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Evaluation of antigravitational support levels provided by a passive upper-limb occupational exoskeleton in repetitive arm movements

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ABSTRACT

Upper-limb occupational exoskeletons to support the workers' upper arms are typically designed to provide antigravitational support. Although typical work activities require workers to perform static and dynamic actions, the majority of the studies in literature investigated the effects of upper-limb occupational exoskeletons in static and quasi-static activities, while only a few works focused on dynamic tasks. This article presents a systematic evaluation of the effects of different levels of antigravitational support (from about 60% to 100% of the arm gravitational load) provided by a passive upper-limb occupational exoskeleton on muscles' activity during repetitive arm movements. The effect of the exoskeleton on muscle activity was evaluated by the comparison of muscle activations with and without the exoskeleton. The average muscle activation was computed considering shoulder full flexion-extension cycles, and sub-movements, namely the arm-lifting (i.e., flexion) and arm-lowering (i.e., extension) movements. Results showed a quasi-linear correlation between antigravitational support and muscle activity reductions, both when considering the full flexion-extension cycle and in the arm-lifting movement (reductions were up to 64 and 61% compared to not wearing the exoskeleton, respectively). When considering the arm-lowering movement, providing antigravitational support close to or higher than 100% of the arm gravitational load led to increased muscle activations of the extensors (up to 127%), suggesting that such an amount of antigravitational support may be not effective for a complete biomechanical load reduction on the shoulder district in dynamic tasks.

1. Introduction

Work-related musculoskeletal disorders (MSDs) are one of the most common occupational diseases in Europe, affecting three out of five workers (Kok et al., 2019). Direct consequences of the development of work-related MSDs are the increase in the number of lost work days and the related loss in productivity of up to 2% of the EU gross domestic product (Bevan, 2015). In this context, 23% of industrial workers report suffering from shoulder and neck pain (Hartmann, 2010), typically due to maintaining the arms for a prolonged time in poorly ergonomic postures (e.g., overhead) or to the execution of repetitive gestures (e.g., lifting objects), in some cases using tools of different weights (Eurofound, 2016; Kok et al., 2019). Coping with these occupational diseases requires industry and healthcare systems to face the related costs and the need for providing physical rehabilitation to the workers before reintegrating them into the workplace (Kok et al., 2019). Therefore, the implementation of preventive measures is crucial to contrast the insurgence of work-related disorders, such as shoulder impingement or rotator cuff tendinopathies (Leong et al., 2019).

In the last years, occupational exoskeletons (OEs) have grown as a potential technological tool to support specific body parts (Monica et al., 2020), with many of them designed to assist the upper limbs (Crea et al.,

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2021). Upper-limb OEs have been developed to reduce the biomechanical load on the shoulder joint by providing antigravitational support (Theurel et al., 2018). OEs targeting the shoulder district can be categorized as passive, active, and semi-active devices, although commercially available exoskeletons are mostly passive (Crea et al., 2021). They exploit mechanical elements, such as springs and dampers, to store and release energy in different phases of the movement, thanks to hardware-coded mechanisms. Many studies have demonstrated the potential effectiveness of these devices for reducing the physical strain of users performing in-lab industry-inspired tasks (de Looze et al., 2016; Huysamen et al., 2018; Maurice et al., 2020; Moyon et al., 2019; Pacifico et al., 2020, 2022; Schmalz et al., 2019; Spada et al., 2017; Van Engelhoven and Kazerooni, 2019). The majority of these studies mostly focused on static or quasi-static tasks, whereas fewer examples of dynamic tasks have been considered (De Bock et al., 2023; Grazi et al., 2022; Pacifico et al., 2020; Spada et al., 2017; Theurel et al., 2018; Van Engelhoven et al., 2019). Concerning static or quasi-static tasks, results of the studies generally agree on the fact that, by increasing the level of exoskeleton assistance even up to compensating the full weight of the arm, the activation of shoulder agonist and antagonist muscles decreases, also potentially decreasing the risk of the insurgence of work-related MSDs (de Vries et al., 2019; Kim et al., 2018a; Maurice et al., 2020; Schmalz et al., 2019). Concerning dynamic tasks, the effect of setting different percentages of antigravitational support is still unclear, particularly when the task is very dynamic (i.e., high frequency, high range of movement). The major concern with performing dynamic tasks with a passive exoskeleton is related to the fact that the user may need to contrast the antigravitational support generated by the exoskeleton when moving the arms against the support force/torque, thus potentially increasing muscles activation and perceived discomfort, as suggested in previous research (Van Engelhoven et al., 2019).

Several studies complemented instrumental measurements, such as muscle activity and joint kinematics, with subjective perception-related assessments, usually related to usability and comfort, as these factors play a crucial role the acceptability of OEs in the daily work routine (McFarland et al., 2022). However, the specific relation between the users' perception and levels of assistance provided by OEs has not been explored systematically. To the authors knowledge, only one study by (McFarland et al., 2022) investigated the effects of different levels of assistance on perceived exertion and comfort, showing that for overhead tasks or tasks entailing postures with arms raised the level of assistance of a spring-loaded upper-limb exoskeleton does not affect discomfort. In other studies this aspect was investigated less systematically. For instance, Van Engelhoven and colleagues reported that users in their study preferred setting the exoskeleton with a level of assistance close to 10 Nm instead of setting it to the maximum, namely 15 Nm, regardless of the task type and mass of the tools used; likely the maximum assistance corresponded to an overcompensation of the arms gravitational load for all participants but the work did not report the percentage of antigravitational support in different conditions (Van Engelhoven et al., 2019). Other studies reported a relation between the level of assistance and perceived reduced physical demand and exertion (Grazi et al., 2020), but did not investigate comfort. Moreover, the perception of effectiveness, comfort and acceptance seem to be highly associated with the model of the exoskeleton used (Perez Luque et al., 2020), the type of tasks performed (Theurel et al., 2018), and naturalness of the movement (Moeller et al., 2022). While comfort and usability are very inter-related concepts, to the authors' knowledge no studies investigated specifically the correlation between levels of assistance and device usability. In general, gathering these perception-related information is paramount when studying the effects of OEs with experienced operators in final scenarios of use, as the user's experience is essential for successful adoption of exoskeleton technology in the working environment (de Vries, 2020).

