An Occupational Shoulder Exoskeleton Reduces Muscle Activity and Fatigue During Overhead Work

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***Abstract*—*Objective:* This paper assesses the effect of a passive shoulder exoskeleton prototype, Exo4Work, on muscle activity, muscle fatigue and subjective experience during simulated occupational overhead and non-overhead work. *Methods:* Twenty-two healthy males performed six simulated industrial tasks with and without Exo4Work exoskeleton in a randomized counterbalanced cross-over design. During these tasks electromyography, heart rate, metabolic cost, subjective parameters and performance parameters were acquired. The effect of the exoskeleton and the body side on these parameters was investigated. *Results:* Anterior deltoid activity and fatigue reduced up to 16% and 41%, respectively, during isometric overhead work, and minimized hindrance of the device during non-overhead tasks. Wearing the exoskeleton increased feelings of frustration and increased discomfort in the areas where the exoskeleton and the body interfaced. The assistive effect of the exoskeleton was less prominent during dynamic tasks. *Conclusion:* This exoskeleton may reduce muscle activity and delay development of muscle fatigue in an overhead working scenario. For dynamic applications, the exoskeleton's assistive profile, which mimics the gravitational torque of the arm, is potentially sub-optimal. *Significance:* This evaluation paper is the first to report reduced muscle fatigue and activity when working with an occupational shoulder exoskeleton providing one third of the gravitational torque of the arm during overhead work. These results stress the potential of occupational shoulder exoskeletons in overhead working situations and may direct towards longitudinal field experiments. Additionally, this experiment may stimulate future work to further investigate the effect of different assistive profiles.**

***Index Terms*—Device evaluation, electromyography, ergonomics, industrial work, wearable robotics.**

Manuscript received 26 November 2021; revised 27 January 2022 and 22 February 2022; accepted 3 March 2022. Date of publication 15 March 2022; date of current version 20 September 2022. This work was supported in part by Research Foundation - Flanders (FWO) under Grant S000118N SBO Exo4Work project, in part by Strategic Research Program Exercise and the Brain in Health and Disease: The Added Value of Human-Centered Robotics, Vrije Universiteit Brussel, Belgium, and in part by NVIDIA Corporation, by donating a Titan X GPU. *(Corresponding author: Kevin De Pauw.)*

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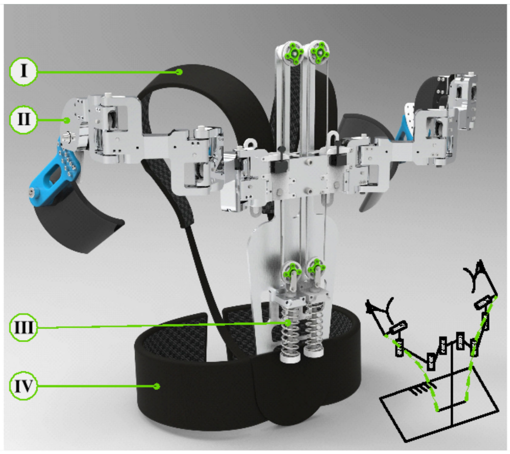
This article has supplementary downloadable material available at https://doi.org/10.1109/TBME.2022.3159094, provided by the authors.

Digital Object Identifier 10.1109/TBME.2022.3159094

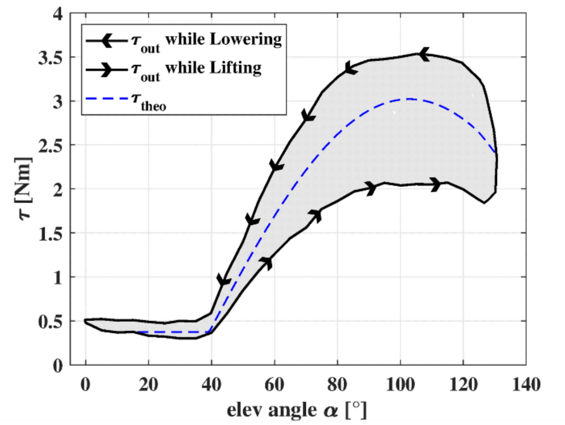
I. Introduction

RESEARCH efforts identified biomechanical, psychosocial and individual risk factors in order to decrease the prevalence of work-related musculoskeletal disorders (WMSDs) [1], [2]. Biomechanical risk factors included heavy object manipulation, repetitive work and non-ergonomic body postures [1]. The identified psychosocial risk factors were monotonous work and limited job control [2]. Older age, high BMI and sedentary lifestyle were classified as individual risk factors for developing WMSDs [2]. Despite increasing attention for these risk factors, repetitive movements are still reported in 61% of the European working population [3]. Fifty-one percent of the workers within this population suffered from shoulder disorders in the past year [4]. A more specific risk factor for these upper extremity WMSDs is overhead work, which places complex and concurrent stresses on tissues of the upper extremities [5]. Exercise programs have shown limited effects on the prevention of WMSDs, and preventive ergonomic interventions struggle to meet the flexibility and agility requirements of the occupational environment [6]. Therefore, the industry has high interest in exoskeletons as a mean to decrease the risk of developing WMSDs [7]–[9].

While most powered exoskeletons are still constrained to laboratory environments, passive exoskeletons are already being used in industry, as they are cheaper and provide a compromise between effectiveness and wearability [11]. Laboratory-based passive shoulder exoskeleton assessments showed promising effects [12], but up to now, implementation of this technology in working environments is still low [13]–[15]. Limitations in wearability and functional performance [16]–[18], and the quest for the optimal exoskeleton assistance [19], [20] are still open challenges.



(a)



(b)

Fig. 1. (a) Passive shoulder exoskeleton with its kinematic representation. The green dashed lines represent the cable driven remote actuation system: I) shoulder harnesses; II) shoulder joint of the exoskeleton; III) compression springs for energy storage; IV) hip belt; (b) Delivered assistance during lifting/lowering the arms. Figures adapted from [10].

Several shoulder exoskeleton assessment studies have been published. Most of them focused only on overhead work [19], [21]–[28]. These studies show that, in general, shoulder exoskeletons substantially decrease muscle activity around the shoulder joint during overhead work [12], [29]. Relative muscle activity reductions between 5 and 73% were reported for shoulder anteflexion and abductor muscles [12], [19], [22]–[26], [29] and upper trapezius activity reduced up to 32% [19], [24], [25], [30]. Besides changes in muscle activity, anterior deltoid muscle fatigue reduced and reductions up to 19 and 33% were reported for heart rate and oxygen uptake, respectively, during continuous overhead work [31]–[33].

Physiological evaluations are one important aspect of exoskeleton assessment [13], [15]. It was shown that effort expectancy affects exoskeleton acceptance [34], suggesting that the worker's preferred tool is likely to be the tool that is easy to use, optimizing the worker's well-being and overall performance without compromising its natural kinematics or comfort [35], [36], while it also reduces the physical workload. This is a delicate balance, as higher torques result in higher forces applied on the body, and higher pressures at the level of the human-robot interfaces, which were associated with discomfort [37], [38].

Although the reported positive effects on physiological parameters support exoskeleton implementation in the field, discrepancy between the effectiveness of exoskeletons in the field and a laboratory environment was recently reported [39]. This emphasizes the importance of simulating characteristics of occupational tasks during the evaluation of exoskeleton prototypes in the lab when the device's technology readiness level is too low for assessments in the field [15], [40].

In our previous work [10], [41], the design and validation of a passive and cable-driven occupational shoulder exoskeleton, Exo4Work, was presented. The kinematic structure of Exo4Work was proven to be compatible with the motion of the human arm [41]. Moreover, the potential beneficial effect of a low assistance provided to the exoskeleton user was preliminarily investigated [10]. A low assistance may potentially avoid the increased muscle activity observed in muscles working against the assistance of the exoskeleton (e.g. triceps brachii) [19], [26], [29].

The current study aims to assess the impact of the Exo4Work exoskeleton on muscle activity, muscle fatigue and the subjective experience during simulated occupational overhead tasks. A priori, the assistance of the Exo4Work exoskeleton was set at 3 Nm, with the aim of relieving load on the shoulder, without limiting movements (Section II-A). Therefore, the assistive effect of the exoskeleton was expected to be smaller compared to other exoskeleton evaluations where higher levels of assistance were provided [19], [20]. It was hypothesized this moderate amount of assistance may also result in an attenuated development of muscle fatigue. The evaluation protocol also included common occupational tasks beyond the functionality of the device. Here, it was hypothesized that the exoskeleton's design and support characteristics would limit hindrance in terms of increased metabolic cost or task performance (Section II-A).

