Pacifico et al., 2020; Schmalz et al., 2019a; Schmalz et al., 2019b; Theurel et al., 2018; Van Engelhoven et al., 2019). Nevertheless, differences in the exoskeletons, testing methods, and assistance tuning strategies make it difficult to compare the quantitative reductions observed in all studies. In this study, the tuning of exoskeleton assistance depended on anthropometric considerations and was fine-tuned according to the user's preferences (in all cases, the support was higher than 50% of the arm gravitational torque at the shoulder) and was maintained unchanged throughout the tasks. Such task-agnostic tuning criteria may represent a good, practical reference for setting each individual's level of assistance for a broad variety of tasks. Indeed, results suggest that by compensating just 50% - 70% of the arm's weight, the user is not required to actively counteract the exoskeleton assistance to return to the rest position, which may be advantageous particularly during highly dynamic tasks, thus confirming previous results obtained in laboratory conditions, which have documented positive kinematics and kinetics of human-robot interaction (Pacifico et al., 2020). The assistance tuning strategy could be further refined by accounting for additional circumstantial factors such as the manipulated load or the user's fatigue state. The consideration of such aspects could provide evidence for an improved human-robot interaction in highly-tailored (subject- and task-specific) scenarios (Otten et al., 2018; Van Engelhoven et al., 2019). As an example, in our previous study we tested a semi-passive upper-limb exoskeleton, functionally equivalent to the exoskeleton here presented, in static overhead tasks under different conditions of assistive support, finding that in static tasks, higher levels of assistance can lead to more significant reductions of the upper-limb muscle strain (Grazi et al., 2020). Here, considering the dynamism of the three tasks investigated, these previous results could not be replicated in a straightforward manner, as excessive assistance could have hindered lowering the arms. Hence, further studies would be necessary to illuminate appropriate methods to optimize assistance levels in dynamic tasks.

Interestingly, greater variability was observed in ES muscle activity, whose response to EXO assistance varied substantially, in both intensity and sign, among operators. This mixed effect on spine loading was also observed by Kim et al. (Kim et al., 2018a), whereas Hyun et al. (Hyun et al., 2019) found increased ES muscle activity during drilling tasks with a load. Importantly, in this study, the placement of the ES EMG electrode (as well as BB and TB) fell close to the physical human-exoskeleton interface (in particular, the back support and arm cuffs). The uncontrolled external pressure (including normal and shear forces) applied to the electrode-tissue interface represents a well-acknowledged confounding factor when dealing with surface EMG measurements (Konrad, 2005) in the control or assessment of wearable assistive devices (Toxiri et al., 2018). Here, in line with other validation studies with occupational exoskeletons (Baltrusch et al., 2020), the experimenters ensured in the electrode placement phase that the probes were not in contact with the exoskeleton structures. Nevertheless, the pressure on the electrode-tissue interface could not be controlled during task execution and may thus have increased the between-subject variability of the measured activity of the affected muscles.

The attenuated reductions observed in the *in-field session* compared to the *simulated session*, with special regard to the UT muscle, may have resulted from the intrinsically higher variability of the experimental conditions. Reasonably, the across-day nature of the *in-field* sessions, the fact that subjects handled pieces of different sizes and weights, and the less-constrained gesture kinematics and kinetics all contributed to different EMG results in the *in-field* compared to the *simulated* session for the same performed tasks. While *in-field* trends nevertheless confirm the positive effects of the exoskeleton in reducing muscle strain, this outcome further emphasizes the need to conduct *in-field* experiments to provide more realistic evaluations.