In this work, we studied the relation between the percentage of antigravitational support exerted by an upper-limb spring-loaded exoskeleton and muscle activations when users perform highly dynamic work activities. We studied muscle activations of the entire shoulder complex with a comprehensive approach, including one back muscle, assuming that the effect of the exoskeleton on antagonist and back muscles could be representative of user's discomfort. Here, given the nature of participants (all non-expert subjects) and laboratory conditions, usability was not investigated.

2. Methods

2.1. Exoskeleton

The device used in this study is the MATE-XT (COMAU S.p.a., Grugliasco, Turin, Italy) (Fig. 1A). The exoskeleton is a passive upper-limb device designed to assist workers in physically demanding working activities, which typically involve keeping the arms overhead for prolonged periods or performing repetitive arms movements. The exoskeleton is conceptually similar to the pre-market prototype presented by (Pacifico et al., 2020) and it is an improved version of the one tested by (Pacifico et al., 2022). It is composed of three main elements, namely: (i) two torque-generator boxes (one for each arm), containing a spring-based mechanism generating the assistive torque profile (τ_{exo}), which is hard-coded in the mechanical assembly and resembles the arm gravitational torque profile (τ_{grav}); (ii) a physical human-machine interface (pHMI) to bear the weight of the device and unload the reaction forces on the user's pelvis; (iii) a kinematic chain of passive degrees of freedom (pDOFs), to allow the self-alignment of the device axis of rotation with the human joint axes. The exoskeleton implements eight discrete levels of assistive support, corresponding to peak assistive torques from 3.5 to 6 N m. In this study a subset of three assistive support levels has been selected, as shown in Fig. 1B. The exoskeleton weighs about 3 kg.

2.2. Participants and procedures

Twelve healthy subjects were recruited for the experiment (11 women, 1 man; age: 25.6 ± 1.4 years, height: 166.7 ± 5 cm, weight: 53.8 ± 3.9 kg). Participants were selected with anthropometric parameters (i.e., height and weight) that entailed an estimated antigravitational support by the exoskeleton, when set to provide the maximum level of assistance, of about 100% of the arm gravitational torque. The arm gravitational torque and related percentage of antigravitational support provided by the exoskeleton were estimated using the method described in Section 2.3.

The study was carried out at the premises of The BioRobotics Institute of Scuola Superiore Sant'Anna (Pontedera, Pisa, Italy). The experimental procedures were approved by the Institutional Review Board (approval n.24/2022) and were conducted following the principles stated in the Declaration of Helsinki.

2.3. Experimental activities

The experimental task consisted of a dynamic arm movement, where subjects were requested to perform a pointing task repetitively, while holding a lightweight screwdriver, from waist level to overhead and vice-versa. The range of movement (RoM) was approximately 100 deg to simulate overhead tasks, while the pace was set to a fixed value (i.e., 50 bpm) through a metronome to reduce intra- and inter-subject movement variability. The experimental setup consisted of a vertical stand with adjustable shelves, which were placed at the waist and overhead levels (Fig. 1C).

Upon arrival, participants received information about the study and signed the written informed consent. Then, helped by an experimenter, they wore the exoskeleton and set the size regulations to fit the device comfortably. They were allowed to familiarize themselves with the exoskeleton and the experimental task. Before starting the experimental