II. Methods

A. Exo4Work: A Passive & Cable-Driven Shoulder Exoskeleton

Fig. 1(a) shows the passive cable-driven shoulder exoskeleton, Exo4Work, evaluated in this experiment [10]. The device weighs 3.8 kg and has 6 degrees of freedom incorporated, as illustrated in Fig. 1(a), in order to achieve full kinematic compatibility with the user's shoulder joint [41]. The Exo4Work is connected to the user through an interface composed of two shoulder harnesses (I) and a hip belt (IV). A passive Remote Actuation System (pRAS) equipped with compression springs (Fig. 1(a) III) allows the exoskeleton to store energy and release it in the form of an assistive torque at the level of the shoulder joint (Fig. 1(a) II) [42]. When the user lifts the arm the torque profile delivered by the pRAS peaks at about 100^o (Fig. 1(b)). On the other hand, a low-assistance zone between 0 and 35° is generated by the pRAS to prevent the exoskeleton from delivering unwanted assistance while walking or working at lower heights. Rossini *et al.* [10] a priori determined that the arm's gravitational torque around the shoulder approximates 9 Nm, using the 50^{th} percentile of the anthropometric data of a male [43]–[45], and the 95^{th} percentile of the shoulder and elbow kinematics of overhead work [46]. The assistance of the shoulder exoskeleton was set to provide up to one third of the arm's gravitational torque (i.e. 3 Nm), since this level of support was suggested to represent the balance between effectively reducing muscle activity, and hindering the wearer whilst lowering the arms [47], [48]. However, Rossini *et al.* [10] experimentally found out that the pRAS suffers from mechanical hysteresis. This results in a higher assistance delivered by the exoskeleton for arm movements involving shoulder extension or adduction compared to shoulder flexion or abduction (Fig. 1(b)). When wearing the Exo4Work, the user may experience a higher resistance when returning from a high elevation angle to a more neutral position.

The exoskeleton, which is worn like a backpack, was fitted to each participant at the start of the experiment. The shoulder harness was kept loose while donning the device to ensure weight transfer towards the hips. Then, the arm cuffs were tightened to ensure torque transmittance to the subject during movement. Donning and fitting the device was accomplished with the assistance of one or two researchers and took approximately one minute.

B. Participants

Twenty-two healthy males (age: 23.7 y ± 0.5, mass: 75.9 kg ± 1.8, height: 181.6 cm ± 1.4) without current musculoskeletal disorders were recruited. Every participant gave informed consent and completed the physical activity readiness questionnaire (Par-Q) [49] prior to demographic and anthropometric measurements. To determine the individual's *overhead working height*, the height of the participant's highest fingertip was measured with shoulder and elbow in a 90° flexion angle (190.0 ± 1.5 cm). The *low working height* was set at the individual's trochanter major height (94.2 ± 1.1 cm). The experimental protocol received approval from the local ethical commission (Vrije Universiteit Brussel and Universitair Ziekenhuis Brussel, BUN: 143201941463, November 20 2019).

C. Procedure

A randomized counterbalanced crossover design was implemented to evaluate the exoskeleton. All participants completed the protocol twice; once with and once without exoskeleton. In between tasks, 5 minutes of rest was provided and participants rested for 10 minutes between 2 experimental conditions. Dependent variables were surface electromyography (EMG) derived muscle activity parameters, heart rate, metabolic cost, performance parameters and subjective measures.

Upon entering the laboratory, participants were given a verbal explanation of the testing procedure. After reading and signing the informed consent, the Par-Q was filled out and demographic and anthropometric characteristics were obtained. The height of two workbenches were individually adjusted depending on the *overhead* and *low working height*. Skin

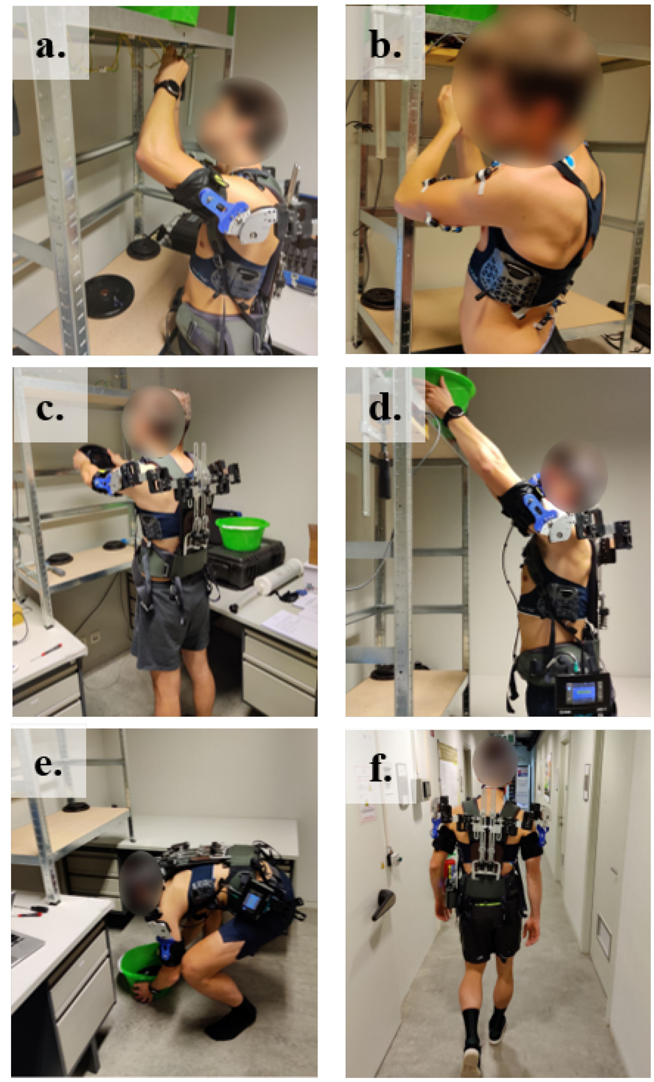


Fig. 2. (a) Wiring task, (b) drilling task, (c) lifting task, (d) repeated overhead lifting task, (e) repeated low lifting task, (f) 6 minute walking task.

preparations and EMG electrode application (Bluesensor P, Ambu, Denmark) were performed with respect to the SENIAM guidelines [50]. The EMG signal of 7 muscles was bilaterally captured: anterior deltoid (AD), biceps brachii (BB), triceps brachii's long head (TB), upper trapezius (UT), erector spinae longissimus (ES), pectoralis major (PM) and latissimus dorsi (LD). To set reference EMG values, the average of peak values of the highest two out of three maximal voluntary isometric contractions (MVC) were selected. The duration per contraction was five seconds, interspersed by 1 minute of rest.

The protocol contained six tasks per condition, of which four were included because of their overhead working posture or lifting movement (wiring, drilling, lifting, repeated high lifting) (Fig. 2(a), (b), (c), and (d)). The two remaining tasks were included because these tasks are common movements in the occupational environment (repeated low lifting and walking) (Fig. 2(e) and (f)).

During the 90-seconds wiring task, participants were instructed to connect as many wires as possible in screw terminals using a screwdriver (mass: 15 g) at *overhead height* (Fig. 2(a)). This task mimics relevant overhead work commonly found in the automotive industry.

The second task comprised a drilling task (mass: 150 g) where participants were instructed to press 60 N for 30 seconds against a force sensor mounted on the shelf at *overhead height*. This scenario relates to overhead work with heavy tools, such as the aircraft manufacturing industry [24]. Data collection started when 30 N was exceeded and the performance was evaluated as the deviation from 60 N. The participants used visual feedback provided on a computer monitor (22 inches) on which the temporal evolution of the measured force was displayed (visual range: 0-100 N) (Fig. 2(b)).

A lifting task was embedded in the protocol to assess the effect of the exoskeleton's support during a dynamic task. This task started from a neutral standing position while holding a free weight of 5 kg relaxed in front of the body. The weight was lifted until it touched the shelf at overhead height, after which the participant returned to the starting position (Fig. 2(a)). This movement was repeated five times at a self-selected, but calm pace. The arms were comfortably extended, i.e. no forced elbow extension. At the start of the repeated overhead lifting task, a 10-kg box was positioned at the lower work height. Participants were instructed to grasp the box, lift and place it on the shelf at overhead height (Fig. 2(d)). Subsequently, the box was lowered back to the lower shelf. This cycle was repeated for six minutes taking into account a standardized working speed of 6 BPM indicated by a metronome, which represents three lifting and lowering movements per minute [51]. Participants were instructed to move the box in the sagittal plane, so both limbs were equally loaded and aberrant movements were avoided.

To evaluate the effect of the exoskeleton and its the remote actuation system and the low assistive zone on physiological parameters during common industrial non-overhead activities, a repeated low lifting task was performed. In this task, a procedure similar to the repeated overhead lifting task was executed, but instead of overhead lifting, the box was moved between low working height and ground level (Fig. 2(e)).

Additionally, a 6 minute walking task was included (Fig. 2(f)), where participants were instructed to walk at their preferred walking speed, back and forth in a hallway over a length of 17 m.

