

Article

Evaluation of Muscle Activity and Usability of an Upper-Limb Exoskeleton in Power Grid Maintenance Tasks

Xu Jin , Yun Wang  and Lihua He *

Department of Occupational and Environmental Health, School of Public Health, Peking University, Beijing 100191, China; xjin96@pku.edu.cn (X.J.); wangyun@bjmu.edu.cn (Y.W.)

* Correspondence: alihe2009@126.com; Tel.: +86-010-82801728

Abstract

Power grid maintenance tasks often involve sustained arm elevation, asymmetric upper-limb loading, and repetitive pulling, all of which may increase the risk of work-related musculoskeletal disorders. This study evaluated the effects of a passive upper-limb exoskeleton on muscle activity, subjective fatigue, task workload, and usability in three representative power grid maintenance tasks: insulator installation, insulated rod handling, and hand-chain hoist operation. A randomized crossover design was adopted, and twenty-two healthy young male participants completed all tasks under exoskeleton (EXO) and no-exoskeleton (NoEXO) conditions. Surface electromyography was used to quantify muscle activity, and subjective assessments included Borg CR-10, NASA-TLX, an exoskeleton wearing experience questionnaire, and the System Usability Scale (SUS). In the static tasks, the exoskeleton significantly reduced %MVC of the trapezius, deltoid, and biceps brachii, while in the dynamic task, significant reductions were mainly observed in the deltoid and trapezius during the arm-raising phase. The exoskeleton also reduced local discomfort in the shoulders, elbows, and wrists and improved selected workload dimensions, particularly physical demand and effort. The mean SUS score was 74.2, indicating acceptable usability. These findings suggest that the passive upper-limb exoskeleton can effectively reduce proximal upper-limb loading in power grid maintenance tasks, with the greatest benefit observed in static overhead work.

Keywords: work-related musculoskeletal disorders; exoskeleton; occupational ergonomics; power grid maintenance; muscle activity

1. Introduction

Work-related musculoskeletal disorders (WMSDs) remain a major occupational health concern in physically demanding industries [1–3]. Tasks involving sustained arm elevation, repetitive upper-limb movement, forceful exertion, and awkward postures are well-recognized contributors to shoulder and neck loading and may increase the risk of fatigue, discomfort, and cumulative musculoskeletal injury [4]. In power grid maintenance, these biomechanical demands are especially prominent. Many routine operations require workers to hold tools or components above shoulder level, maintain static elevated-arm postures, or perform repetitive pulling and handling actions in constrained environments [5]. Such task characteristics place considerable mechanical demands on the upper limbs and shoulder girdle and may contribute to the development of WMSDs over time [6,7].

In recent years, occupational exoskeletons have attracted increasing attention as a potential ergonomic intervention for reducing physical workload in industrial settings [8–11].



Academic Editor: Claudio Belvedere

Received: 3 June 2026

Revised: 2 July 2026

Accepted: 8 July 2026

Published: 10 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Among them, passive upper-limb exoskeletons are of particular interest because they can provide shoulder support through elastic or spring-based mechanisms without the need for external power. Compared with active systems, passive devices are generally lighter, simpler, and more feasible for field use. Previous laboratory-based studies have shown that passive shoulder-support exoskeletons can reduce muscle activity, delay fatigue development, and improve perceived exertion during overhead work [12–14]. However, their effectiveness is not uniform across tasks. The unloading effect appears to depend strongly on task type, movement phase, posture symmetry, and whether the assistive torque matches the actual biomechanical demand. In particular, benefits observed in static or quasi-static overhead tasks may not be equally evident in more dynamic operations requiring pulling, distal force generation, or complex whole-body coordination [15,16].

Despite this growing body of research, evidence remains limited for occupation-specific applications in the power industry. Most previous studies have focused on generic industrial tasks such as overhead drilling, assembly, or lifting, whereas representative power grid maintenance tasks have received much less attention [17,18]. This is an important gap, because the physical demands of power grid work are not fully captured by conventional laboratory tasks. Maintenance operations often combine prolonged static holding, asymmetric upper-limb use, tool manipulation, and intermittent dynamic exertion [19]. As a result, the effectiveness of upper-limb exoskeletons observed in general industrial settings cannot be directly assumed to apply to power grid maintenance. In addition, beyond physiological unloading, practical implementation also depends on user acceptance, perceived comfort, and usability during task execution [20].

Therefore, this study aimed to evaluate the effects of a passive upper-limb exoskeleton on muscle activity, subjective fatigue, task workload, and usability in three representative power grid maintenance tasks: insulator installation, insulated rod handling, and hand-chain hoist operation. A randomized crossover design was adopted, and task performance was compared under exoskeleton and no-exoskeleton conditions. Surface electromyography (sEMG) was used to quantify muscle activity, while subjective assessments were used to characterize discomfort, workload, and user experience [21]. sEMG was selected as the primary physiological outcome because it allows direct quantification of task-related muscle activation in the muscles most likely to be affected by upper-limb exoskeleton assistance. Compared with subjective scales alone, EMG provides an objective and time-sensitive measure of muscular demand and can help determine whether the mechanical support provided by the device translates into reduced activation of the target muscles. Unlike previous studies that mainly focused on generic overhead work, assembly, or construction tasks, the present study compared three power grid maintenance tasks with distinct biomechanical characteristics: sustained bilateral overhead work, asymmetric static tool holding, and dynamic pulling. We hypothesized that the exoskeleton would reduce proximal upper-limb muscle activity and perceived workload, with the most pronounced benefit occurring in tasks involving sustained or repeated arm elevation. By focusing on task-specific responses, this study sought to provide experimental evidence for the ergonomic application of passive upper-limb exoskeletons in the power grid maintenance context.

2. Materials and Methods

2.1. Participant

A total of 22 healthy young adult male volunteers were recruited for this study. To improve the consistency of the experimental conditions and reduce the potential influence of sex-related differences in muscle strength, movement patterns, and exoskeleton fit, only male participants were included. Inclusion criteria were age 18–35 years; good general health with no evident organic disease on physical examination; no history of

acute or chronic musculoskeletal injury or related surgery; and ability to understand the experimental requirements and complete the entire study protocol. Exclusion criteria included: a history of neurological disorders or peripheral nerve injury; cardiovascular disease, such as hypertension or coronary heart disease; strenuous physical activity within 48 h prior to testing; skin allergy or intolerance to surface electrode adhesive materials; use of medications that might affect muscle function or neural conduction within 7 d before testing, including muscle relaxants, analgesics, and anticholinergic drugs; intake of caffeine-containing substances, such as coffee, strong tea, or energy drinks, within 24 h prior to testing; and refusal or inability to complete the full experimental procedure.

Before enrollment, all participants completed a health questionnaire and underwent basic physical assessments to confirm that they met the safety requirements for the experiment. Restricting the sample to healthy young adult males helped reduce inter-individual variability in physiological workload responses associated with sex and health status, thereby improving the internal consistency of the study. In addition, the sample was considered relatively homogeneous because all participants were healthy young adult males within a restricted age range, had no history of musculoskeletal or neurological disorders, and met the same pre-test restrictions regarding strenuous physical activity, medication use, and caffeine intake. This restriction was intended to reduce inter-individual variability in EMG amplitude, movement strategy, and perceived workload responses under controlled laboratory conditions. Participants were also asked about their regular physical activity habits before enrollment. None of the participants was a professional athlete or engaged in occupation-related heavy manual work; most reported recreational physical activity at a light-to-moderate level. Because physical activity level was recorded descriptively rather than using a validated physical activity questionnaire, this factor was not included as a covariate in the statistical models. All participants also received standardized task training before the formal experiment to ensure familiarity with the procedures and task requirements. The mean (SD) age, body mass, height, and body mass index (BMI) of the participants were 25.5 (3.8) years, 69.6 (7.8) kg, 175.5 (6.6) cm and 22.6 (2.3) kg/cm², respectively. The basic characteristics of the participants are shown in Table 1.