Finally, the setting of this entire investigation entirely in a manufacturing plant prevented the use of optical motion capture systems to reveal subtle changes in gesture kinematics among conditions, as desirable for deeper biomechanical analysis (e.g., assessment of the coordination and smoothness of the movement, Grazioso et al., 2019). Indeed, setting up these cumbersome systems in the production plant would have limited the ecological nature of the evaluation (i.e., due to the large dedicated spaces, long calibration procedure, and the use of dedicated clothes that such devices require), thereby undermining the study’s intention to investigate the use of the exoskeleton in real manufacturing operations. Nevertheless, three considerations made us hypothesize that the gesture’s kinematics has not been altered among conditions. First, a careful inspection of videos revealed no visually appreciable changes in the execution of movements. Second, even though the EGN signals may have been altered over time (e.g., as a result of slippage over the skin due to sweat or contact with the exoskeleton), the difference in median EGN signal excursion among conditions varied within a limited interval, and, in both cases of increased or decreased excursion, the EMG activity of the agonist's muscles was always lower in the EXO than in NOEXO condition. Third, the subjects performed the experiment in a geometrically constrained and controlled set-up.

4.2 Perception-related assessment

In line with observed trends in muscle activity, reductions in perceived exertion were observed in the arms and shoulders in the EXO compared to the NOEXO condition. Interestingly, participants reported higher LPE scores in the *in-field* session compared to the *simulated* session, therefore confirming the hypothesis that the operators have a greater awareness of the workload as well as of the effect of the device when used in real conditions.

The results of this study confirm the evidence of Huysamen et al., 2018a, who observed an approximately 11% reduction (relative to the maximum value of 10) in the arm's perceived exertion while using an active exoskeleton during laboratory tests involving static postures. In addition, participants of this study all reported lower perceived exertion of the lower back when using the exoskeleton. Reduced perception of back effort could be the result of the postural support provided by the ergonomic physical human-machine interface of the exoskeleton, which indirectly helps to maintain a neutral trunk position. While this was not confirmed by Rashedi et al., 2014a and Huysamen et al., 2018a, who observed a slight non-significant increase in discomfort and physical demand on the trunk or lower back, Van Engelhoven et al., 2019 concurred with the outcome of the current study and reported a reduced the lower back effort by less than 10%.

As a relevant psychological effect, given the non-controlled nature of the study, the reduced exertion perceived in the shoulders and the arms could be partially attributable to the users' positive expectations of the device (placebo effects) which have been documented in previous studies with exoskeletons, (Lindheimer et al., 2020). In order to counteract this effect, Van Engelhoven et al., 2019 evaluated the perceived effort in a *null-support* condition in a single-blind fashion. In this study, due to time and technical difficulties in modifying the device (as the exoskeleton presented here does not include a *zero-torque* working modality by default, and modifying the system would have affected the validity of the device certification), a *control* condition was not included in the protocol. Despite the potential contribution of placebo effects to the present findings on the subjective perception of strain, these perceptual results are corroborated by corresponding reduction trends in EMG measures, thereby minimizing the concern of undue bias that may have altered the interpretation of the study outcomes.

In addition, being limited by the short time available to perform the test in the *simulated* session, the LPE scoring was conducted at the end of the experiment, regarding the combination of all the tasks, whereas in the *in-field* session, operators gave the LPE score after individual tasks. In other words, in the *in-field* session, LPE scores are representative of the specific gestures of a single workstation (mounting or dismounting, depending on which workstation the participant was assigned to), whereas, in the *simulated* session, LPE scores are comprehensive of all the three simulated working gestures (mounting, dismounting and hook hanging) typical of the painting area.

As a major advancement compared to the previous laboratory study by Pacifico et al., 2020, this study evaluates the perception of the technology by end-users with the conscious experience, perspective, and desire of using the device in his\her working conditions. This case series's evaluation of user experience provided important information about the system's usability and acceptance. At the individual factor level, operators rated most favorably statements implying the intention to use, perceived usefulness, job relevance and, result demonstrability, while lower scores were observed on aspects related to image and output quality, consistent with previous studies (Spada et al., 2018, 2017). Those findings confirm that the device was perceived as reducing strain in the shoulder complex but did not affect the perception of the output quality, nor did it improve the image or prestige of workers.