Three-dimensional accelerometers were attached to the weights and their signals were synchronously recorded with muscle activity (2000 Hz, Miniwave, Cometa, Italy). Heart rate (Equivital, National Instruments, Cambridge, United Kingdom) and respiratory data were gathered (K5, Cosmed, Rome, Italy) for repeated lifting and walking tasks. After each task a Borg scale was used to determine the participant's RPE [52]. When all tasks within one condition were completed, participants filled out the body-part discomfort scale [53] and the NASA-TLX questionnaire, evaluating workload. After the exoskeleton was worn, the System Usability Scale (SUS) was filled out [54].

D. Data Analysis

1) Accelerometry: The three-axis acceleration of the weights was computed as the vector sum of the low pass filtered (4^{th} order Butterworth, 40 Hz) 3-D acceleration components and corrected for gravitation. To determine the start and end of each lifting repetition a threshold of 0.03 g was used, with minimally 2 seconds of rest in between repetitions.

2) Electromyography: Raw EMG signals were band-pass filtered (4^{th} order Butterworth, 10-500 Hz). To compute muscle activity features, these signals were full-wave rectified, smoothed (4^{th} order low-pass Butterworth, 6 Hz) and normalized to MVC. To process the EMG signals of the quasi-static tasks (wiring and drilling task), the first and last 2 seconds of the tasks were excluded from further analysis to avoid artificially induced variance caused by initial positioning or premature ending of the task. The average signal amplitude and the activity of non-overlapping 1-second epochs were calculated. Additionally, a Fast Fourier Transform (FFT) converted non-overlapping 1-second epochs of the bandpass filtered signal into the frequency domain. Subsequently, the mean power frequency (MPF) was determined from the FFT for each epoch [55]–[57]. The average muscle activity and muscle effort (activity integrated over time) [58] of lifting tasks were determined between the acceleration-based start and end markers. For continuous analysis, muscle activities of each lifting repetition were linearly interpolated to time series containing 1000 data points.

3) Energy Expenditure and Cardiovascular Load.: The oxygen consumption (VO_2) and carbon dioxide output (VCO_2) of the last minute of data collection during the 6-min walking task, and the low and high repeated lifting tasks indicated energy expenditure. To compute the metabolic cost, the caloric equivalent was determined through the respiratory exchange ratio [59]. This equivalent was multiplied with the VO_2 and converted to Watts per kg. The rest metabolic cost was subtracted from working metabolic cost to isolate the net metabolic cost of these tasks.

E. Statistical Analysis

Custom-made Python scripts (Anaconda Inc., Austin, TX, United States) were used for statistical data analysis. Values are displayed as mean values with standard errors. Shapiro-Wilk tests and Q-Q plots were interpreted to check normality. When a normal distribution could not be assumed, parameters were analyzed with non-parametric inference tests. The effect of the exoskeleton and the body-side on muscle activity was analyzed through two-way within-subjects ANOVA tests. Muscle activity during the repeated overhead lifting task was analyzed through three-way within subject ANOVA tests with repetitions as additional factor. Muscle fatigue during the wiring and drilling tasks was analyzed when the average muscle activity exceeded 10%MVC. Linear regressions were fit through the 1-second epochs of muscle activity and MPF of the static tasks. Subsequently, the MPF and the muscle activity time series were normalized to the y-intercept of the corresponding linear regression fit on these data [57]. The slope of the linear regression

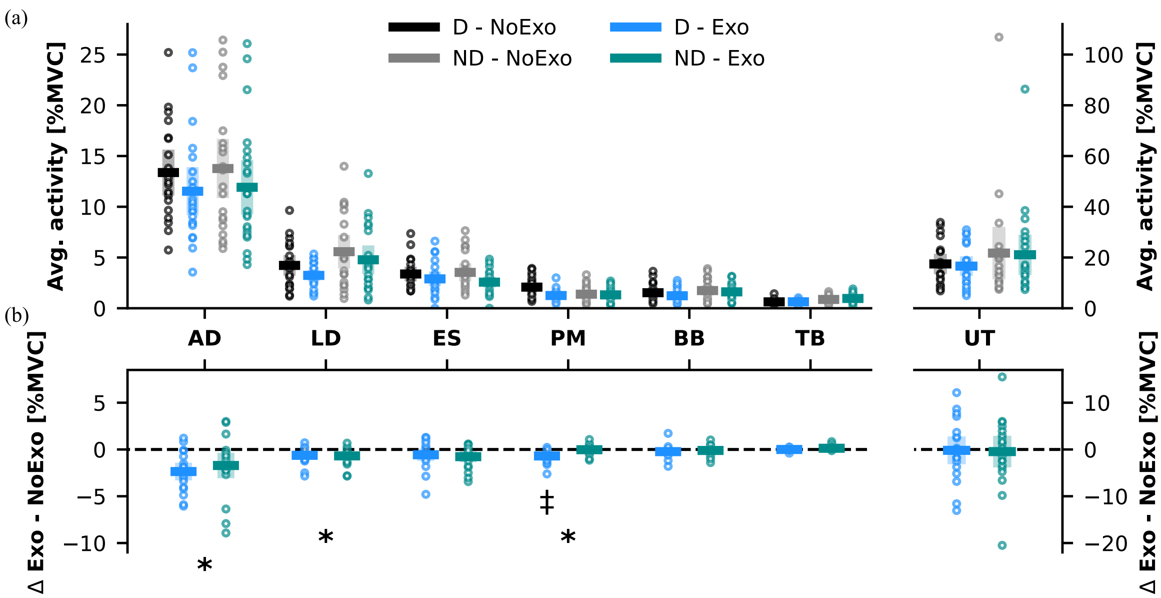


Fig. 3. (a) The average muscle activity observed during the overhead wiring task with and without exoskeleton. (b) The differences in average muscle activity between wiring with and without exoskeleton, where negative values indicate that the exoskeleton reduced muscle activity. DA = anterior deltoid, LD = latissimus dorsi, ES = lumbar erector spinae longissimus, PM = pectoralis major, BB = biceps brachii, TB = long head of the triceps brachii, UT = upper trapezius, D = dominant side, ND = non-dominant side. Dots represent individual observations. The mean is indicated as a horizontal line. 95%CI are displayed as colored areas. * indicates a significant main effect of condition, ‡ indicates significant interaction effect of side and condition.

on these normalized data was used to analyze muscle fatigue through two-way within-subjects ANOVA tests.

Average muscle activity and muscle effort during the lifting task were modeled with linear mixed effects models in which subject-specific random intercepts. Continuous muscle activity time series were analyzed with 1-dimensional Statistical Parametric Mapping (SPM), implemented in the Python open-source package [60], [61], which allowed non-directed hypothesis testing and avoided reducing the data set to a zero-dimensional subset sensitive to selection bias [62], [63]. Two-way within-subject ANOVA tests evaluated the effect of exoskeleton and body side on muscle activation levels throughout the lifting motion with subject-specific random intercepts. Metabolic cost, RPE, heart rate and task performance with and without exoskeleton were compared with a paired-sample T-test. Significance level in this study was set at 0.05. The standardized mean difference (Cohen's d) was calculated to quantify the size of difference between both conditions. Large (>0.8), medium (>0.5) and small effect sizes (>0.2) were distinguished.

III. Results

A. Overhead Wiring Task

The exoskeleton did not significantly influence the RPE and the amount of wires connected during the wiring period (Appendix Table I). The exoskeleton reduced AD activity by 2.1%MVC (95%CI: [−3.0, −1.3], d = 0.40) and LD activity by 0.6%MVC (95%CI: [−0.9, −0.3], d=0.28). PM activity in the dominant side was reduced by 0.7%MVC ($p < 0.001$, 95%CI: [−1.0, −0.4], d=0.93) when wearing the exoskeleton, while the non-dominant PM activity was not significantly affected. Post hoc tests focusing on the interaction effect on TB activity did not reach statistical significance. An overview of the ANOVA is available in appendix (Table II), and the muscle activity levels observed during the wiring task were illustrated in Fig. 3.

On the dominant side, the AD MPF decayed by 0.095 ± 0.019 %/s with the exoskeleton, while the AD MPF decayed 1.7 times faster without exoskeleton at a rate of 0.160 ± 0.014 %/s (p = 0.007, 95%CI: [0.020, 0.111], d = 0.86). On the non-dominant side, this effect was not observed, although all these MPF slopes were also negative (Fig. 5). An overview of the linear regressions on AD and UT activity and MPF time-series is available in appendix (Table III).

B. Overhead Drilling Task

Precision of the drilling force and RPE were not significantly different between overhead drilling with and without exoskeleton (Appendix Table I). The exoskeleton reduced AD activity by 2.8%MVC (95%CI: [−5.2, −0.5], d=0.25) and increased TB activity by 0.2%MVC (95%CI: [0.1, 0.4], d=0.31) compared to overhead drilling without exoskeleton. On the dominant side, TB activity was 0.3%MVC (95%CI: [−0.6, −0.1], d=0.48) higher compared to the activity on the non-dominant side. Details of the ANOVA tests on muscle activities are available in appendix (Table II), and muscle activity levels during the drilling task were visualized in Fig. 4.