Table 1. Basic Characteristics of the participants (mean $\pm$ SD).

Characteristics	Mean	SD
Age, years	25.5	3.8
BMI, kg/m ²	22.6	2.3
Body Mass, kg	69.6	7.8
Height, cm	175.5	6.6
Arm Span, cm	174.3	7.5
Foot Length, cm	25.9	1.6
Hip Height, cm	96.2	7.16
Shoulder Height, cm	145.4	5.9
Hip Width, cm	31.4	2.5
Shoulder Width, cm	39.8	5.5
Knee Height, cm	50.1	3.6
Elbow Span, cm	90.2	4.7
Ankle Height, cm	8.6	2.6
Wrist Span, cm	151.8	8.1
Sole Height, cm	2.6	1.1

Written informed consent was obtained from all participants after they had been fully informed of the study purpose, experimental procedures, and potential risks. The study protocol was approved by the Ethics Committee of Guangdong Province Institute

for Occupational Disease Prevention and Control (protocol code GDHOD MEC 2025061, 4 December 2025).

2.2. Exoskeletons

In this study, a passive upper-limb exoskeleton (PES-U; ULS Robotics Co., Ltd., Shanghai, China) was used. The device adopts a spring-based elastic energy storage mechanism to provide assistive torque during shoulder elevation, thereby reducing upper-limb loading during sustained or repetitive overhead tasks. As a passive system, it does not require an external power source. The exoskeleton weighs 1.9 kg, is suitable for users 160–190 cm in height, and has eight degrees of freedom. It is primarily constructed from engineering plastics, aluminum alloys, and carbon-fiber materials. Figure 1 shows the physical schematic of the upper-limb exoskeleton.



Figure 1. Physical schematic of the upper-limb exoskeleton: (a) Front view of the exoskeleton; (b) Back view of the exoskeleton. The device weighs 1.9 kg and uses a passive spring-based elastic energy storage mechanism to provide assistive torque during shoulder elevation. The maximum assistive torque is 15 N·m.

2.3. Study Design

This study adopted a randomized balanced crossover design to evaluate exoskeleton effects on three representative upper-limb maintenance tasks, selected via field studies for their frequency and biomechanical demand: (1) insulator installation (static task), simulating overhead installation/fastening by holding and manipulating an insulator with both hands above head. Each trial lasted 1 min, followed by a 30 s rest, repeated 5 times; (2) insulating rod handling (static task), simulating prolonged live-line work by statically holding a vertical insulating rod. Participants held a real insulating rod (2.4 kg) vertically with both hands (dominant hand upper) in a static posture for 5 min, requiring sustained isometric contraction against gravity; and (3) chain hoist operation (dynamic task), simulating manual lifting using a hoist by repeatedly pulling the handle to lift a weight. Participants repeatedly pulled the handle of a chain hoist with their right hand to vertically lift a 20 kg standard weight over a 1 m height. All participant completed all tasks under two conditions: while wearing the exoskeleton (EXO condition) and without wearing the exoskeleton (NoEXO condition). All participants received standardized task familiarization before formal testing. The order of EXO and NoEXO conditions was randomized across participants, and task order was randomized within each session to reduce systematic order effects. The interval between the two experimental sessions was at least 24 h to reduce acute fatigue carryover. The experimental procedure is illustrated in Figure 2.

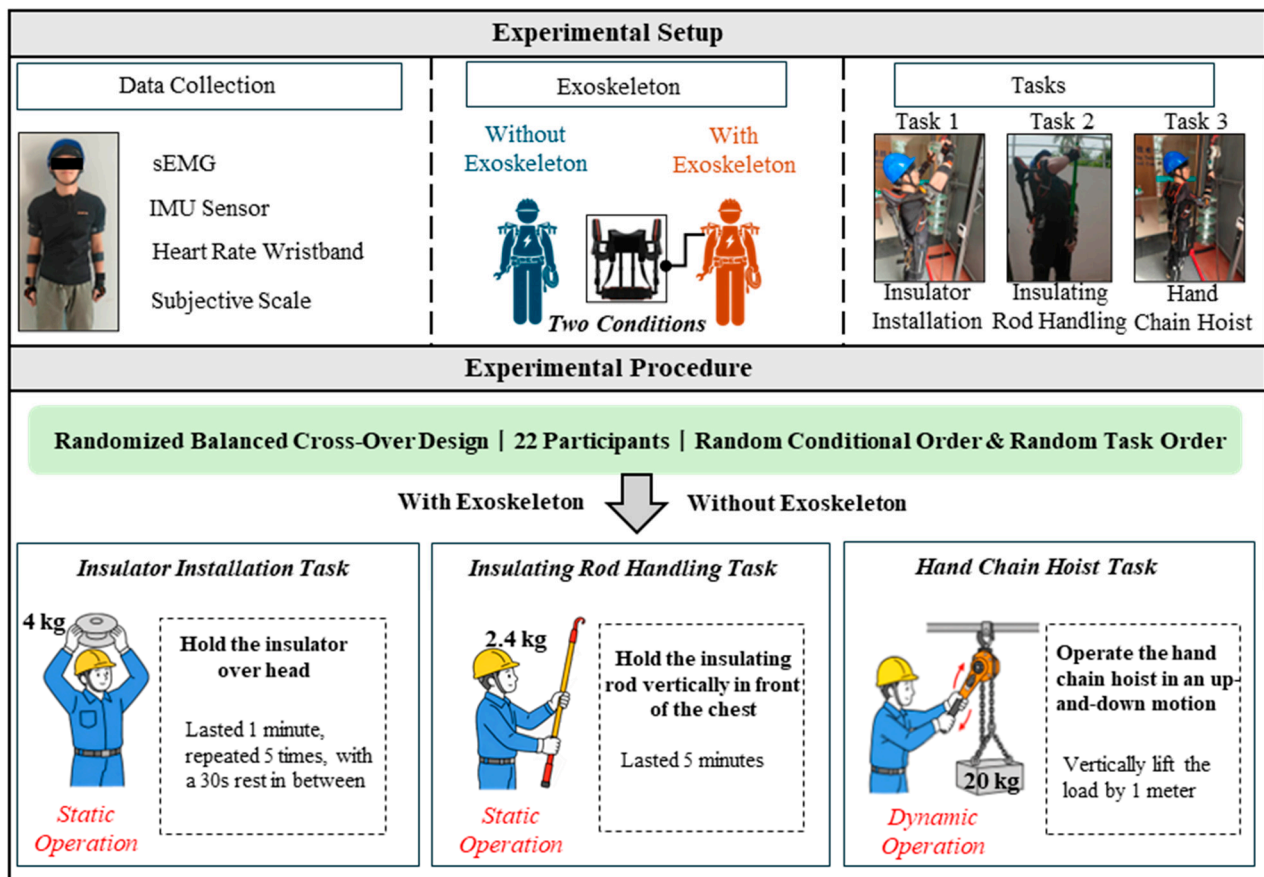


Figure 2. The experimental procedure of this study.