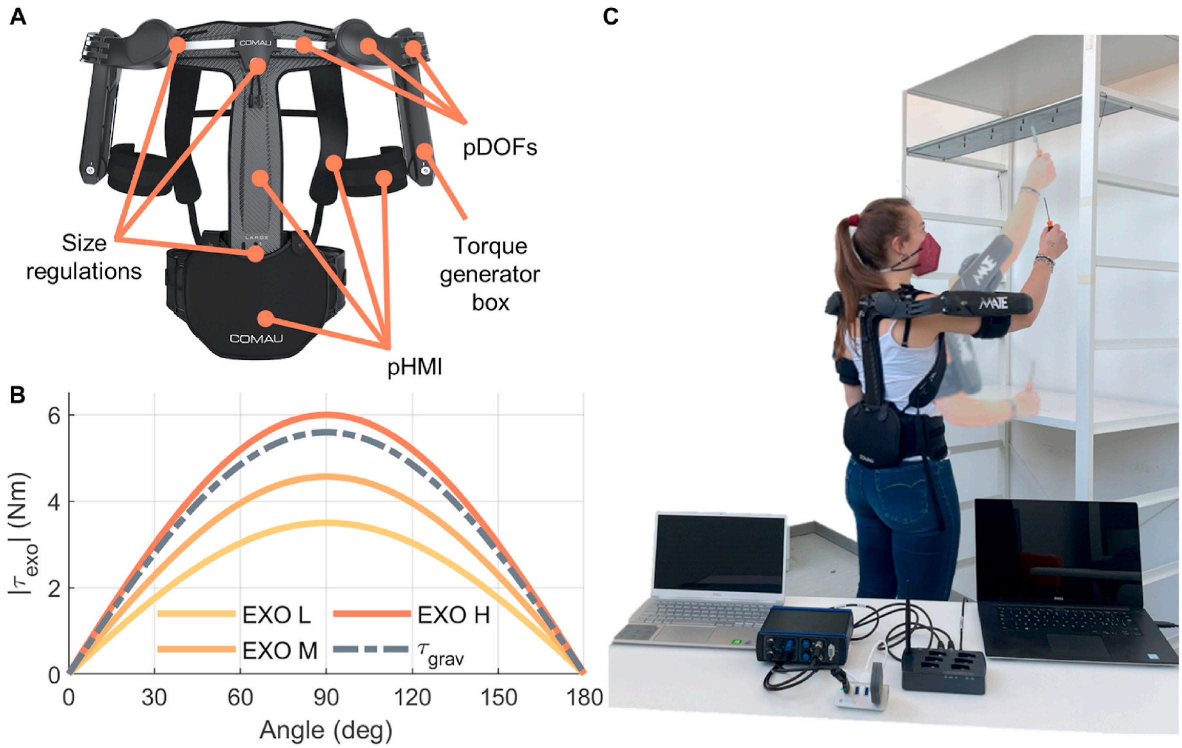

Fig. 1. Passive upper-limb exoskeleton and experimental setup. (A) The main components of the exoskeleton are the torque generator boxes, the physical human-machine interface (pHMI) and the kinematic chain of passive degrees of freedom (pDOFs). A number of size regulations allow users with different anthropometries to wear the device comfortably. (B) Torques profiles corresponding to the arm gravitational torque (τ_{grav}) and EXO antigravitational support (τ_{exo}). (C) Experimental task setup and instrumentation, with a subject wearing the exoskeleton.

activities, subjects were prepared for data collection, namely for placement of electromyography (EMG) electrodes and probes for muscles' activity recording, and inertial measurement unit (IMU) sensors for tracking the arm kinematics (Fig. 2A).

EMG activity was measured using a wireless EMG recording system (FREEEMG 1000, BTS Bioengineering, Milan, Italy). The EMG probes were placed on six muscles on the right side of the body: Anterior Deltoid (AD), Medial Deltoid (MD), Posterior Deltoid (PD), Upper Trapezius (UT), Triceps Brachii (TB), and Latissimus Dorsi (LD) (Fig. 2A). To record the muscles' activity, Ag/AgCl bipolar surface electrodes (Pirrone & Co., Milan, Italy) were positioned on the muscles following the SENIAM recommendations (Hermens et al., 2000). Shoulder kinematics (i.e., shoulder flexion-extension angle) was measured using the XSens MTw motion capture system (XSens, Enschede, The Netherlands). Two IMUs were fixed to the sternum and the right upper arm through elastic bands. Finally, the FREEEMG Trigger Box (BTS Bioengineering, Milan, Italy) was used to offline synchronize EMG and kinematics data. The instrumentation modules used in this study are schematically depicted in Fig. 2B.

Then, for each muscle, participants were asked to perform three 5-s isometric maximum voluntary contractions (MVCs) against resistance.

Four trials were carried out, namely without wearing the exoskeleton (NO EXO) and while wearing the exoskeleton regulated at three different levels of assistance. The three levels of assistance were regulated so that the exoskeleton compensated about 60%, 80%, and 100% of the arm gravitational torque estimated at the glenohumeral joint

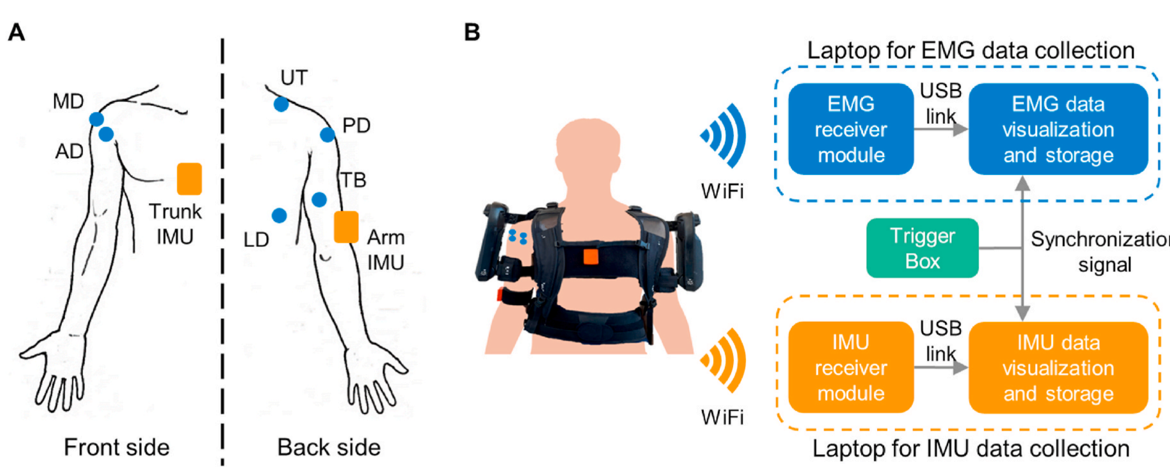

Fig. 2. Sensors placement and measurement systems integration and communication. (A) Schematic representation of the placement of EMG electrodes and IMUs on the user's upper body. (B) Data collection block diagram.