Analysis of the MPF slopes showed that all AD MPF signals decayed over time, but a main effect of condition (p = 0.018)

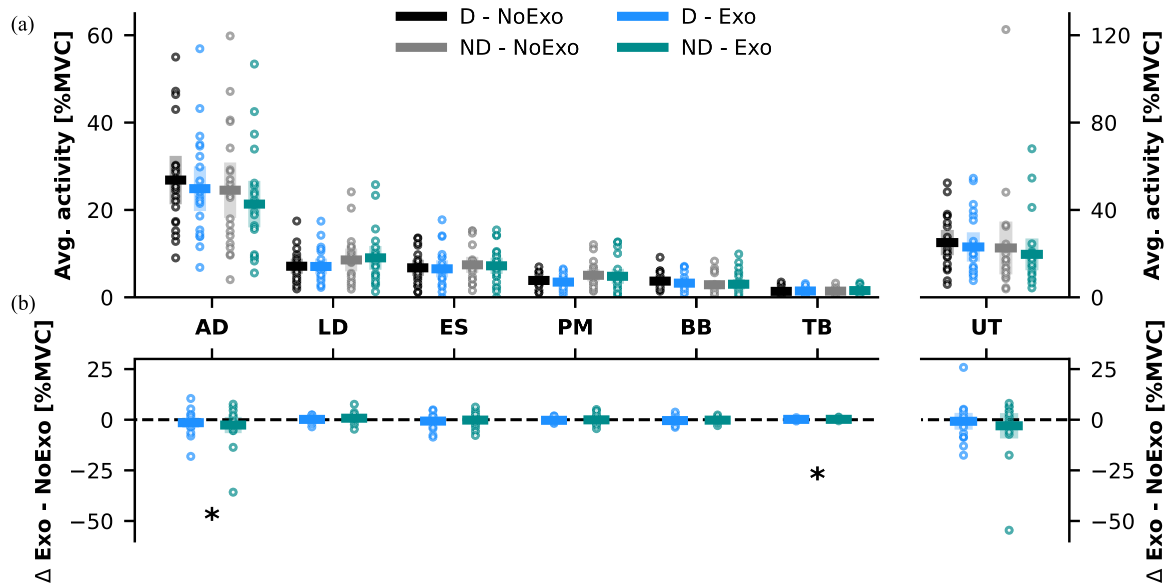


Fig. 4. (a) The average muscle activity observed during the overhead drilling task with and without exoskeleton. Participants exerted a force of 60 N against a load cell overhead. (b) The differences in average muscle activity between drilling with and without exoskeleton, where negative values indicate that the exoskeleton reduced muscle activity. AD = anterior deltoid, LD = latissimus dorsi, ES = lumbar erector spinae longissimus, PM = pectoralis major, BB = biceps brachii, TB = long head of the triceps brachii, UT = upper trapezius, D = dominant side, ND = non-dominant side. Dots represent individual observations. The mean is indicated as a horizontal line. 95%CI are displayed as colored areas. * indicates a significant main effect of condition.

indicated a 1.2 times faster decay without exoskeleton with 0.497 ± 0.031 %/s, compared to a decay of 0.427 ± 0.021 %/s with exoskeleton ($p = 0.026$, 95%CI: [−0.103, −0.007], $d = 0.37$) (Fig. 5). An overview of the linear regressions on AD and UT activity and MPF time-series is available in appendix (Table V).

C. Lifting Task

On average, one repetition of the lifting task was executed 0.5 seconds slower with exoskeleton compared to the lifting movements without exoskeleton ($p < 0.001$, 95%CI: [−0.6, −0.3], $d = 0.64$), while the exoskeleton did not significantly influence the RPE (Appendix Table I). Compared to NoExo, the exoskeleton's assistance significantly reduced AD activity between 16.8 and 21.7% of the execution ($p < 0.001$). This reduction reached up to −6.9%MVC (95%CI: [−9.2, −3.5]). Similarly, PM activity with the exoskeleton was significantly lower between 12.9 and 14.9% of the execution cycle ($p = 0.002$). The reduction reached up to −0.8%MVC (95%CI: [−1.1, −0.4]). Furthermore, the exoskeleton reduced the BB activity at several moments between 15 and 57% of the execution cycle, with a maximal reduction of −1.9 %MVC ($p = 0.002$, 95%CI: [−2.8, −1.0]). The other muscle activities were not significantly affected by the exoskeleton's assistance. All muscle activity time-series were visualized in Fig. 6.

Compared to lifting without exoskeleton, the prototype reduced the average AD activity by 1.3%MVC ($p = 0.031$) and the peak DA activity by 4.2%MVC ($p = 0.043$), while the integrated DA activity was not significantly affected. The average BB activity was reduced by 0.9%MVC ($p = 0.001$), the peak BB activity was reduced by 2.8%MVC ($p = 0.001$), and the integrated DA activity was 1.6 %MVC*s lower when lifting with the exoskeleton ($p = 0.041$). Peak PM activity reduced by 0.7%MVC ($p = 0.024$). Integrated ESL and TB significantly increased by 5.5%MVC*s ($p = 0.024$) and 0.9%MVC*s ($p = 0.006$), respectively. Regardless of the exoskeleton condition, significantly higher average, peak and integrated TB and LD activities were observed on the non-dominant side compared to the dominant side ($p < 0.030$). A detailed overview of the two-way within-subjects ANOVA tests on average, peak and integrated muscle activity during the lifting task is available in appendix (Tables VI and VII).

D. Repeated Overhead Lifting

No three-way or two-way interaction of movement direction, exoskeleton condition and time was observed in the lifting duration, but main effects revealed that the duration of lifting and lowering movements decreased over time ($p < 0.001$) and that lifting movements were executed significantly faster than lowering movements ($p = 0.034$). During this task, the exoskeleton did not significantly influence the RPE, heart rate or metabolic cost (Appendix Table I). On muscle activity, no three-way interactions or two-way interactions involving the exoskeleton condition were revealed. A main effect of time was observed during the lifting and the lowering movements, where integrated, average and peak AD activity of both movements reduced over time ($p < 0.001$). No significant main effect of the exoskeleton was observed in muscle activity during this repeated lifting task.

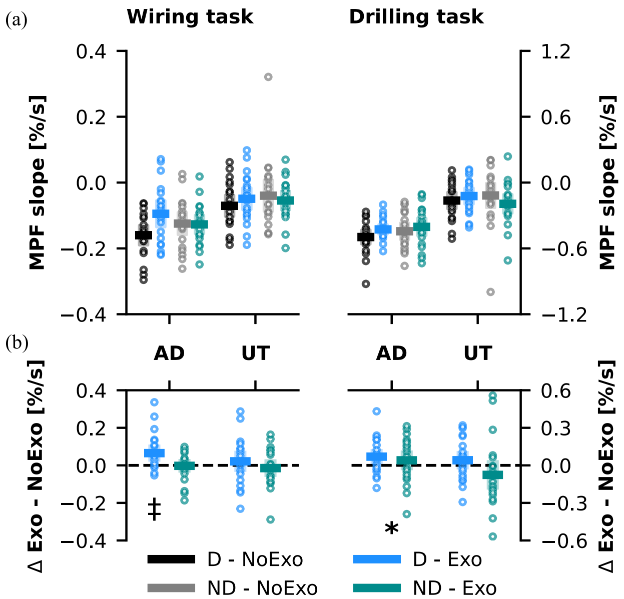


Fig. 5. (a) The slope of the linear regression of the mean power frequency time series during overhead wiring (left) and drilling (right) is displayed. (b) The differences in slope of the MPF time series is illustrated, negative values indicate that the MPF time series' slope was more negative with exoskeleton. AD = deltoideus anterior, UT = upper trapezius, D = dominant side, ND = non-dominant side. Dots represent individual observations. The mean is indicated as a horizontal line. 95%CI are displayed as colored areas. * indicates a significant main effect of condition, ‡ indicates significant interaction effect of side and condition.

E. Overall Impression and Common Work-Related Tasks

The participants scored the exoskeleton 72.3 ± 2.2 on the SUS. The workload of the protocol was not differently perceived between both conditions within the mental, physical, temporal, performance, and effort subscales of the NASA-TLX, but frustration, which was scored 2.5 ± 0.2 out of 20 without exoskeleton, increased by 1.2 ($p = 0.001$, 95%CI: [0.7, 1.7], d=) when wearing the device (Fig. 7(a)). The exoskeleton significantly increased the perception of discomfort at the shoulders, abdomen, frontal pelvis, and the chest compared to the condition without exoskeleton ($p \leq 0.041$, Fig. 7(b)), while discomfort in other regions was not significantly affected. During the 5 minute repeated lifting task between trochanter major height and ground-level, and during the six-minute walking test, the exoskeleton did not significantly affect the RPE, heart rate or metabolic cost (Appendix Table I).