2.4. Data Collection and Analysis

2.4.1. Surface Electromyographic Signals

sEMG signals were collected using the wireless sEMG system (2000 Hz, PicoX, Cometa, Milan, Italy). Ten muscles related to upper-body loading, including the bilateral upper trapezius, deltoid, biceps brachii, brachioradialis, and erector spinae, were monitored. Before electrode placement, the skin was shaved, lightly abraded, and cleaned with 75% alcohol. Disposable 3 M Ag/AgCl self-adhesive surface electrodes were placed at standardized anatomical locations according to the SENIAM recommendations [22]. For the upper trapezius, electrodes were placed midway between the acromion and the spinous process of C7. For the deltoid, electrodes were placed over the middle deltoid belly, approximately midway between the acromion and the deltoid tuberosity. For the biceps brachii, electrodes were placed on the line between the medial acromion and the fossa cubit, over the muscle belly. For the brachioradialis, electrodes were placed on the proximal forearm over the muscle belly along the line from the lateral supracondylar ridge to the radial styloid. For the erector spinae, electrodes were placed bilaterally approximately 3 cm lateral to the spinous process at the lumbar level. The inter-electrode distance was approximately 20 mm, and electrodes were aligned parallel to the presumed muscle fiber direction.

To standardize muscle activation levels across participants and experimental conditions, maximum voluntary contraction (MVC) tests were performed for each target muscle. Each muscle completed three 5 s MVC trials with 1 min rest between trials. For the upper trapezius, participants performed resisted shoulder shrugging in a seated posture. For the deltoid, participants performed resisted shoulder abduction at approximately 90°. For the biceps brachii, participants performed resisted elbow flexion at approximately 90° of elbow flexion with the forearm supinated. For the brachioradialis, participants performed resisted

elbow flexion with the forearm in a neutral position. For the erector spinae, participants performed resisted trunk extension in a prone posture. The highest root mean square (RMS) value across the three trials was taken as the maximum voluntary electrical activation reference value. Raw EMG signals were processed offline using Python and custom scripts. A fourth-order zero-lag Butterworth band-pass filter of 20–450 Hz was applied, followed by a 50 Hz notch filter to reduce power-line interference. The filtered signals were full-wave rectified and then smoothed using a moving RMS window of 100 ms. For each muscle, EMG amplitude during the experimental tasks was normalized to the highest RMS value obtained during the corresponding MVC trials and expressed as %MVC.

For the insulator installation task, each trial lasted 60 s. After excluding the first and last 3 s to avoid transition-related artifacts, the middle 54 s of each trial was analyzed, and the values were averaged across repeated trials. For the insulated rod handling task, the static holding duration was 5 min. After excluding the first and last 3 s, the middle 294 s was analyzed. For the dynamic hand chain hoist task, each pulling action was defined as one movement cycle, normalized to 0–100% of the cycle, and then averaged across cycles.

2.4.2. Cardiovascular Load

Heart rate was continuously monitored throughout the experiment using heart rate wristband (Qingyun H9D2, Huawei, Shenzhen, China). Before the experiment, the participant's resting heart rate and resting blood pressure were measured as baseline physiological values. During the experiment, the device continuously records heart rate data. During the rest period after the end of each task state, heart rate and blood pressure were recorded immediately and the average heart rate for that task was extracted as an auxiliary indicator of cardiovascular load.

2.4.3. Subjective Assessment

Immediately after completion of each task, participants completed subjective assessments of fatigue and task workload. The Borg CR-10 scale was used to assess subjective fatigue and discomfort in different body regions, including the neck, shoulder, elbow, wrist, upper back, lower back, thigh, knee, and ankle. Subjective task workload was evaluated using the NASA Task Load Index (NASA-TLX), which assesses six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [23,24].

After completion of all experimental conditions, participants completed an exoskeleton wearing experience questionnaire, and the overall system usability was assessed using the System Usability Scale (SUS) [25]. The exoskeleton experience questionnaire covered six aspects, including ease of donning and doffing, overall comfort, perceived pressure and friction, impact on work flexibility, perceived potential for musculoskeletal injury prevention, and willingness to use the device voluntarily, with all items rated on a 5-point Likert scale. The SUS consists of 10 items, and the total score is converted to a standardized scale ranging from 0 to 100, with higher scores indicating better system usability.

2.5. Statistical Methods

All statistical analyses were performed using R version 4.4.1 in RStudio (Posit Software, PBC, Boston, MA, USA) and Python (v3.12, Python Software Foundation, Wilmington, DE, USA) within Jupyter Notebook (v6.5, <https://jupyter.org/>). Values with a normal distribution were described as mean and standard deviation, whereas non-normally distributed values were presented as median and interquartile range.

The effects of side (left vs. right) and exoskeleton condition (EXO vs. NoEXO) on electromyographic and kinematic variables were analyzed using linear mixed-effects models. For the dynamic task, time-normalized %MVC curves were analyzed using one-dimensional statistical parametric mapping (1D-SPM). This method allows statistical

comparison of continuous biomechanical or physiological waveforms across the entire movement cycle rather than reducing the signal to a single discrete value. The EMG waveform of each pulling cycle was normalized to 0–100% of the movement cycle, and condition effects were tested at each time point while controlling for temporal correlation across the waveform. A supra-threshold cluster was considered statistically significant when the test statistic exceeded the critical threshold.

Mean heart rate and immediate post-task systolic and diastolic blood pressure were compared between the EXO and NoEXO conditions using paired t-tests. Borg CR-10 ratings and NASA-TLX dimension scores and total scores were also compared between the EXO and NoEXO conditions using paired t-tests.

3. Results

It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Static Tasks

The %MVC results for the static tasks are presented in Figure 3.

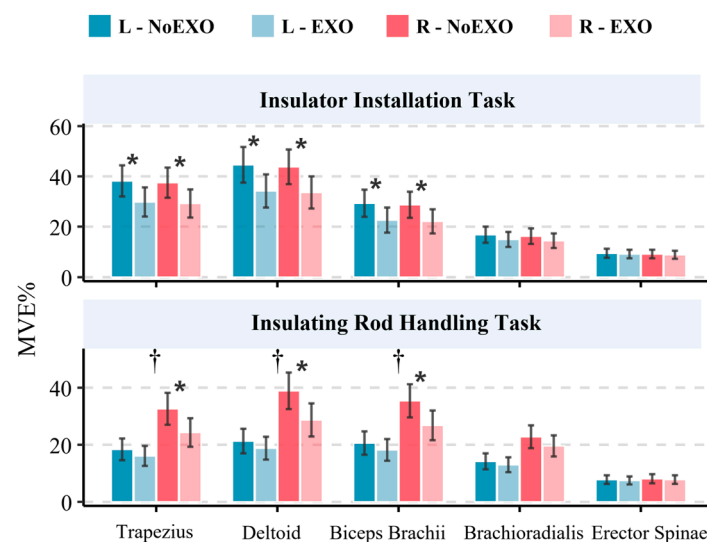


Figure 3. The average muscle activity during the insulator installation task and insulating rod handling task with and without exoskeleton. * Indicates a significant main effect of condition. † Indicates a significant interaction effect between condition and side.

For the insulator installation task, which was characterized by sustained overhead holding, the deltoid and trapezius showed the highest activation levels, followed by the biceps brachii, whereas the brachioradialis and erector spinae remained at relatively low activation levels (all < 18%). No significant side effect was found for any muscle. Compared with the NoEXO condition, the EXO condition significantly reduced %MVC in the trapezius ($F = 8.42$, $p = 0.009$, $\eta^2 = 0.286$), deltoid ($F = 9.16$, $p = 0.006$, $\eta^2 = 0.304$), and biceps brachii ($F = 7.83$, $p = 0.011$, $\eta^2 = 0.272$), with reductions of 21–24%. No significant condition effect was observed for the brachioradialis ($F = 2.14$, $p = 0.158$) or erector spinae ($F = 0.38$, $p = 0.544$). No significant condition $\times$ side interaction was detected for any muscle.