In general, questionnaire results delivered during the *in-field* session indicated global usability and acceptance scores greater than 60%, and free comments provided during the experiments confirmed the intention to use the device. This result agrees with the results of two laboratory studies by Spada et al., where the exoskeleton investigated in this study and the Levitate^{TM} were tested with experienced workers (Spada et al., 2019; 2018) and both yielded usability and acceptability scores greater than 4 out of 7.

Overall, the metrics employed in this case-series study may serve more generally to analyze the impact of wearable robots on ergonomic risk indicators (Takala et al., 2010), given its integrated evaluation of both objective and subjective aspects of physical impact. Further investigations may be necessary to highlight possible differential effects of the exoskeleton during the eccentric and concentric phases of movement.

4.3 Limitations of this study

While promising, the current study has some noteworthy limitations. First, the short-term nature of this study renders it unable to assess both potential long-term benefits such as prevention of occurrence of musculoskeletal disorders (Howard et al., 2020; McFarland and Fischer, 2019; Theurel and Desbrosses, 2019), as well as potential issues that may arise from longer-term use of the technology (e.g. loss of muscular tone, rate of injury, and increased incidence of back pain (Rashedi et al., 2014; Theurel et al., 2018). Long-term investigations are essential to provide evidence about the safe use of technology and will be the focus of future interventional studies. Second, the small sample size limits the generalizability of the findings to broader populations, emphasizing the need to conduct more extensive validation studies in natural use scenarios for a wider range of users. Third, in the *simulated* session, the use of a multiple baseline A-B-A design or randomization strategies would have been more appropriate to avoid potential order-related confounding factors, such as fatigue, stress, or task adaptation. However, fatigue has been observed to increase EMG amplitude (Moritani et al., 1986) under submaximal and isometric exercise conditions. Since the EXO condition was always performed at the end (i.e. in the most demanding part of the experiments), reduction trends registered during the *simulated* session can be reasonably confirmed as a legitimate finding – or may even have *underestimated* the real effect of the exoskeleton. As far as task adaptation is concerned, it was expected to be minimal-to-null, since participants were experienced workers skilled in performing repeatable and optimal gestures. Lastly, the differing extent of *in-field* testing between *mounting* and *dismounting* tasks (3-day vs. 1-day sessions, respectively) requires careful consideration when comparing the device efficacy between the two tasks.

5 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 offer a valuable worker complement for performing repetitive overhead work tasks with reduced physical strain on the shoulder.

In-field tests of this type are paramount to provide more realistic evaluations of device performance and to validate whether laboratory study results are coherent to the relevant field conditions. Such in-lab to in-field comparison is not straightforward, since working gestures in real-case scenarios are subject- and task-specific, in contrast with simulated stereotyped tasks wherein the task duration, rhythm, body movements, and the structured experimental context are defined and controlled by the experimenters. In this study, while the electromyographic outcomes showed a lower reduction in the *in-field* compared to the *simulated* session due to the unavoidable variability experienced in real contexts, the end-users perception of the exoskeleton technology's impact improved when it was assessed in real-case scenarios. Further, evidence of muscular activity reduction during short-term exoskeleton use paves the way for the systematic assessment and progressive deployment of similar technologies on industrial work floors. A long-term investigation on a larger cohort of participants will be necessary to draw more robust conclusions and to validate the device's safety and effectiveness over time, with reference to musculoskeletal health indicators such as muscular tone, the incidence of shoulder pain, and rate of injury.

6 Acknowledgments

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7 Supplementary materials

The video file ("Movie.mp4") shows the execution of *in-field* and *simulated* sessions in the two experimental conditions, i.e., EXO and NOEXO. "**Error! Reference source not found.**" illustrates the EMG results from individual muscles obtained during the *simulated* session.

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cannot be disclosed. The industrial partner has no financial relationships with any organization that might have an interest in the submitted work.

9 Competing interest

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. Vitiello, and S. Crea are scientific advisors of IUVO S.r.l.

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