IV. Discussion

The passive shoulder exoskeleton prototype evaluated in this study was designed to provide 3Nm assistance during overhead work, while avoiding hindrance for the user during common occupational non-overhead tasks. Physiological, subjective and task performance data were gathered to map the effect of the Exo4Work in a young, healthy male population. During isometric overhead work, the device reduced AD activity up to 16% and attenuated the MPF decay up to 41% compared to

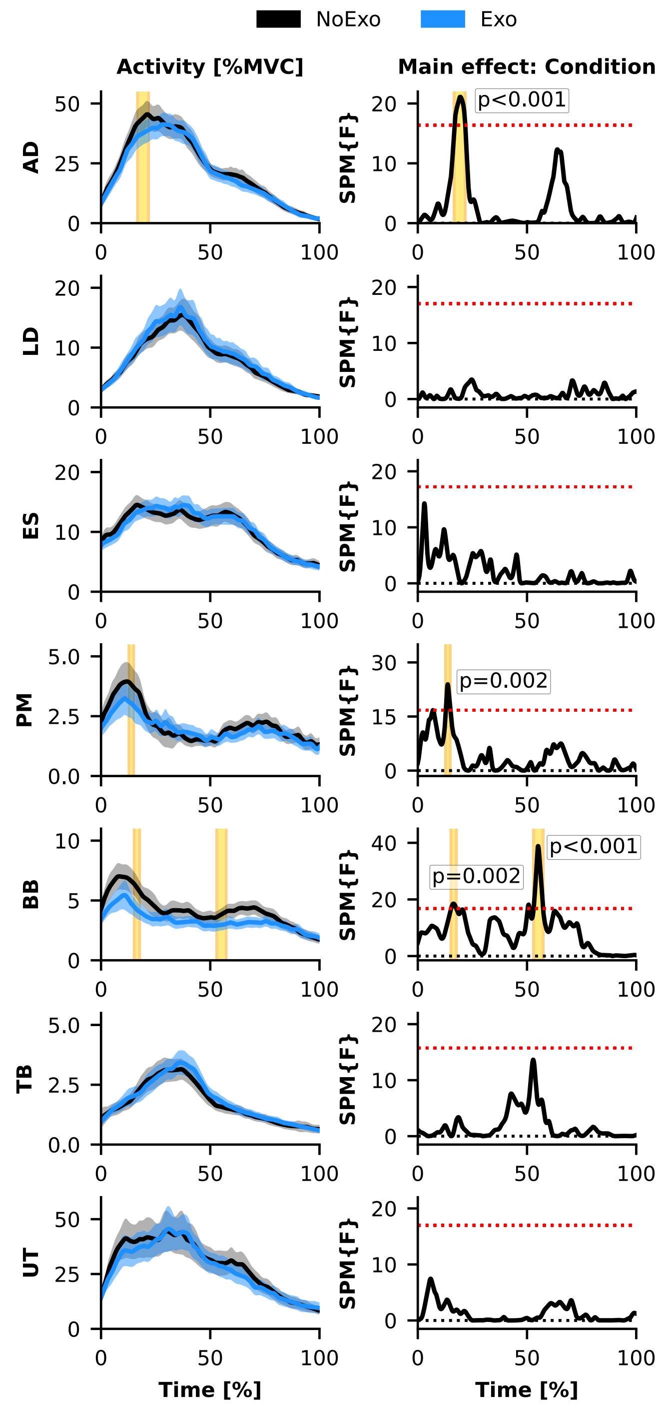


Fig. 6. Average muscle activity time series during the lifting task with and without exoskeleton are illustrated (left). The shaded clouds represent the standard error of the mean. The main effect of condition on the one-dimensional within-subject ANOVA on muscle activity is illustrated (right). The y-axis displays the one-dimensional F-statistic and the horizontal red dotted line illustrates the critical F-value given the analysis's degrees of freedom. The yellow areas indicate a significant effect of the exoskeleton. The horizontal axes display normalized cycle time. No significant interaction effects or main effects of side were observed in these within-subject ANOVA tests. AD = anterior deltoid, LD = latissimus dorsi, ES = lumbar erector spinae longissimus, PM = pectoralis major, BB = biceps brachii, TB = long head of the triceps brachii, UT = upper trapezius.

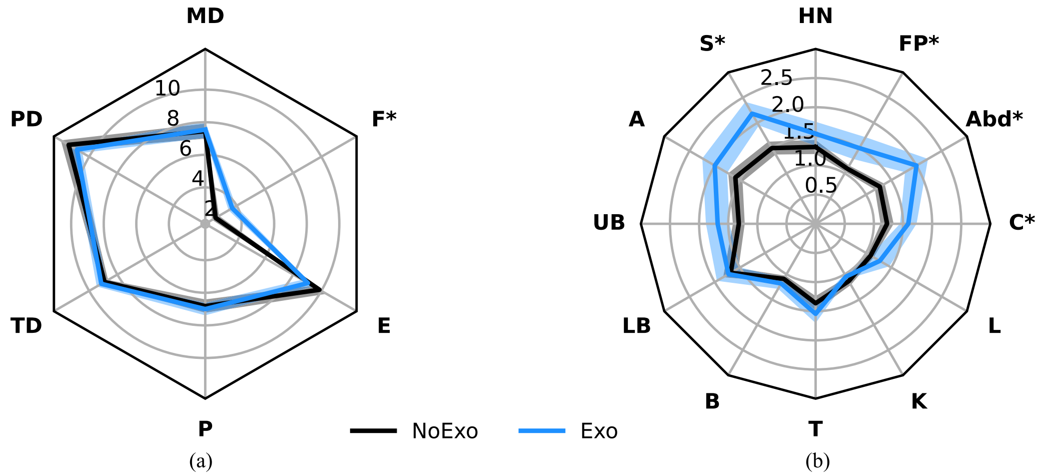


Fig. 7. (a) NASA TLX subscale scores and (b) local discomfort scores were presented with and without exoskeleton. MD = mental demand, PD = physical demand, TD = temporal demand, P = performance, E = effort and F = frustration, HN = head and neck, S = shoulders, A = arms, UB = upper back, LB = lower back, B = buttocks, t = thighs, K = knees, L = legs, C = chest, Abd = abdomen, FP = frontal pelvis. * indicates p-values below 0.05.

overhead work without exoskeleton. Dynamic overhead tasks yielded smaller, but still substantial AD activity reductions. The participants experienced increased feelings of frustration and indicated increased discomfort in the areas where the exoskeleton and the body interfaced. Despite this burden, the exoskeleton received a *system usability score* of 72, indicating *good* usability according to Bangor *et al.* [64]. Metabolic cost, heart rate and RPE were not affected by wearing the exoskeleton during the non-overhead working tasks and the walking distance was not altered when wearing the exoskeleton.

Although previous passive shoulder exoskeleton evaluations reported larger reductions in muscle activity [12], the magnitudes of the observed muscle activity reductions during overhead wiring and drilling were in line with the hypothesis. In contrast to exoskeletons with a higher level of assistance level, where an increase in antagonist activity up to 150% was shown [19], no increments of this magnitude were observed in the current evaluation assessment. Only during the drilling task, TB activity increased by 17%. Due to the low activity level, this relative increase seems substantial, but may be negligible in the context of workspace ergonomics. These findings confirm previously reported results from a pilot test with this prototype [10]. Additionally, the AD MPF decayed 1.7 times faster during the wiring task and 1.2 times faster in the drilling task when executing the tasks without exoskeleton, compared to the condition with exoskeleton. This indicates that, despite the limited amount of assistance, the exoskeleton also attenuated the development of AD fatigue, which is in accordance to Schmalz *et al.* [32].

Similar to previous research, the exoskeleton reduced the average AD activity when lifting 5 kg [19]. This study is the first to investigate effect of the Exo4Work exoskeleton throughout the lifting cycle and documented that the most prominent muscle activity reduction was observed in the zone where muscle activity peaked. The exoskeleton's hysteresis did not result in larger muscle activity reductions, or increased antagonist activity when returning from high shoulder elevation to the starting position. This may be related to the relative small level of support the exoskeleton provided, yet, the increased execution time may suggest that the user's experienced some additional resistance of the exoskeleton when returning to the initial pose. This hindrance may have contributed to the user's increased frustration level when wearing the exoskeleton. When lifting 10 kg freely, however, the exoskeleton did not significantly affect muscle activity and metabolic cost. The latter was reduced by another passive shoulder exoskeleton during continuous, isometric overhead work [31], [32]. In general, this shows that the assistive effect of the exoskeleton is less prominent in dynamic situations compared to isometric tasks, which can be related to the varying assistive needs of the user. The assistive requirements change with the gravitational torque of the arms, and are the highest when the arms are elevated. Most passive shoulder exoskeletons' assistive torque profiles, including the assistive profile of the currently evaluated exoskeleton, were designed ad-hoc. When lifting a 10-kg load freely, such as during the repeated lifting task, the user spends the majority of the energy in accelerating the load, as dictated by the natural coordination pattern which strives to minimize the movement's jerk [65]. As a result, the user might need the majority of the assistance to start the motion when executing dynamic tasks. In the case of the repeated lifting task, the lifting motion started from a neutral standing position where the exoskeleton's delivered assistance was very low, yet the need for support was high (Fig. 1). This may partially explain why the metabolic cost of lifting was not affected by the exoskeleton and endorses the limited support of the exoskeleton in a repeated lifting task from hip to overhead height.