For the insulated rod holding task, performed with an asymmetric grip posture (right hand above and left hand below), %MVC values of the dominant right-side deltoid, trapezius, and biceps brachii were significantly higher than those of the left side (all $p < 0.05$). Under the EXO condition, %MVC in the right trapezius ($F = 7.64$, $p = 0.012$, $\eta^2 = 0.267$), deltoid ($F = 8.91$, $p = 0.007$, $\eta^2 = 0.298$), and biceps brachii ($F = 8.23$, $p = 0.009$, $\eta^2 = 0.281$) was

significantly reduced, with decreases of 24–26%. In contrast, the corresponding reductions on the left side were smaller (11–12%) and not statistically significant. Significant condition $\times$ side interactions were identified for the trapezius ($F = 6.38$, $p = 0.020$, $\eta^2 = 0.233$), deltoid ($F = 7.12$, $p = 0.014$, $\eta^2 = 0.253$), and biceps brachii ($F = 5.94$, $p = 0.024$, $\eta^2 = 0.220$), whereas no significant interaction effect was found for the brachioradialis or erector spinae.

Heart rate and blood pressure responses are shown in Figure A1. During the insulator installation task, heart rate was significantly lower in the EXO condition than in the NoEXO condition (94.1 ± 8.8 bpm vs. 98.4 ± 9.2 bpm, $\Delta = -4.3$ bpm, 95% CI: -7.1 to -1.5 , $p = 0.005$). During the insulated rod handling task, heart rate was also significantly lower in the EXO condition than in the NoEXO condition (90.8 ± 8.4 bpm vs. 93.6 ± 8.7 bpm, $\Delta = -2.8$ bpm, 95% CI: -5.2 to -0.4 , $p = 0.025$).

3.2. Dynamic Task

The time-normalized %MVC curves and corresponding 1D-SPM results for the dynamic task are presented in Figure 4.

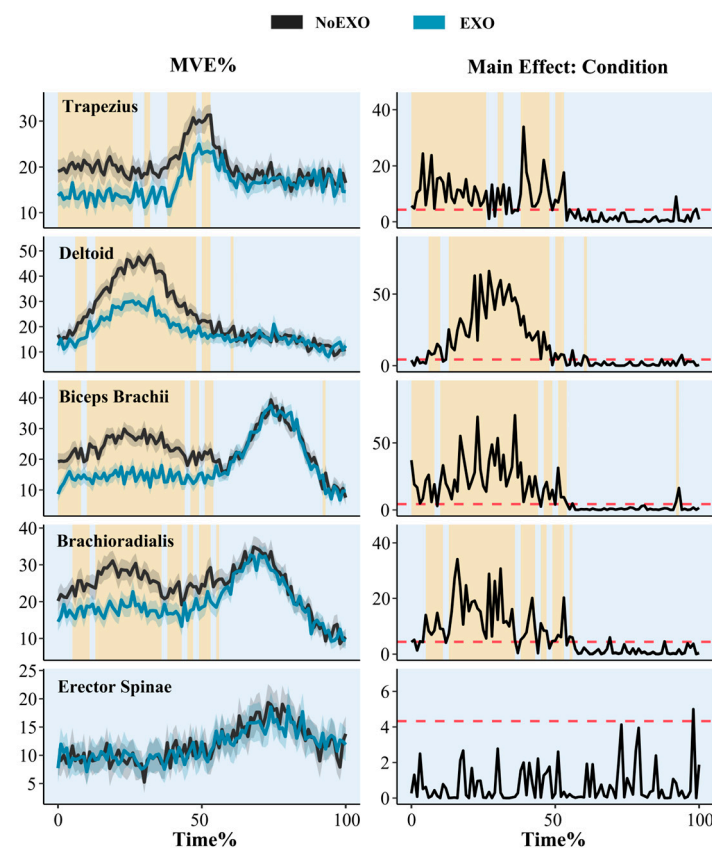


Figure 4. The average muscle activity times series during the hand chain hoist task (**left**). The main effect of condition on muscle activity (**right**). The y-axis shows the one-dimensional F-value, and the red dotted line represents the critical F-value at the analytical degrees of freedom. The yellow shadow area indicates a significant effect.

Each pulling action was analyzed as a single movement cycle (0–100% normalized). During the arm-raising preparation phase (0–50% of the cycle), the deltoid reached peak activation, which was significantly lower under the EXO condition compared with NoEXO ($p < 0.001$). The biceps brachii and brachioradialis peaked during the downward force phase (50–100% of the cycle); however, no significant differences were observed between EXO and NoEXO, consistent with the passive exoskeleton being in its spring energy storage state. Trapezius activation remained relatively stable throughout the cycle, primarily con-

tributing to scapular stabilization, with significantly lower activation in the EXO condition during the arm-raising phase ($p < 0.05$), but no significant difference during the downward phase. Erector spinae showed slight activation during the downward force phase, with no significant differences across conditions.

Overall, these results indicate that the passive exoskeleton effectively reduced deltoid and trapezius activation during the lifting phase, while its effect on distal upper-limb muscles and postural trunk muscles was minimal.

During the hand-chain hoist task, no significant difference in heart rate was observed between conditions. Systolic blood pressure, diastolic blood pressure, and mean arterial pressure did not differ significantly between EXO and NoEXO conditions in any task.

3.3. Subjective Workload and Usability

Figure 5 presents the Borg CR-10 and NASA-TLX scores across the three tasks.

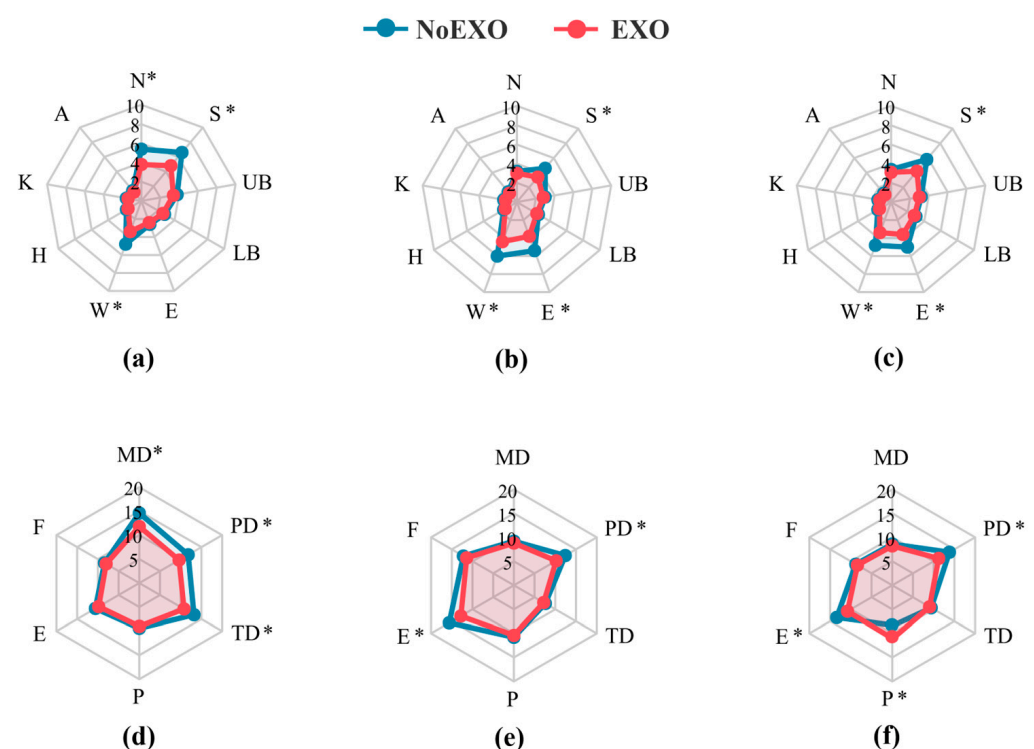


Figure 5. Local discomfort and NASA-TLX scores with and without the exoskeleton across the three tasks. (a–c) Borg CR-10 local discomfort scores for the insulator installation, insulated rod handling, and hand chain hoist tasks, respectively. (d–f) NASA-TLX scores for the insulator installation, insulated rod handling, and hand chain hoist tasks, respectively. N = neck, S = shoulder, UB = upper back, LB = low back, E = elbow, W = wrist, H = Hip, K = knee, A = ankle. MD = mental demand, PD = physical demand, TD = temporal demand, P = performance, E = effort, F = frustration. * $p < 0.05$.