(these conditions were called, respectively, EXO L, EXO M, and EXO H). To estimate the antigravitational contribution provided by the exoskeleton to the user, the arm gravity torque was computed from the anthropometric data of each subject (Table 1), according to Winter's anthropometric tables (Winter, 2009) as in Eq. (1):

$$\tau_{grav} = l_{arm} \cdot F_{gravity} \cdot \sin\theta \tag{1}$$

where l_{arm} is the position of the arm center of mass computed from the subject's height, $F_{gravity} = w_{arm} \cdot g$ is the gravity force of the human arm (w_{arm} is the estimated weight of the arm and g is the gravitational acceleration), and θ is the shoulder flexion-extension (sFE) angle. To have an estimate of the maximum arm gravitational torque, τ_{grav}^{max} was computed at 90 deg of sFE (with the elbow fully extended). Then, the percentage of antigravitational relief (τ_{relief}) generated by the exoskeleton can be computed as in Eq. (2):

$$\tau_{relief} = \frac{\tau_{exo}}{\tau_{grav}^{max}} \cdot 100\ (\%) \tag{2}$$

Tested conditions were pseudo-randomized to avoid order effects, with the NO EXO condition always being performed as the first or last trial of the sequence. Each trial lasted 2 min and between conditions subjects were allowed to rest for 5 min to prevent fatigue effects.

The total duration of the experimental activities was about 90 min.

2.4. Data analysis

Data analysis was performed using custom routines in MATLAB R2019b (The MathWorks, Natick, MA, USA). The EMG signals, collected at 1 kHz, were processed to obtain the linear envelope with the following cascade of processing: band-pass filter (4th order Butterworth filter, cut-off frequencies 20–400 Hz), rectification, notch filter (4th order Butterworth filter, cut-off frequency 50 Hz), and low-pass filter (zero-lag 100-ms moving average filter). The IMUs data, collected at 100 Hz, were processed offline to obtain the sFE angle. IMUs raw data consisted of rotation quaternions that were elaborated to compute the Euler angles of the arm, of which one represented the sFE angle. The sFE angle profiles were segmented into cycles and within each cycle the lifting and lowering sub-phases were identified (Fig. 3). To identify the lifting and lowering movements while mitigating the contribution of movement artifacts to the EMG signals due to changes in the movement direction, the 10% of the RoM was removed at the beginning and end of the selected intervals, similar to (Caragnano et al., 2021).

The EMG envelopes and sFE angle signals were segmented into three separate groups according to the indices extracted from the kinematics data, namely the full flexion-extension cycle, the arm-lifting phase, and the arm-lowering phase. For each trial, the integrated EMG (*iEMG*) value was computed, over the last 30 flexion-extension movements, for each group according to Eq. (3):

$$iEMG = \int_{t_1}^{t_2} \frac{EMG_{envelope}(t)}{t_2 - t_1} dt \tag{3}$$

where t_1 and t_2 correspond to the beginning and end of the considered interval. Then, for each subject, muscle, and condition, the *iEMG* values were normalized by the corresponding MVC value to allow for inter-condition and inter-subject comparison.

Additionally, to assess that the exoskeleton assistance did not affect the shoulder kinematics, the sFE RoM was computed for each full flexion-extension cycle as in Eq. (4):

$$RoM = \theta_{max} - \theta_{min} \tag{4}$$

where θ_{max} is the maximum sFE angle and θ_{min} is the minimum sFE angle in each movement repetition.

2.5. Statistics

Statistical analysis was performed to evaluate differences in the four experimental conditions. Normality of the computed metrics' distributions was verified through the Lilliefors test and parametric or non-parametric statistical tests were applied accordingly. τ_{relief} values were normally distributed, hence parametric one-way analysis of variance (ANOVA) was applied to check for differences across the EXO conditions. Then, the *t*-test was used for post-hoc comparisons. Both the *iEMG* and sFE RoM metrics were not normally distributed, therefore non-parametric one-way repeated-measures ANOVA (Friedman test) was performed to check for between-conditions differences. Then, the Wilcoxon signed-rank test was used for post-hoc comparisons. All statistical analyses were conducted in MATLAB R2019b using a significance level $\alpha < 0.05$.

3. Results

Experimental results are shown for the three different movement phases, namely for the total cycle and the lifting and lowering phases. Table 1 reports the values of τ_{grav} and τ_{relief} for the different participants in all the tested conditions, namely NO EXO, EXO L, EXO M, and EXO H. τ_{relief} was around 62.5%, 82.1%, and 107.8% for EXO L, EXO M, and EXO H conditions, respectively. τ_{relief} in each condition was significantly different from each other ($p = 2 \times 10^{-13}$ for all pairwise comparisons).

Table 1
Subjects' anthropometric values, estimated arm gravitational torque, and percentage of antigravitational relief for the three assistance conditions. Average values are reported as mean ± standard deviation. The arm gravitational torque and the percentage of antigravitational relief are estimated with the arm flexed at 90 deg and elbow fully extended (0 deg).

Subject (#)	Height (cm)	Weight (kg)	τ_{grav} (N·m)	τ_{relief} (%)		
				EXO L	EXO M	EXO H
1	170	54	5.7	61	80	105
2	174	50	5.4	64	84	111
3	169	60	6.3	55	72	95
4	163	53	5.4	64	85	111
5	166	58	6.0	58	76	100
6	167	55	5.7	61	80	105
7	162	52	5.3	66	87	114
8	168	56	5.9	59	78	102
9	168	45	4.7	74	97	127
10	167	53	5.5	63	83	109
11	155	53	5.1	68	89	117
12	172	57	6.1	57	75	98
Mean ± SD	166.7 ± 5	53.8 ± 3.9	5.6 ± 0.4	62.5 ± 5.2	82.1 ± 6.8	107.8 ± 8.9

3.1. Total cycle

The kinematics of the shoulder joint did not show significant differences between the NO EXO condition and the EXO conditions with different levels of assistance. Fig. 4A shows the sFE angle profiles for a representative subject. The sFE RoM values were comparable across all conditions ($p = 0.079$; $\chi^2 = 6.8$), as shown in Fig. 4B.