Although the overhead tasks yielded clear reductions in muscle activity when working with the exoskeleton, the device did not significantly affect RPE, suggesting that the participants experienced little or no effect of the exoskeleton's support. The lack of changes in RPE may be related to the short duration of the tests and the discomfort caused by the presence of the exoskeleton. Additionally, differences in exoskeleton fit among participants may differently affect the exoskeletons efficiency and subjective experience [18].

In this study, no biomechanical data were acquired, which limits interpretation the observed outcomes. Furthermore, this study did not allow for an extensive familiarization period, which may explain the large variability in the outcomes [66], [67]. In this study the exoskeleton condition was compared to a condition without exoskeleton. A recent review suggested that a placebo effect, caused by the presence of the exoskeleton device, might be occurring [15]. Evaluating the exoskeleton in a transparent mode, while blinding the participants, may avoid this placebo effect in future work. Within this experiment, physiological parameters were affected by the exoskeleton's assistance, but no effect on task performance was observed. This may be related to the limited familiarization allowed in the study, but the task performance related observations may have been lacking sensitivity too. Future studies could focus on the performance related aspects of industrial work, and their interaction with effect of the exoskeleton on the wearer's physiological and biomechanical load, as they may influence productivity and safety [68].

Even though the design and assistance of the exoskeleton was adapted to fit the majority of the working population, participants indicated decreased comfort at places where the exoskeleton interfaced with the body. The comfort is influenced by a multitude of parameters, such as the assistive profile, the mass and mass distribution of the device, and the way the exoskeleton and the human body interface. The current experiment did not measure the strapping pressure of the exoskeleton, and thus by extension the tightness of the exoskeleton fit [18]. Recent evidence showed that this tightness affects the dissipated energy, the stiffness and the dampening characteristics of the exoskeleton, the perceived comfort at the level of the interface [18] and the exoskeleton's efficiency [69]. Therefore, future work should assess the exoskeleton fit.

The relieving effects of the Exo4Work exoskeleton on the user, even with this moderate level of assistance, while avoiding excessive hindrance, highlight the delicate balance in assistive needs. Additionally, the muscle activity analysis of dynamic work in this paper highlighted the discrepancy in assistive needs between static and dynamic tasks. These outcomes stimulate the ongoing search towards ideal exoskeleton assistance. In contrast to targeting a one size fits all, an individualized approach might potentially improve the exoskeleton's efficiency and experience. This was already proven successful in exoskeletons for locomotion [70]–[72]. Even though the efficacy and experience of such individualized exoskeleton might surpass one size fits all exoskeletons, the commercial attractiveness, incorporating the concomitant cost increase, still has to be confirmed.

V. Conclusion

We evaluated the effect of the Exo4Work exoskeleton, a passive shoulder exoskeleton prototype, on the user during overhead and non-overhead work. Despite the moderate assistance provided, the prototype reduced muscle activity and attenuated muscle fatigue development during overhead work. This effect was the most pronounced in isometric tasks, such as overhead wiring. Furthermore, the assistive profile of this passive exoskeleton was not optimal for dynamic tasks, such as lifting and lowering loads. No indications of excessive hindrance of the exoskeleton were observed during walking and lifting from the ground to hip level. This may suggest that such remote actuation system, which relocated the heavier parts of the exoskeleton closer to the center of mass, is a suited strategy in scenarios where weight reduction options are limited. Despite the promising physiological results presented in this study, the participants subjective experience was not altered by wearing the exoskeleton. Future work should investigate the gap between physiological results and these subjective outcomes, improving both the experience and the effectiveness of the exoskeleton's assistance, preferably during longitudinal experiments.

Appendix

TABLE I
RPE, Heart Rate, Metabolic Cost, Task Difficulty and Performance During Lifting, Wiring, Drilling, Walking, Repeated High Lifting or Repeated Low Lifting

RPE [6-20]					
Task		NoExo	Exo4W	p-value	Cohen's d
Wiring		8.8 ± 0.4	9.4 ± 0.5	0.288	0.26
Drilling		11.0 ± 0.6	11.5 ± 0.6	0.211	0.16
Lifting		8.4 ± 0.5	8.4 ± 0.5	0.923	0.02
Repeated high lifting		13.1 ± 0.4	12.6 ± 0.6	0.294	0.21
Repeated low lifting		12.4 ± 0.5	11.8 ± 0.5	0.064	0.27
Walking		8.6 ± 0.4	8.0 ± 0.4	0.120	0.32
Heart rate [bpm]					
Task		NoExo	Exo4W	p-value	Cohen's d
Repeated high lifting		99.2 ± 3.4	99.8 ± 3.7	0.748	0.03
Repeated low lifting		105.3 ± 3.7	104.2 ± 3.7	0.342	0.06
Walking		92.6 ± 3.0	92.9 ± 3.4	0.850	0.02
Metabolic cost [W/kg]					
Task		NoExo	Exo4W	p-value	Cohen's d
Walking		4.87 ± 0.17	5.15 ± 0.19	0.119	0.33
Repeated high lifting		4.45 ± 0.13	4.56 ± 0.16	0.336	0.15
Repeated low lifting		4.92 ± 0.20	5.16 ± 0.19	0.068	0.26
Performance					
Task	Parameter	NoExo	Exo4W	p-value	Cohen's d
Wiring	# Wires [pcs]	7.3 ± 0.5	7.3 ± 0.5	1.000	< 0.01
Drilling	MAE [N]	4.59 ± 0.26	5.00 ± 0.33	0.358	0.30
Lifting	Duration [sec]	3.4 ± 0.2	3.8 ± 0.2	< 0.001*	0.64
Walking	Speed [km/h]	4.7 ± 0.1	4.8 ± 0.1	0.520	0.06

MAE: Mean absolute error. * indicates $p < 0.05$.

TABLE II
F and P-Values of the Two-Way Within-Subjects Anovas on Average Muscle Activity During the Wire Task with Main Effects of Condition (NOEXO, EXO4W), Side (Dominant, Non-Dominant) and Their Interaction

	Condition		Side		Condition x Side	
	F	p	F	p	F	p
DA	17.73	0.001*	0.16	0.696	1.18	0.291
TD	0.00	0.984	0.23	0.639	0.92	0.351
PM	14.99	0.001*	4.76	0.042*	12.39	0.002*
BB	1.46	0.243	2.18	0.158	0.30	0.588
ESL	4.28	0.055	0.92	0.351	0.06	0.816
LD	14.63	0.001*	1.58	0.225	0.00	0.966
TB	3.70	0.072	11.64	0.003*	5.73	0.028*

DA: deltoideus anterior, TD: trapezius descendens, PM: pectoralis major, BB: biceps brachii, ESL: lumbar erector spinae longissimus, LD: latissumus dorsi, TB: triceps brachii. * indicates $p < 0.05$.

TABLE III
LINEAR REGRESSIONS WERE FITTED ON THE INDIVIDUAL TIME SERIES OF DA AND TD ACTIVITY AND MPF OF THE WIRE TASK. THE COEFFICIENTS OF DETERMINATION, THE RATIO OF SIGNIFICANTLY FITTING REGRESSIONS, Y-INTERCEPTS AND THE SLOPE (β) OF THE REGRESSION WERE DISPLAYED

DA			R^2	$p < 0.05$	y	β
Activity	Dominant	NoExo	0.06 ± 0.01	10/21	14.24 ± 1.88	0.014 ± 0.004
		Exo4W	0.09 ± 0.02	9/21	11.65 ± 1.09	-0.005 ± 0.008
	N-dominant	NoExo	0.12 ± 0.03	10/21	13.50 ± 1.36	0.001 ± 0.011
		Exo4W	0.14 ± 0.03	14/21	12.09 ± 1.40	-0.003 ± 0.007
MPF	Dominant	NoExo	0.50 ± 0.04	21/21	85.40 ± 2.26	-0.150 ± 0.014
		Exo4W	0.28 ± 0.05	18/21	84.68 ± 2.59	-0.083 ± 0.017
	N-dominant	NoExo	0.41 ± 0.05	19/21	85.85 ± 2.09	-0.110 ± 0.015
		Exo4W	0.40 ± 0.04	19/21	89.01 ± 1.90	-0.113 ± 0.012
TD			R^2	$p < 0.05$	y	β
Activity	Dominant	NoExo	0.22 ± 0.05	16/21	15.77 ± 1.57	0.028 ± 0.047
		Exo4W	0.21 ± 0.04	14/21	18.24 ± 2.63	0.019 ± 0.045
	N-dominant	NoExo	0.21 ± 0.05	15/21	24.13 ± 5.85	0.063 ± 0.047
		Exo4W	0.21 ± 0.04	16/21	26.46 ± 7.48	-0.018 ± 0.039
MPF	Dominant	NoExo	0.22 ± 0.05	15/21	80.72 ± 3.17	-0.062 ± 0.015
		Exo4W	0.21 ± 0.05	14/21	76.53 ± 1.80	-0.036 ± 0.012
	N-dominant	NoExo	0.24 ± 0.05	15/21	78.86 ± 2.43	-0.033 ± 0.019
		Exo4W	0.20 ± 0.04	15/21	75.69 ± 1.84	-0.040 ± 0.010

DA: deltoideus anterior, TD: trapezius descendens. * indicates $p \leq 0.05$.