In the insulator installation task, wearing the exoskeleton significantly reduced perceived fatigue in the neck (5.4 ± 1.3 vs. 3.8 ± 1.1 , $p < 0.05$), shoulders (6.6 ± 1.4 vs. 4.8 ± 1.2 , $p < 0.05$), and wrists (4.8 ± 1.2 vs. 3.4 ± 1.2 , $p < 0.05$). Notably, the shoulder score under the NoEXO condition (6.6) was the highest among all three tasks, indicating the exoskeleton's most pronounced unloading effect in high-arm, overhead postures. For the insulating rod handling task, exoskeleton use significantly lowered Borg CR-10 scores for the wrists (6.0 ± 1.3 vs. 4.4 ± 1.1 , $p < 0.05$), elbows (5.4 ± 1.2 vs. 3.8 ± 1.3 , $p < 0.05$), and shoulders (4.6 ± 1.2 vs. 3.4 ± 1.3 , $p < 0.05$). The wrist and elbow were the most fatigued regions in this task, whereas differences in other body regions were not significant. In the hand chain hoist task, perceived fatigue was significantly reduced in the shoulders (5.8 ± 1.3 vs. 4.2 ± 1.1 ,

$p < 0.05$), elbows (5.0 ± 1.2 vs. 3.6 ± 1.3 , $p < 0.05$), and wrists (4.8 ± 1.2 vs. 3.4 ± 1.4 , $p < 0.05$), with no significant differences observed in the neck, back, or lower limbs.

Regarding task load assessed by NASA-TLX, in the insulator installation task, exoskeleton use significantly decreased mental demand (14.6 ± 2.6 vs. 11.8 ± 2.2 , $p < 0.05$), temporal demand (13.2 ± 2.4 vs. 10.8 ± 2.6 , $p < 0.05$), and physical demand (11.8 ± 2.2 vs. 9.6 ± 2.3 , $p < 0.05$), with no significant differences in other dimensions. In the insulating rod handling task, effort (15.6 ± 2.8 vs. 12.8 ± 2.4 , $p < 0.05$) and physical demand (12.4 ± 2.2 vs. 10.2 ± 2.1 , $p < 0.05$) were significantly reduced under the EXO condition; other dimensions showed no significant changes. For the hand chain hoist task, physical demand (13.8 ± 2.4 vs. 11.2 ± 2.5 , $p < 0.05$) and effort (13.4 ± 2.4 vs. 10.8 ± 2.3 , $p < 0.05$) decreased, whereas task performance scores increased significantly (13.6 ± 2.4 vs. 10.8 ± 2.6 , $p < 0.05$). No significant differences were observed for the remaining dimensions.

The results of the exoskeleton wearing experience questionnaire and the system usability are summarized in Table 2. Participants rated ease of donning and doffing with a mean of 3.2 ± 0.2 (median 3, IQR 2–4), and overall comfort was rated 3.5 ± 0.7 (median 4, IQR 3–4). Pressure and friction sensations scored 3.8 ± 0.5 (median 4, IQR 3–4), while the impact on task flexibility was 3.4 ± 0.8 (median 3, IQR 3–4). Participants perceived a high potential for musculoskeletal injury prevention (4.2 ± 0.4 , median 4, IQR 4–5) and expressed a strong willingness to use the exoskeleton (4.0 ± 0.8 , median 4, IQR 3–5).

Table 2. Evaluation of exoskeleton wearing experience and system usability.

Category	Item	Mean $\pm$ SD	Median (IQR)
Wearing experience ¹	Ease of donning and doffing	3.2 ± 0.2	3 (2, 4)
	Overall comfort	3.5 ± 0.7	4 (3, 4)
	Pressure and friction sensation	3.8 ± 0.5	4 (3, 4)
	Impact on task flexibility	3.4 ± 0.8	3 (3, 4)
	Perceived potential for injury prevention	4.2 ± 0.4	4 (4, 5)
	Willingness to use	4.0 ± 0.8	4 (3, 5)
System usability ²	Total SUS score (0–100 points)	74.2 ± 8.6	74 (68, 80)

¹ Wearing experience items were rated using a 1–5 Likert scale. For ease of donning and doffing, overall comfort, perceived potential for injury prevention, and willingness to use, higher scores indicate more favorable evaluations. For pressure and friction sensation and impact on task flexibility, higher scores indicate stronger perceived pressure/friction or greater perceived restriction. ² The SUS total score ranges from 0 to 100, with higher scores indicating better perceived usability.

4. Discussion

This study examined the effects of a passive upper-limb exoskeleton on muscle activity, subjective fatigue, task workload, and usability in three representative power grid maintenance tasks. Overall, the exoskeleton reduced proximal upper-limb muscle activity in both static tasks, while its effect in the dynamic task was mainly confined to the arm-raising phase. These physiological changes were accompanied by lower task-specific discomfort scores and partial improvements in perceived workload. In addition, the usability results indicated that the device was generally well accepted by participants. Taken together, the findings suggest that the ergonomic benefit of the exoskeleton was evident but strongly depended on task demands and movement characteristics [26].

The clearest unloading effect was observed in the insulator installation task. This task required sustained bilateral overhead holding and imposed the greatest burden on the shoulder region, as reflected by the high activation of the deltoid and trapezius and the highest shoulder discomfort score under the NoEXO condition. Under the EXO condition, %MVC of the trapezius, deltoid, and biceps brachii decreased significantly, indicating that the device effectively reduced the muscular demand associated with maintaining

the upper limbs in an elevated position. This pattern is consistent with the mechanical design of the exoskeleton, which provides passive support during shoulder elevation and is therefore better matched to static or semi-static overhead work than to movements dominated by distal force production [27]. The simultaneous reduction in neck, shoulder, and wrist discomfort further suggests that the unloading effect was not only detectable at the physiological level but was also perceived by the wearer during task performance [28].

A different pattern was found in the insulated rod handling task. Unlike insulator installation, this task involved an asymmetric posture, with the dominant right hand positioned above the left. Accordingly, the right-side deltoid, trapezius, and biceps brachii showed higher activation than the corresponding muscles on the left side. Under the EXO condition, the reduction in muscle activity was more pronounced on the dominant side, and significant condition $\times$ side interactions were observed for the main shoulder-related muscles. This finding indicates that the assistive effect of the device was influenced not only by task type, but also by the side-specific distribution of biomechanical load. In practical terms, the exoskeleton appeared to be more effective when the assisted arm was also the primary load-bearing arm. This is relevant for power grid maintenance, where many operations are posture-dependent and often involve asymmetrical upper-limb use rather than perfectly balanced bilateral effort [29].