When assisted by the exoskeleton, regardless of the assistance level, all muscles showed a quasi-linear correlation between antigravitational support and muscle activity reductions, exhibiting lower activity compared to the NO EXO condition (Fig. 5). In particular, flexion-agonist muscles showed reduced activity as the assistance magnitude increased. Reductions reached up to 62% ($p = 4.8 \times 10^{-4}$), 64% ($p = 4.8 \times 10^{-4}$), and 58% ($p = 4.8 \times 10^{-4}$) for AD, MD, and UT, respectively. These muscles also showed significant differences between the assisted conditions. Flexion-antagonist muscles also showed significant reductions in assistive mode compared to NO EXO condition: 39% ($p = 9.3 \times 10^{-3}$), 17% ($p = 0.17$), and 24% ($p = 0.034$) for PD, TB, and LD,

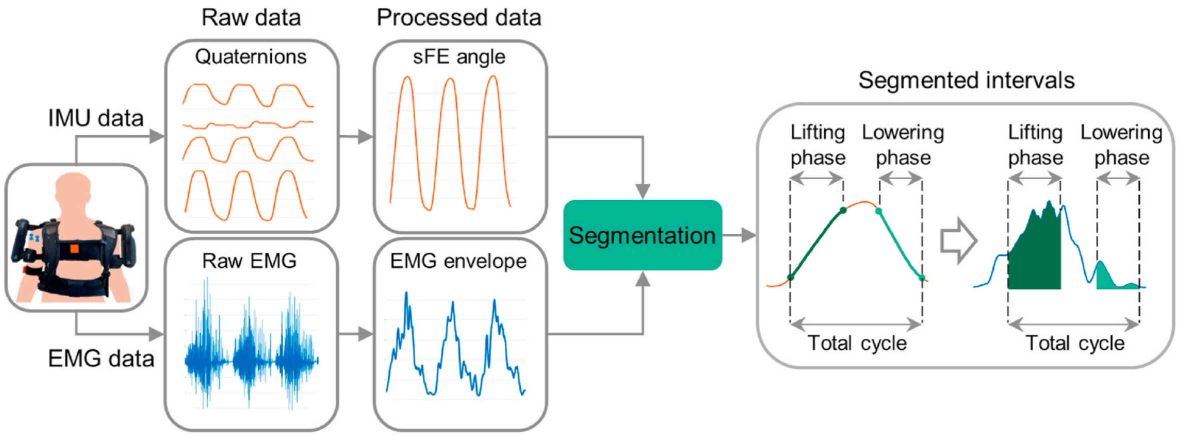

Fig. 3. Schematic representation of the data processing. The sFE angle is computed from quaternions estimated by IMU signals. EMG envelopes are obtained by filtering of raw EMG signals. The sFE angle is used to offline segment data into cycles, and to identify lifting and lowering sub-phases of the movement. EMG metrics are then computed over these intervals.

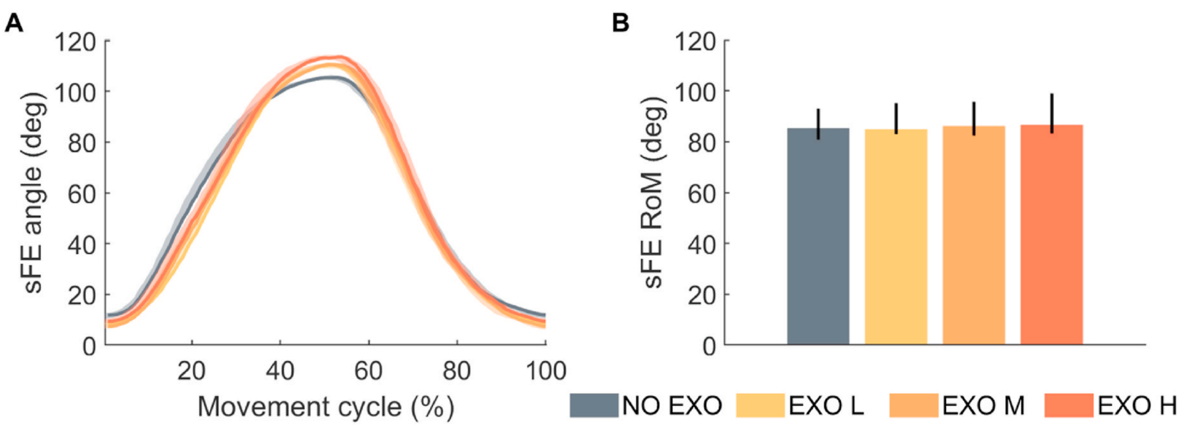

Fig. 4. Kinematics results. (A) sFE flexion/extension cycles for a representative subject, in the four experimental conditions. (B) sFE RoM averaged across all subjects. All data are reported as median values and interquartile range.