TABLE IV
F AND P-VALUES OF THE 2×2 TWO-WAY REPEATED MEASAURES ANOVAS ON THE AVERAGE MUSCLE ACTIVITY DURING THE DRILLING TASK WITH MAIN EFFECTS OF CONDITION (NOEXO, EXO4W), SIDE (DOMINANT, NON-DOMINANT) AND THEIR INTERACTION

	Condition		Side		Condition x Side	
	F	p	F	p	F	p
DA	4.94	0.039*	0.98	0.335	1.11	0.749
TD	0.19	0.667	2.62	0.123	0.09	0.767
PM	0.75	0.400	1.94	0.181	0.37	0.549
BB	1.23	0.282	1.60	0.221	0.25	0.626
ESL	0.53	0.474	0.82	0.378	0.26	0.618
LD	4.41	0.051	1.29	0.272	1.61	0.221
TM	6.67	0.019*	4.52	0.003*	0.08	0.773

DA: deltoideus anterior, TD: trapezius descendens, PM: pectoralis major, BB: biceps brachii, ESL: lumbar erector spinae longissimus, LD: latissumus dorsi, TM: triceps medialis. * indicates $p \leq 0.05$.

TABLE V
LINEAR REGRESSIONS WERE FITTED ON THE INDIVIDUAL TIME SERIES OF DA AND TD ACTIVITY AND MPF OF THE DRILL TASK. THE COEFFICIENTS OF DETERMINATION, THE RATIO OF SIGNIFICANTLY FITTING REGRESSIONS, Y-INTERCEPTS AND THE SLOPE (β) OF THE REGRESSION WERE DISPLAYED

DA			R^2	$p < 0.05$	y	β
Activity	Dominant	NoExo	0.25 ± 0.04	15/22	27.22 ± 2.87	-0.086 ± 0.051
		Exo4W	0.27 ± 0.04	15/22	23.63 ± 2.28	0.008 ± 0.036
	N-dominant	NoExo	0.36 ± 0.05	16/22	23.39 ± 3.44	0.003 ± 0.057
		Exo4W	0.35 ± 0.06	16/22	19.80 ± 2.33	0.070 ± 0.050
MPF	Dominant	NoExo	0.69 ± 0.05	22/22	85.29 ± 2.22	-0.425 ± 0.029
		Exo4W	0.63 ± 0.03	22/22	85.45 ± 2.35	-0.365 ± 0.021
	N-dominant	NoExo	0.64 ± 0.05	21/22	86.92 ± 2.15	-0.389 ± 0.036
		Exo4W	0.57 ± 0.05	21/22	87.80 ± 1.83	-0.362 ± 0.039
TD			R^2	$p < 0.05$	y	β
Activity	Dominant	NoExo	0.34 ± 0.05	16/22	23.01 ± 2.57	0.069 ± 0.046
		Exo4W	0.31 ± 0.07	11/22	23.98 ± 4.18	0.107 ± 0.048
	N-dominant	NoExo	0.46 ± 0.07	17/22	25.20 ± 7.25	0.164 ± 0.162
		Exo4W	0.35 ± 0.08	14/22	20.79 ± 4.78	0.142 ± 0.036
MPF	Dominant	NoExo	0.33 ± 0.06	13/22	80.27 ± 2.27	-0.139 ± 0.031
		Exo4W	0.29 ± 0.06	12/22	77.48 ± 1.10	-0.094 ± 0.027
	N-dominant	NoExo	0.25 ± 0.05	12/22	78.34 ± 2.47	-0.100 ± 0.042
		Exo4W	0.29 ± 0.04	17/22	77.75 ± 1.68	-0.155 ± 0.032

DA: deltoideus anterior, TD: trapezius descendens. * indicates $p \leq 0.05$.

TABLE VI
F AND P-VALUES OF THE 2×2 TWO-WAY WITHIN-SUBJECTS ANOVAS ON THE AVERAGE MUSCLE ACTIVITY DURING THE LIFT TASK WITH MAIN EFFECTS OF CONDITION (NOEXO, EXO4W), SIDE (DOMINANT, NON-DOMINANT) AND THEIR INTERACTION

		Condition		Side		Condition x Side	
		F	p	F	p	F	p
Average activity	DA	5.39	0.031*	0.44	0.516	0.03	0.873
	TD	0.83	0.375	1.32	0.264	1.97	0.177
	PM	3.39	0.080	0.01	0.937	0.47	0.501
	BB	16.67	0.001*	2.34	0.142	1.45	0.242
	ESL	0.01	0.909	0.02	0.887	1.96	0.177
	LD	0.86	0.366	5.95	0.024*	0.27	0.607
	TM	1.32	0.264	7.26	0.014*	0.79	0.385
Peak activity	DA	4.68	0.043*	0.50	0.490	0.16	0.694
	TD	0.13	0.720	2.53	0.134	0.79	0.067
	PM	5.94	0.024*	1.30	0.268	1.33	0.262
	BB	13.82	0.001*	2.46	0.134	1.75	0.202
	ESL	0.01	0.977	0.04	0.840	3.69	0.069
	LD	0.24	0.629	5.42	0.030*	0.16	0.691
	TM	0.41	0.529	7.33	0.013*	0.01	0.909
Integrated activity	DA	2.40	0.137	0.49	0.493	0.02	0.892
	TD	0.13	0.720	1.82	0.193	0.58	0.546
	PM	1.31	0.100	0.10	0.756	0.39	0.542
	BB	4.79	0.041*	2.17	0.157	1.03	0.323
	ESL	5.93	0.024*	0.01	0.945	0.98	0.334
	LD	4.09	0.056	5.48	0.029*	1.52	0.232
	TM	9.39	0.006*	6.73	0.017*	0.11	0.747

DA: deltoideus anterior, TD: trapezius descendens, PM: pectoralis major, BB: biceps brachii, ESL: lumbar erector spinae longissimus, LD: latissumus dorsi, TM: triceps medialis. * indicates $p \leq 0.05$.

TABLE VII
DETAILS OF MAIN EFFECTS OF CONDITION AND SIDE OF THE TWO-WAY REPEATED MEASURES ANOVAS ON MUSCLE ACTIVITY DURING THE LIFT TASK AND THE POST HOC ANALYSES OF THE RELEVANT INTERACTION EFFECTS. AVERAGES WERE DISPLAYED WITH STANDARD ERRORS, COHEN'S D EFFECT SIZES AND 95% CONFIDENCE INTERVALS (95%CI) WERE PRESENTED

Main effect: Condition						
	NoExo	Exo4W	F	p	Cohen's d	95%CI
Avg. DA (%MVC)	22.9 ± 2.6	21.6 ± 2.6	5.39	0.031*	0.11	$[-2.46, -0.13]$
Avg. BB (%MVC)	4.2 ± 0.5	3.3 ± 0.4	16.67	0.001*	0.45	$[-1.32, -0.42]$
Peak DA (%MVC)	63.1 ± 7.1	58.9 ± 6.4	4.68	0.043*	0.14	$[-6.44, -1.98]$
Peak PM (%MVC)	6.4 ± 1.1	5.7 ± 0.9	5.94	0.024*	0.14	$[-1.11, -0.22]$
Peak BB (%MVC)	11.2 ± 1.5	8.4 ± 1.4	13.82	0.001*	0.45	$[-3.68, -2.00]$
Int. BB (%MVC*s)	13.8 ± 1.0	12.2 ± 1.0	4.79	0.041*	0.25	$[-3.19, -0.07]$
Int. ESL (%MVC*s)	35.1 ± 3.3	40.5 ± 3.8	5.93	0.024*	0.28	$[1.41, 9.54]$
Int. TB (%MVC*s)	5.9 ± 0.7	6.8 ± 0.7	9.39	0.006*	0.24	$[0.30, 1.58]$
Main effect: Side						
	Dominant	N-dominant	F	p	Cohen's d	95%CI
Avg. LD (%MVC)	6.7 ± 0.9	9.9 ± 1.4	5.96	0.024*	0.59	$[2.35, 3.99]$
Avg. TB (%MVC)	1.5 ± 0.2	2.1 ± 0.3	7.26	0.014*	0.60	$[0.47, 0.76]$
Peak LD (%MVC)	18.6 ± 2.6	28.1 ± 4.4	5.42	0.030*	0.56	$[6.80, 12.12]$
Peak TB (%MVC)	3.8 ± 0.5	5.5 ± 0.8	7.33	0.013*	0.54	$[1.25, 2.10]$
Int. LD (%MVC*s)	23.2 ± 2.8	34.3 ± 4.6	5.48	0.029*	0.52	$[2.48, 19.60]$
Int. TB (%MVC*s)	5.3 ± 0.6	7.4 ± 0.9	6.73	0.017*	0.55	$[0.42, 3.77]$

DA: deltoideus anterior,PM: pectoralis major, BB: biceps brachii, ESL: lumbar erector spinae longissimus, LD: latissumus dorsi, TB: triceps brachii. * indicates $p \leq 0.05$.