The hand-chain hoist task further highlighted the task-phase specificity of passive assistance. The time-normalized analysis showed that the exoskeleton significantly reduced deltoid activation during the arm-raising phase and reduced trapezius activation mainly over the same period. By contrast, no clear reduction was observed in the biceps brachii, brachioradialis, or erector spinae during most of the movement cycle. This pattern is biomechanically reasonable. As a passive shoulder-support device, the exoskeleton primarily assists shoulder elevation, but it does not directly support the pulling action itself [30,31]. During the downward force phase, when the biceps brachii and brachioradialis were most active, the device was mainly in a spring-loading state, and its capacity to reduce distal muscle demand was therefore limited. The absence of a significant effect on erector spinae activity also suggests that trunk involvement in this task was not substantially altered by the device. These results indicate that the current exoskeleton is more suitable for reducing shoulder load during lifting or holding phases than for assisting tasks dominated by downward pulling or coordinated whole-body force generation.

The subjective findings were broadly consistent with the physiological results. Across the three tasks, the exoskeleton reduced Borg CR-10 scores in the body regions most directly involved in the task, particularly the shoulders, elbows, and wrists. The pattern of reduction differed by task, which further supports the view that the device acted in a task-specific manner rather than producing a generalized reduction in discomfort. Similar task dependence was also observed in the NASA-TLX results. Physical demand and effort were the dimensions most consistently improved under the EXO condition, which is in line with the primary purpose of the device [32]. In the insulator installation task, mental demand and temporal demand were also reduced, possibly because relief of shoulder loading made prolonged overhead work feel less urgent and less difficult to sustain. In the hand-chain hoist task, perceived performance improved under the EXO condition, suggesting that the device did not interfere with operation and may have enhanced perceived control during task execution. From an application perspective, these subjective outcomes are important because user acceptance in the workplace depends not only on objective unloading, but also on whether workers feel that the device reduces effort without disrupting task completion [33,34].

The usability results also support the practical potential of the device. The SUS score of 74.2 indicates above-average usability, and participants gave relatively high ratings

for perceived injury-prevention potential and willingness to use the exoskeleton [35]. Although participants reported acceptable overall usability, the ratings for pressure/friction sensation and impact on task flexibility indicate that comfort and mobility restrictions remain important barriers to field adoption. Pressure or friction may occur at the shoulder straps, chest and waist fixation components, and arm-support interfaces, particularly during repeated arm elevation, asymmetric holding, or dynamic pulling. Restricted flexibility may also arise from the shoulder-support mechanism and harness structure when the task requires three-dimensional upper-limb movements. If such discomfort accumulates during prolonged work, workers may reduce their use of the device or refuse to wear it. This trade-off is important. For occupational exoskeletons, effective assistance alone is not sufficient; the device must also be wearable over time and compatible with real work movements [35]. In the present study, participants recognized the protective value of the exoskeleton, but their responses also suggest room for improvement in interface comfort and movement adaptability. Optimizing harness structure, contact pressure distribution, and fit to asymmetric upper-limb movements may further improve field acceptability.

These findings have direct implications for exoskeleton use in power grid maintenance. The present results suggest that passive upper-limb exoskeletons are most suitable for tasks involving sustained or repeated arm elevation, such as insulator installation, where the shoulder bears the main biomechanical load and the assistive mechanism is well aligned with the task demand. The device may also be beneficial in asymmetric support tasks such as insulated rod handling, although the magnitude of benefit may differ between sides depending on posture and force distribution. By contrast, in dynamic pulling tasks such as hand-chain hoist operation, the benefit appears to be limited to specific phases of movement. Therefore, exoskeleton implementation in this occupational setting should be task-oriented rather than generalized. Matching device characteristics to the dominant biomechanical features of a given task is likely to be critical for achieving meaningful ergonomic benefit [36].

Several limitations should be acknowledged. First, the study included only healthy young male volunteers rather than actual power grid maintenance workers. Although this design improved experimental safety and reduced inter-individual variability, it limits the ecological validity and generalizability of the findings. Actual power grid workers may be older, more experienced, exposed to long-term occupational fatigue, and may have pre-existing musculoskeletal symptoms. Their movement strategies, tolerance to external devices, perceived workload, and acceptance of exoskeleton use may therefore differ from those of the present participants. Second, the experiment was conducted in a controlled laboratory setting using simulated representative tasks. This allowed tighter experimental control, but could not fully reproduce the environmental complexity and behavioral variability of actual field operations. Third, the present study focused on short-term responses. It therefore remains unclear whether the observed reductions in muscle activity and discomfort would translate into lower cumulative fatigue or reduced risk of musculoskeletal disorders during long-term use. Finally, kinematic outcomes were not analyzed in the present study. Therefore, we cannot completely exclude the possibility that reduced EMG activity in the monitored muscles was accompanied by altered movement strategies or load redistribution. Although task posture and execution were standardized and supervised during the experiment, future studies should integrate motion capture or wearable inertial sensors with EMG to evaluate whether exoskeleton assistance changes joint motion, trunk posture, or compensatory strategies. Future studies also should examine longer-term use in real working environments, include more diverse worker populations, compare devices with different assistive profiles, integrate data-driven modelling to predict

individual responses to exoskeleton assistance, and apply more systematic multifactorial and optimisation-based analytical frameworks [37–40].

5. Conclusions

In conclusion, the passive upper-limb exoskeleton evaluated in this study reduced proximal upper-limb muscle activity, particularly in the upper trapezius, deltoid, and biceps brachii, and task-related discomfort in representative power grid maintenance tasks, particularly those involving sustained or repeated arm elevation. Its effects were clearly task-dependent, with the strongest benefit observed in static overhead work and more limited effects in dynamic pulling work. These findings support the potential value of passive exoskeletons in occupational ergonomics while also highlighting the importance of task-specific deployment and continued device optimization.

Author Contributions: Conceptualization: X.J. and L.H.; Methodology: X.J., Y.W., and L.H.; Software: X.J.; Validation: L.H.; Formal analysis: X.J.; Resources: L.H.; Writing: X.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Power Science Research Institute of Guangdong Power Grid Co., Ltd., China Southern Power Grid, grant number GDKJM20231512, and the funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Guangdong Province Institute for Occupational Disease Prevention and Control (protocol code GDHOD MEC 2025061, 4 December 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Thanks to Guangdong Province Institute for Occupational Disease Prevention and Control for the support.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WMSDs	Work-related musculoskeletal disorders
BMI	Body mass index
RMS	Root mean square
MVC	Maximum voluntary contraction
NASA-TLX	NASA Task Load Index
SUS	System Usability Scale