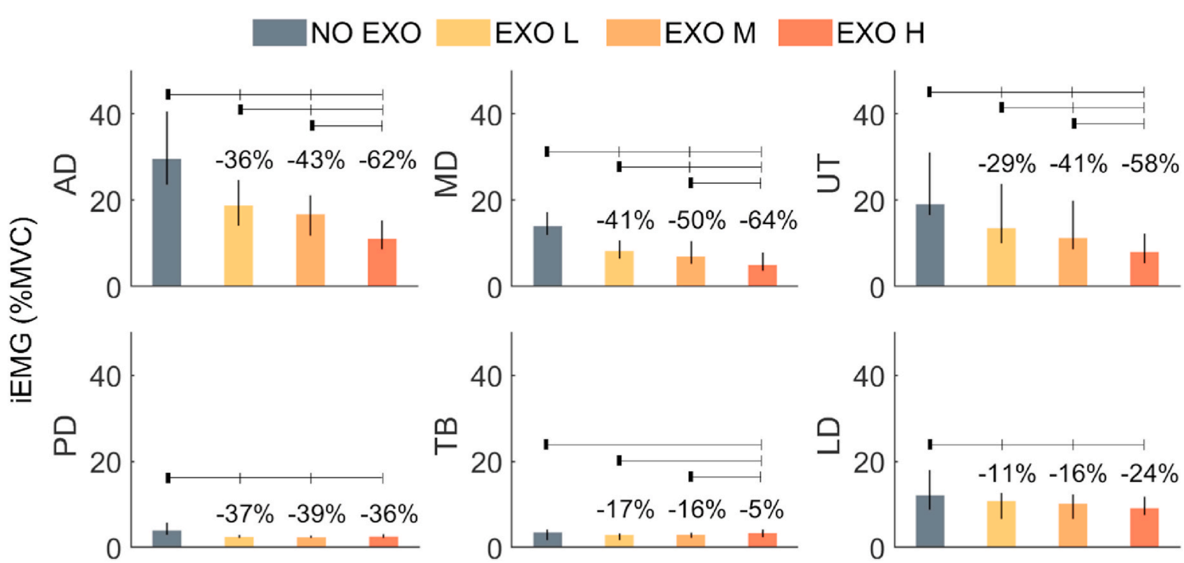

Fig. 5. Average EMG results for the full cycles. EMG results are shown for Anterior Deltoid (AD), Medial Deltoid (MD), Posterior Deltoid (PD), Upper Trapezius (UT), Triceps Brachii (TB), and Latissimus Dorsi (LD). Bars represent median iEMG values expressed as percentage of the MVC. Ticks on the horizontal lines mark statistically significant differences between conditions and the one identified by the bold tick. Median percentage variations with respect to the NO EXO condition are shown in correspondence of each bar.

respectively (Fig. 5).

3.2. Lifting and lowering phases

Concerning the lifting phase, results confirmed that, when assisted by the exoskeleton, all muscles reduced their activation with respect to the NO EXO condition (Fig. 6A). In particular, higher levels of assistance were associated with lower muscular activations, with a quasi-linear correlation. AD, MD, UT, and LD muscles showed significant differences between NO EXO and all EXO conditions. The highest reductions were achieved in the EXO H condition of flexion-agonist muscles, where the assistive torque exceeded the arm gravitational one: 61% for AD ($p = 4.8 \times 10^{-4}$), −61% for MD ($p = 4.8 \times 10^{-4}$), and −57% for UT ($p = 4.8 \times 10^{-4}$).

The lowering phase was characterized by lower muscle activation than the lifting phase, with normalized iEMG values that, on average, did not exceed 20% of the MVC. Also in this condition, the exoskeleton assistance led to reduced activation compared to the NO EXO condition for the AD, MD, and UT (Fig. 6B). Conversely, PD and LD exhibited increased EMG activations in EXO M and EXO H conditions with respect to the NO EXO, while TB showed higher EMG activity in all assisted conditions. The highest increases were observed in the EXO H condition, where the assistive torque exceeded the arm gravitational one: 76% for PD ($p = 0.0068$), 127% for TB ($p = 4.8 \times 10^{-4}$), 38% for LD ($p = 0.15$).

4. Discussion

While in static or quasi-static tasks (such as those characterizing underbody operations in automotive manufacturing plants) previous studies demonstrated that the antigravitational support exerted by passive exoskeletons lead to reductions in muscle activations and that higher reductions were associated with higher assistance levels (de Vries et al., 2019; Grazi et al., 2020; Maurice et al., 2020; Van Engelhoven et al., 2019), dynamic movements have not been investigated sufficiently in detail yet. Nevertheless, the analysis of dynamic movements has is necessary to set the exoskeleton assistance when workers perform such gestures (Pacifico et al., 2022). We designed an experiment in which we tested various levels of antigravitational support using a passive upper-limb exoskeleton (spanning from around 60%–100% of the estimated arm's gravitational load at the glenohumeral joint) and