Appendix A

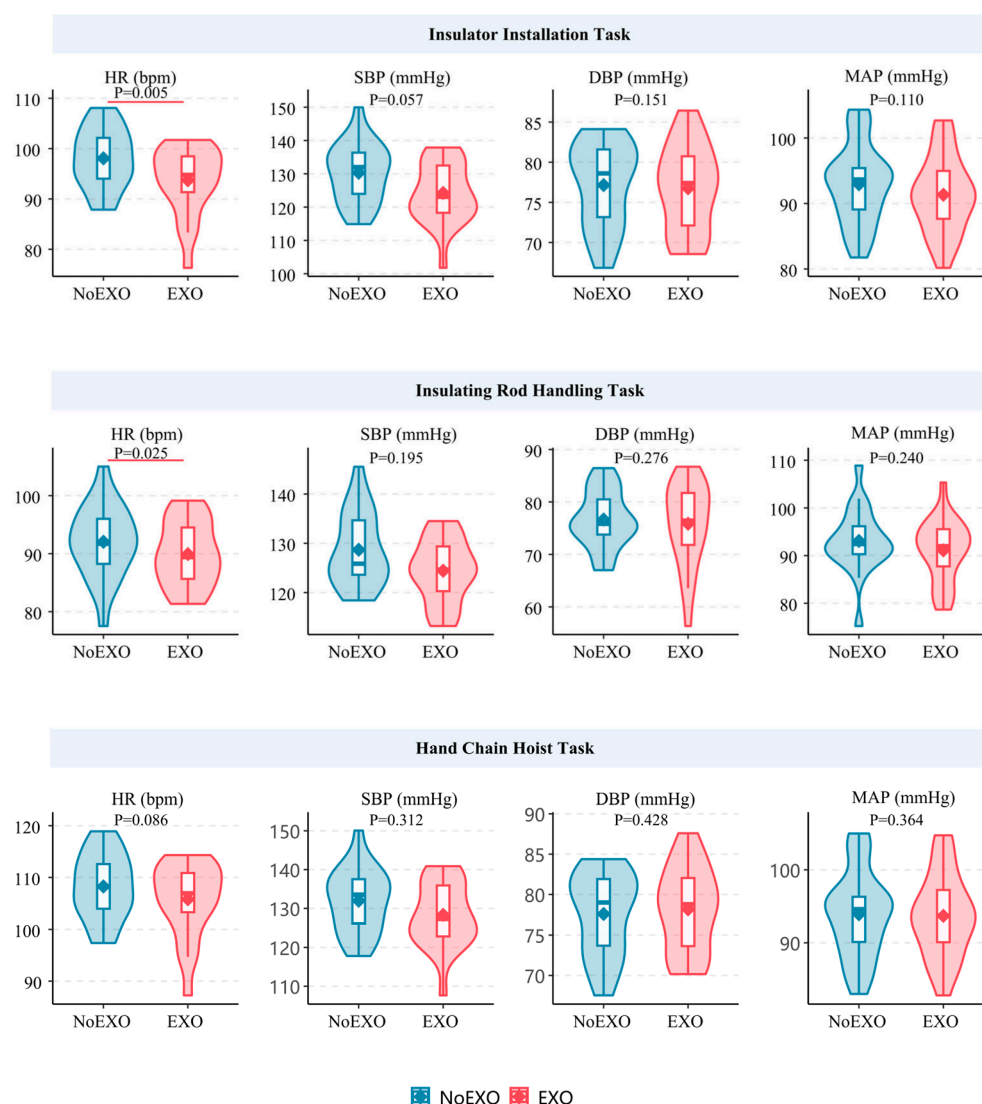


Figure A1. Cardiovascular responses during the three tasks under EXO and NoEXO conditions. HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure. The red underline in the figure indicates $p < 0.05$.

References

1. Lan, Y.; Zhan, X.; Wang, Z.; Jiang, D.; Li, X.; Peng, C. Global prevalence and associated risk factors of work-related musculoskeletal disorders among steelworkers: A systematic review and meta-analysis. *Front. Public Health* **2026**, *14*, 1718101. [[CrossRef](#)]
2. Sundstrup, E.; Seeberg, K.G.V.; Bengtsen, E.; Andersen, L.L. A Systematic Review of Workplace Interventions to Rehabilitate Musculoskeletal Disorders Among Employees with Physical Demanding Work. *J. Occup. Rehabil.* **2020**, *30*, 588–612. [[CrossRef](#)] [[PubMed](#)]
3. Gregg, C.; Visconti, V.V.; Albanese, M.; Gasperini, B.; Chiavoghilefu, A.; Prezioso, C.; Persechino, B.; Iavicoli, S.; Gasbarra, E.; Iundusi, R.; et al. Work-Related Musculoskeletal Disorders: A Systematic Review and Meta-Analysis. *J. Clin. Med.* **2024**, *13*, 3964. [[CrossRef](#)] [[PubMed](#)]
4. Keir, P.J.; Zuniga, A.F.; Mulla, D.M.; Somasundram, K.G. Relationships and Mechanisms Between Occupational Risk Factors and Distal Upper Extremity Disorders. *Hum. Factors* **2021**, *63*, 5–31. [[CrossRef](#)] [[PubMed](#)]
5. Padmanathan, V.; Joseph, L.; Omar, B.; Nawawi, A. Prevalence of musculoskeletal disorders and related occupational causative factors among electricity linemen: A narrative review. *Int. J. Occup. Med. Environ. Health* **2016**, *29*, 725–734. [[CrossRef](#)] [[PubMed](#)]
6. Seidler, A.; Starke, K.R.; Freiberg, A.; Hegewald, J.; Nienhaus, A.; Bolm-Audorff, U. Dose-Response Relationship between Physical Workload and Specific Shoulder Diseases-A Systematic Review with Meta-Analysis. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1243. [[CrossRef](#)] [[PubMed](#)]