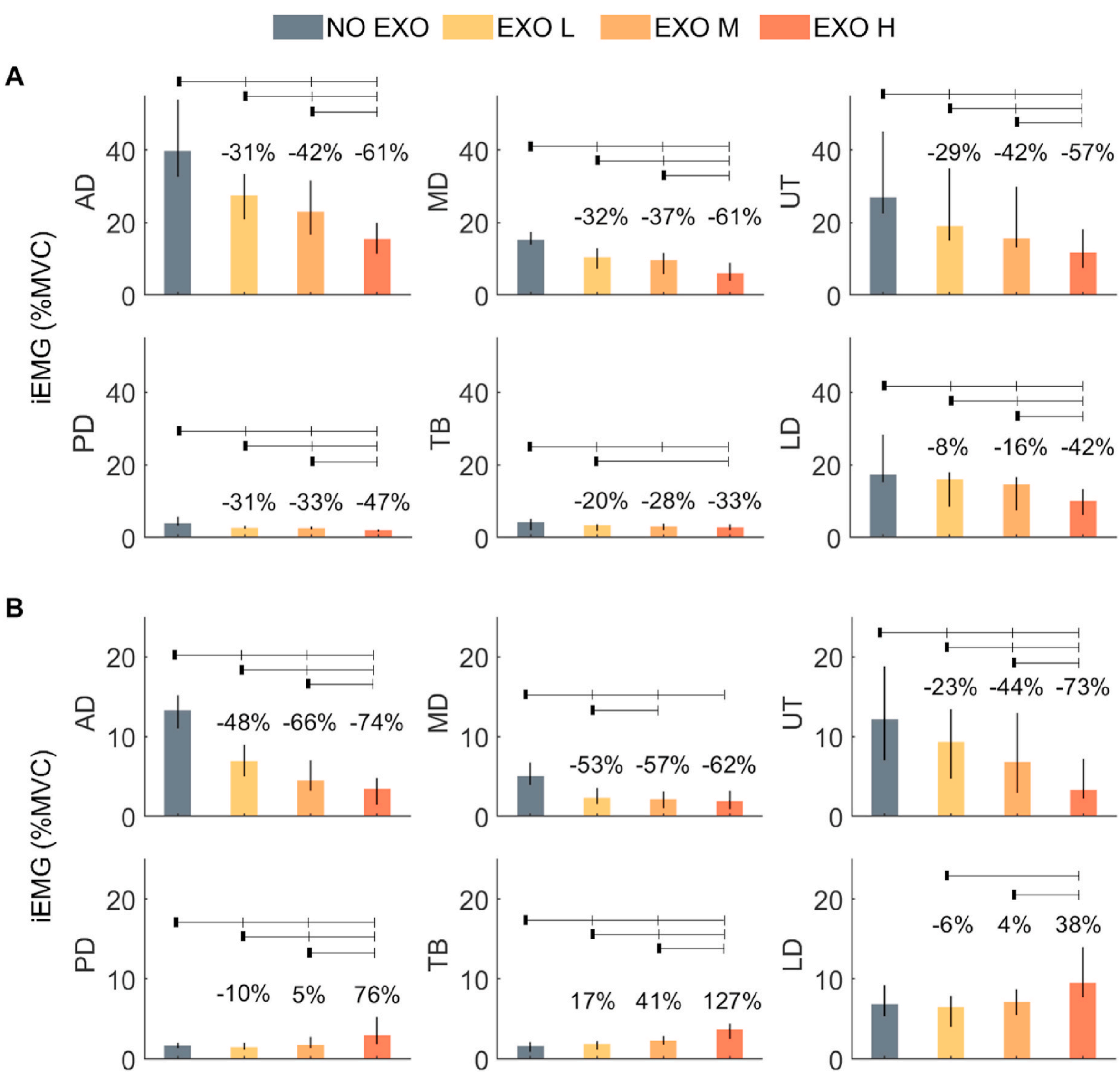

Fig. 6. Average EMG results for the (A) lifting and (B) lowering cycles. EMG results are shown for Anterior Deltoid (AD), Medial Deltoid (MD), Posterior Deltoid (PD), Upper Trapezius (UT), Triceps Brachii (TB), and Latissimus Dorsi (LD). Bars represent median iEMG values expressed as percentage of the MVC. Ticks on the horizontal lines mark statistically significant differences between conditions and the one identified by the bold tick. Median percentage variations with respect to the NO EXO condition are shown in correspondence of each bar.

quantified its effects on EMG signals acquired from shoulder flexor and extensor muscles. Additionally, to perform a comprehensive investigation, average muscle activations were computed on complete cycles, and also on subphases, namely during the arm lifting and lowering phases to underline possible different effects of the exoskeleton during the eccentric and concentric phases of movement, as suggested in (Pacifico et al., 2022).

Concerning complete flexion-extension cycles, results showed that the use of the exoskeleton led to reduced EMG activations of all muscles compared to the NO EXO condition. The absolute value of EMG reductions increased with higher levels of assistance. Reductions were more evident in the flexor muscles (up to 64%), with the highest reductions observed for AD and MD, namely, the main contributors to arm movements in the sagittal and frontal planes (Eovaldi and Varacallo, 2018), and for the UT, which contributes to the arm flexion by elevating the scapula (Di Giacomo et al., 2008). Reduced muscle activations were observed also in extensor muscles (i.e., PD, TB, LD), but reductions were less evident. The overall reduced EMG activation of the muscles of the whole shoulder district might potentially have a long-term positive effect, since it may be indicative of a reduced load on the shoulder joint possibly lowering the incidence of shoulder disorders due to repetitive working gestures (Frost and Andersen, 1999; Leong et al., 2019). Compared to previous studies focusing more on static and quasi-static tasks (de Vries et al., 2019; Grazi et al., 2020; Huysamen et al., 2018; Kim et al., 2018a; Kim and Nussbaum, 2019; Pacifico et al., 2020; Schmalz et al., 2019; Van Engelhoven et al., 2019), our results provide complementary analysis of passive OEs, showing their overall potential benefit to attenuate muscles strain at the shoulder district also in highly dynamic tasks.