7. Dickerson, C.R.; McDonald, A.C.; Chopp-Hurley, J.N. Between Two Rocks and in a Hard Place: Reflecting on the Biomechanical Basis of Shoulder Occupational Musculoskeletal Disorders. *Hum. Factors* **2023**, *65*, 879–890. [[CrossRef](#)] [[PubMed](#)]
8. de Looze, M.P.; Bosch, T.; Krause, F.; Stadler, K.S.; O’Sullivan, L.W. Exoskeletons for industrial application and their potential effects on physical work load. *Ergonomics* **2016**, *59*, 671–681. [[CrossRef](#)] [[PubMed](#)]
9. Baer, M.; Steinhilber, B.; Rieger, M.A.; Luger, T. The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton—A systematic review and meta-analysis. *Appl. Ergon.* **2021**, *94*, 103385. [[CrossRef](#)] [[PubMed](#)]
10. Preethichandra, D.M.G.; Piyathilaka, L.; Sul, J.-H.; Izhar, U.; Samarasinghe, R.; Arachchige, S.D.; de Silva, L.C. Passive and Active Exoskeleton Solutions: Sensors, Actuators, Applications, and Recent Trends. *Sensors* **2024**, *24*, 7095. [[CrossRef](#)] [[PubMed](#)]
11. Khan, M.; Antwi-Afari, M.F.; Seo, J.; Heung, K. Passive exoskeletons in construction: Working principles, challenges, and future research directions. *Ksce J. Civ. Eng.* **2026**, *30*, 100608. [[CrossRef](#)]
12. Lauret, L.; Raiteri, B.J.; Tecchio, P.; Hahn, D. A passive upper limb exoskeleton effectively reduces shoulder muscle activity over a large shoulder workspace. *Wearable Technol.* **2025**, *6*, 10025. [[CrossRef](#)] [[PubMed](#)]
13. Du, B.B.; Somasundram, K.G.; Johnston, A.; Bigelow, P.; Abdoli-Eramaki, M.; Jordan, K.H.; Yung, M.; Yazdani, A. Skilled Workers’ Perspectives on Utilizing a Passive Shoulder Exoskeleton in Construction. *Appl. Sci.-Basel* **2024**, *14*, 8971. [[CrossRef](#)]
14. Ocal, A.E.; Lekesiz, H.; Cetin, S.T. The Development of an Innovative Occupational Passive Upper Extremity Exoskeleton and an Investigation of Its Effects on Muscles. *Appl. Sci.* **2023**, *13*, 6763. [[CrossRef](#)]
15. Baldassarre, A.; Lulli, L.G.; Cavallo, F.; Fiorini, L.; Mariniello, A.; Mucci, N.; Arcangeli, G. Industrial exoskeletons from bench to field: Human-machine interface and user experience in occupational settings and tasks. *Front. Public Health* **2022**, *10*, 1039680. [[CrossRef](#)] [[PubMed](#)]
16. De Bock, S.; Ghillebert, J.; Govaerts, R.; Elprama, S.A.; Marusic, U.; Serrien, B.; Jacobs, A.; Geeroms, J.; Meeusen, R.; De Pauw, K. Passive Shoulder Exoskeletons: More Effective in the Lab Than in the Field? *IEEE Trans. Neural. Syst. Rehabil. Eng.* **2021**, *29*, 173–183. [[CrossRef](#)] [[PubMed](#)]
17. De Bock, S.; Ampe, T.; Rossini, M.; Tassignon, B.; Lefebber, D.; Rodriguez-Guerrero, C.; Roelands, B.; Geeroms, J.; Meeusen, R.; De Pauw, K. Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work. *Appl. Ergon.* **2023**, *106*, 103903. [[CrossRef](#)] [[PubMed](#)]
18. Luger, T.; Baer, M.; Seibt, R.; Rimmele, P.; Rieger, M.A.; Steinhilber, B. A passive back exoskeleton supporting symmetric and asymmetric lifting in stoop and squat posture reduces trunk and hip extensor muscle activity and adjusts body posture—A laboratory study. *Appl. Ergon.* **2021**, *97*, 103530. [[CrossRef](#)] [[PubMed](#)]
19. Chen, H.; Yao, J.; Li, M.; Hu, H.; Yang, Z.; Tu, S.; Liu, Y.; Wang, Z.; Guo, Z. Design and Experimental Evaluation of a Shoulder Assistive Exoskeleton for Insulator Replacement. *Sensors* **2026**, *26*, 2313. [[CrossRef](#)] [[PubMed](#)]
20. Siedl, S.M.; Mara, M. Exoskeleton acceptance and its relationship to self-efficacy enhancement, perceived usefulness, and physical relief: A field study among logistics workers. *Wearable Technol.* **2021**, *2*, e10. [[CrossRef](#)] [[PubMed](#)]
21. Wu, S.; Wu, X.; Liu, J.; Xuan, W.; Zhang, W.; Pang, S.; Xu, H. An Application Review of Full-Process Testing Methods for the Assistive Efficiency of Exoskeleton Robots. *Processes* **2025**, *13*, 3476. [[CrossRef](#)]
22. De Bock, S.; Rossini, M.; Lefebber, D.; Rodriguez-Guerrero, C.; Geeroms, J.; Meeusen, R.; De Pauw, K. An Occupational Shoulder Exoskeleton Reduces Muscle Activity and Fatigue During Overhead Work. *IEEE Trans. Biomed. Eng.* **2022**, *69*, 3008–3020. [[CrossRef](#)] [[PubMed](#)]
23. Javernik, A.; Buchmeister, B.; Ojsteršek, R. The NASA-TLX approach to understand workers workload in humanrobot collaboration. *Int. J. Simul. Model.* **2023**, *22*, 574–585. [[CrossRef](#)]
24. van Leer, E.; van Mersbergen, M. Using the Borg CR10 Physical Exertion Scale to Measure Patient-perceived Vocal Effort Pre and Post Treatment. *J. Voice* **2017**, *31*, 389.e19–389.e25. [[CrossRef](#)] [[PubMed](#)]
25. Lewis, J.R. The System Usability Scale: Past, Present, and Future. *Int. J. Hum.-Comput. Interact.* **2018**, *34*, 577–590. [[CrossRef](#)]
26. Poliero, T.; Fanti, V.; Sposito, M.; Caldwell, D.G.; Di Natali, C. Active and Passive Back-Support Exoskeletons: A Comparison in Static and Dynamic Tasks. *IEEE Robot. Autom. Lett.* **2022**, *7*, 8463–8470. [[CrossRef](#)]
27. Lee, H.-H.; Yoon, K.-T.; Lim, H.-H.; Lee, W.-K.; Jung, J.-H.; Kim, S.-B.; Choi, Y.-M. A Novel Passive Shoulder Exoskeleton Using Link Chains and Magnetic Spring Joints. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2024**, *32*, 708–717. [[CrossRef](#)] [[PubMed](#)]
28. Kermavnar, T.; de Vries, A.W.; de Looze, M.P.; O’Sullivan, L.W. Effects of industrial back-support exoskeletons on body loading and user experience: An updated systematic review. *Ergonomics* **2021**, *64*, 685–711. [[CrossRef](#)] [[PubMed](#)]
29. Wang, Y.; Loh, P.Y.; Muraki, S. Motor control characteristics of upper limbs in response to assistive forces during bilateral tasks. *PLoS ONE* **2021**, *16*, e0245049. [[CrossRef](#)] [[PubMed](#)]
30. Reyes, F.A.; Shuo, D.; Yu, H. Shoulder-Support Exoskeletons for Overhead Work: Current State, Challenges and Future Directions. *IEEE Trans. Med. Robot. Bionics* **2023**, *5*, 516–527. [[CrossRef](#)]

31. Weston, E.B.; Alizadeh, M.; Hani, H.; Knapik, G.G.; Souchereau, R.A.; Marras, W.S. A physiological and biomechanical investigation of three passive upper-extremity exoskeletons during simulated overhead work. *Ergonomics* **2022**, *65*, 105–117. [[CrossRef](#)] [[PubMed](#)]
32. Meade, R.D.; Lauzon, M.; Poirier, M.P.; Flouris, A.D.; Kenny, G.P. An Evaluation of the Physiological Strain Experienced by Electrical Utility Workers in North America. *J. Occup. Environ. Hyg.* **2015**, *12*, 708–720. [[CrossRef](#)] [[PubMed](#)]
33. Botti, L.; Melloni, R. Occupational Exoskeletons: Understanding the Impact on Workers and Suggesting Guidelines for Practitioners and Future Research Needs. *Appl. Sci.* **2024**, *14*, 84. [[CrossRef](#)]
34. Elprama, S.A.; Vanderborght, B.; Jacobs, A. An industrial exoskeleton user acceptance framework based on a literature review of empirical studies. *Appl. Ergon.* **2022**, *100*, 103615. [[CrossRef](#)] [[PubMed](#)]
35. Cescon, M.; Peruzzini, M. Evaluating UX and Usability in Automotive Human-Machine Interfaces: A Systematic Review. *Appl. Sci.-Basel* **2026**, *16*, 3437. [[CrossRef](#)]
36. Coccia, A.; Capodaglio, E.M.; Amitrano, F.; Gabba, V.; Panigazzi, M.; Pagano, G.; D’Addio, G. Biomechanical Effects of Using a Passive Exoskeleton for the Upper Limb in Industrial Manufacturing Activities: A Pilot Study. *Sensors* **2024**, *24*, 1445. [[CrossRef](#)] [[PubMed](#)]
37. Peter, E.K.; Cerny, J. A Hybrid Hamiltonian for the Accelerated Sampling along Experimental Restraints. *Int. J. Mol. Sci.* **2019**, *20*, 370. [[CrossRef](#)] [[PubMed](#)]
38. Lagana, F.; Prattico, D.; Quattrone, M.F.; Pullano, S.A.; Calcagno, S. Hybrid AI-Taguchi-ANOVA Approach for Thermographic Monitoring of Electronic Devices. *Eng* **2026**, *7*, 28. [[CrossRef](#)]
39. Lagana, F.; Prattico, D.; Angiulli, G.; Oliva, G.; Pullano, S.A.; Versaci, M.; La Foresta, F. Development of an Integrated System of sEMG Signal Acquisition, Processing, and Analysis with AI Techniques. *Signals* **2024**, *5*, 476–493. [[CrossRef](#)]
40. Versaci, M.; Angiulli, G.; La Foresta, F.; Lagana, F.; Palumbo, A. Intuitionistic fuzzy divergence for evaluating the mechanical stress state of steel plates subject to bi-axial loads. *Integr. Comput.-Aided Eng.* **2024**, *31*, 363–379. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.