In a previous study by (Van Engelhoven et al., 2019), it was suggested that using passive exoskeletons when performing overhead repetitive tasks can lead to higher activations of the extensors, such as the triceps brachii. Nevertheless, it should be noted that the comparison of studies may not be straightforward: the study by (Van Engelhoven et al., 2019) reported EMG average activations computed in the entire flexion and extension cycles without investigating flexion and extension subphases separately, which may have revealed different insights into muscle activation patterns; in addition, the analysis of the effects of the assistance level was performed without considering body anthropometries and mass of the tool used, which prevents the evaluation of how EMG activations are affected by the percentage of the antigravitational support. Another study, instead, despite testing tasks with similar characteristics, only focused on the effects of the exoskeleton on muscles during arm-lifting movements, without any investigation into possible side effects due to the exoskeleton assistance in the arm-lowering phase (De Bock et al., 2023).

In dynamic tasks, passive exoskeletons exert positive and negative mechanical power, when the user raises and lowers the arms, respectively, mimicking the concentric and eccentric behavior of the flexor muscles. Hence the assistive action of the exoskeleton supports flexor muscles in both flexion and extension phases, and this justifies the reduced activations observed in this work in both subphases. Differently, when the antigravitational support by the exoskeleton exceeds the gravitational torque, extensor muscles have to push the arm downwards, therefore showing higher activations. In addition to studying the effects of the OE's support on main shoulder muscles, we included the analysis of the Latissimus Dorsi, to evaluate whether the load transferred by the exoskeleton to the user's back may affect the activity of trunk muscles (de Vries, 2020; Kim et al., 2018b; Rashedi et al., 2014). Our results revealed that the activation of the LD muscle increased during the extension sub-phase only when the percentage of antigravitational relief was close to 100%, showing that particularly high support levels may hinder the users and likely affect the users' discomfort; this result suggests that further analysis on comfort aspects is needed.

Overall, the results achieved in this study suggest that moderate levels of antigravitational support might be effective to support humans in highly dynamic tasks, without hindering the arms in the lowering phase, whereas overcompensating the gravitational torque may be not effective to reduce the burden of all shoulder muscles. Hence, appropriate strategies shall be considered to select the level of assistance, taking into account the user's anthropometry and the type of task executed, as these aspects have a direct influence on the effectiveness of the exoskeleton and may impact the perceived usefulness. Here, it should be noted that from a methodological point of view, previous studies rarely reported the exoskeleton assistance in terms of the percentage of antigravitational support (Pacifico et al., 2020; Schmalz et al., 2019), while in most of the cases, the assistance was reported using absolute force/torque values. Although the levels of assistance that could be set with the present OE were discrete and therefore experimental conditions were kept approximately around certain values of antigravitational support, the results of this study confirm that such strategies should consider the users' and tasks' specific characteristics and that scientific studies shall report this information more accurately to make studies easier to compare.

Finally, concerning shoulder kinematics, we observed that the RoM did not change across different experimental conditions, similarly to findings reported in other studies (McFarland et al., 2022), suggesting that the exoskeleton did not alter the normal kinematics (Moeller et al., 2022; Theurel et al., 2018).

The results achieved in this study may be potentially exploited in different applications. First, they may be the basis for the refinement of guidelines for passive exoskeleton use. Additionally, since in many cases, real work tasks are usually composed of combinations of dynamic gestures and static postures, such as in the logistics sector (Grosse and Glock, 2015; Könemann et al., 2015), our results may be exploited in the context of semi-active occupational exoskeletons. Such devices represent a tradeoff between active and passive exoskeletons, integrating the advantages of both systems (Crea et al., 2021), with the main feature represented by the capability of automatically adjusting the amount of assistance they can deliver (Grazi et al., 2022). In this scenario, the results of this study can be exploited to design effective control strategies which take into account different assistance levels specifically identified for a different type of movement and specific user's anthropometry.

The results of this study are limited by the fact that the experiment was conducted on a pool of non-experienced subjects in a simulated work task, which prevents the generalization to real working situations. Hence, it might be possible that these results could be different in the case of experienced workers who are physically trained to perform highly dynamic and repetitive work gestures at high biomechanical efficiency (Madeleine et al., 2003). Additionally, perception-related measures were not collected. While the relatively short duration of the experiments and therefore familiarization with each experimental condition may had limited the accuracy of perceptive assessments, as suggested by previous studies which included longer testing conditions (Grazi et al., 2020; Luger et al., 2019; Maurice et al., 2020), such data could have been valid indications of the users preferences anyhow and must be carefully considered in future experiments.

A potential additional limitation to this study is related to the fact that we did not collect the elbow angle, hence it was not possible to estimate the τ_{relief} accurately during the execution of the actual tasks and likely the values reported in this study are low-border approximations as they are computed in conditions of maximal gravitational load on the shoulder joint. While this approximation should be considered for the interpretation of the results it is also important to note that anthropometric-based indications on how to set antigravitational support shall be considered as a starting condition and further modifications shall consider the user's preferences and tasks. Still, quantifying the elbow angle may be useful in future investigations to provide more accurate information about the actual exoskeleton support in specific tasks.

Finally, this study suggests that, while maximum assistance may be optimal in static tasks, moderate support could be more advantageous in dynamic tasks, as it can provide effective support while also preventing increased activation of antagonist muscles.

Declaration of competing interest

F. Giovacchini, N. Vitiello, and S. Crea have commercial interests in IUVO S.r.l. (Pontedera, Italy), a spin-off company of Scuola Superiore Sant'Anna. IUVO S.r.l. has developed the MATE-XT technology and owns the IP protecting the technology, which is licensed to COMAU S.p. A. (Grugliasco, Italy) for commercial purposes in the industrial market. F. Giovacchini is the head of the R&D unit of IUVO S.r.l. N. Vitiello and S. Crea are scientific advisors of IUVO S.r.l.

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