ACKNOWLEDGMENT

The authors would like to thank Jesse Lemmens for his assistance during this study's data collection.

REFERENCES

[1] B. R. Da Costa and E. R. Vieira, "Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies," *Amer. J. Ind. Med.*, vol. 53, no. 3, pp. 285–323, Mar. 2010.

[2] C. H. Linaker and K. Walker-Bone, "Shoulder disorders and occupation," *Best Pract. Res. Clin. Rheumatology*, vol. 29, no. 3, pp. 405–423, Jun. 2015.

[3] A. Parent-Thirion *et al.*, "Sixth european working conditions survey-overview report (2017 update)," EuroFound, Luxembourg, Tech. Rep., 2017.

[4] R. Govaerts *et al.*, "Prevalence and incidence of work-related musculoskeletal disorders in secondary industries of 21st century Europe: A systematic review and meta-analysis," *BMC Musculoskelet. Disord.*, vol. 22, no. 1, p. 751, Dec. 2021.

[5] E. Rashedi *et al.*, "Ergonomic evaluation of a wearable assistive device for overhead work," *Ergonomics*, vol. 57, no. 12, pp. 1864–1874, Dec. 2014.

[6] A. P. Verhagen *et al.*, "Conservative interventions for treating work-related complaints of the arm, neck or shoulder in adults," in *Cochrane Database Syst. Rev.*, A. P. Verhagen, Ed. Hoboken, NJ, USA:Wiley, Oct. 2010.

[7] M. P. de Looze *et al.*, "Exoskeletons for industrial application and their potential effects on physical work load," *Ergonomics*, vol. 59, no. 5, pp. 671–681, May 2016.

[8] T. McFarland and S. Fischer, "Considerations for industrial use: A Systematic review of the impact of active and passive upper limb exoskeletons on physical exposures," *IISE Trans. Occup. Ergonom. Hum. Factors*, vol. 7, no. 3/4, pp. 322–347, Oct. 2019.

[9] M. Bär *et al.*, "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. Ergonom.*, vol. 94, Jul. 2021, Art. no. 103385.

[10] M. Rossini *et al.*, "Design and evaluation of a passive cable-driven occupational shoulder exoskeleton," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 4, pp. 1020–1031, Nov. 2021.

[11] A. Voilque *et al.*, "Industrial exoskeleton technology: Classification, structural analysis, and structural complexity indicator," in *Proc. IEEE Wearable Robot. Assoc. Conf.*, 2019, pp. 13–20.

[12] M. A. Gull *et al.*, "A review on design of upper limb exoskeletons," *Robotics*, vol. 9, no. 1, p. 16, Mar. 2020.

[13] D. Torricelli *et al.*, "Benchmarking wearable robots: Challenges and recommendations from functional, user experience, and methodological perspectives," *Front. Robot. AI*, vol. 7, Nov. 2020.

[14] S. Crea *et al.*, "Occupational exoskeletons: A roadmap toward large-scale adoption. methodology and challenges of bringing exoskeletons to workplaces," *Wearable Technol.*, vol. 2, p. e 11, Sep. 2021.

[15] S. De Bock *et al.*, "Benchmarking occupational exoskeletons: An evidence mapping systematic review," *Appl. Ergonom.*, vol. 98, Jan. 2022, Art. no. 103582.

[16] S. Baltrusch *et al.*, "The effect of a passive trunk exoskeleton on functional performance in healthy individuals," *Appl. Ergonom.*, vol. 72, pp. 94–106, Oct. 2018.

[17] S. Mohammed *et al.*, "Lower-limb movement assistance through wearable robots: State of the art and challenges," *Adv. Robot.*, vol. 26, no. 1/2, pp. 1–22, Jan. 2012.

[18] K. Langlois *et al.*, "Investigating the effects of strapping pressure on human-robot interface dynamics using a soft robotic cuff," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 146–155, Feb. 2021.

[19] L. Van Engelhoven *et al.*, "Experimental evaluation of a shoulder-support exoskeleton for overhead work: Influences of peak torque amplitude, task, and tool mass," *IISE Trans. Occup. Ergonom. Hum. Factors*, vol. 7, no. 3/4, pp. 250–263, Oct. 2019.

[20] L. Grazi *et al.*, "Design and experimental evaluation of a semi-passive upper-limb exoskeleton for workers with motorized tuning of assistance," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 10, pp. 2276–2285, Oct. 2020.

[21] A. de Vries *et al.*, "The amount of support provided by a passive arm support exoskeleton in a range of elevated arm postures," *IISE Trans. Occup. Ergonom. Hum. Factors*, vol. 7, no. 3/4, pp. 311–321, Oct. 2019.

[22] K. Huysamen *et al.*, "Evaluation of a passive exoskeleton for static upper limb activities," *Appl. Ergonom.*, vol. 70, pp. 148–155, Jul. 2018.

[23] K. Huysamen *et al.*, "Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks," *Appl. Ergonom.*, vol. 68, pp. 125–131, Apr. 2018.

[24] S. Kim *et al.*, "Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I. - "Expected" effects on discomfort, shoulder muscle activity, and work task performance," *Appl. Ergonom.*, vol. 70, pp. 315–322, Jul. 2018.

[25] S. Kim *et al.*, "Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II - 'Unexpected' effects on shoulder motion, balance, and spine loading," *Appl. Ergonom.*, vol. 70, pp. 323–330, Jul. 2018.

[26] J. Theurel *et al.*, "Physiological consequences of using an upper limb exoskeleton during manual handling tasks," *Appl. Ergonom.*, vol. 67, pp. 211–217, Feb. 2018.

[27] I. Pacifico *et al.*, "An experimental evaluation of the Proto-MATE: A novel ergonomic upper-limb exoskeleton to reduce workers' physical strain," *IEEE Robot. Autom. Mag.*, vol. 27, no. 1, pp. 54–65, Mar. 2020.

[28] E. B. Weston *et al.*, "A physiological and biomechanical investigation of three passive upper-extremity exoskeletons during simulated overhead work," *Ergonomics*, vol. 65, no. 1, pp. 105–117, Jan. 2022.

[29] A. De Vries and M. De Looze, "The effect of arm support exoskeletons in realistic work activities: A review study," *J. Ergonom.*, vol. 9, no. 4, pp. 1–9, 2019.

[30] S. Iranzo *et al.*, "Ergonomics assessment of passive upper-limb exoskeletons in an automotive assembly plant," *Appl. Ergonom.*, vol. 87, Sep. 2020, Art. no. 103120.

[31] P. Maurice *et al.*, "Objective and subjective effects of a passive exoskeleton on overhead work," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 1, pp. 152–164, Jan. 2020.

[32] T. Schmalz *et al.*, "Biomechanical and metabolic effectiveness of an industrial exoskeleton for overhead work," *Int. J. Environ. Res. Public Health*, vol. 16, no. 23, Nov. 2019, Art. no. 4792.

[33] S. Del Ferraro, T. Falcone, A. Ranavolo and V. Molinaro, "The effects of upper-body exoskeletons on human metabolic cost and thermal response during work tasks-A systematic review," *Int. J. Environ. Res. Public Health*, vol. 17, no. 20, Oct. 2020, Art. no. 7374.

[34] S. A. Elprama *et al.*, "Social processes: What determines industrial workers' intention to use exoskeletons?," *Hum. Factors J. Hum. Factors Ergonom. Soc.*, vol. 62, no. 3, pp. 337–350, May 2020.

[35] N. D'Elia *et al.*, "Physical human-robot interaction of an active pelvis orthosis: Toward ergonomic assessment of wearable robots," *J. Neuroeng. Rehabil.*, vol. 14, no. 1, p 29, Dec. 2017.

[36] R. Hensel and M. Keil, "Subjective evaluation of a passive industrial exoskeleton for lower-back support: A. field study in the automotive sector," *IISE Trans. Occup. Ergonom. Hum. Factors*, vol. 7, no. 3/4, pp. 213–221, Oct. 2019.

[37] L. Levesque *et al.*, "Experimental comfort assessment of an active exoskeleton interface," in *Proc. IEEE Int. Symp. Robot. Intell. Sensors*, 2017, pp. 38–43.

[38] K. Langlois *et al.*, "Integration of 3D printed flexible pressure sensors into physical interfaces for wearable robots," *Sensors*, vol. 21, no. 6, Mar. 2021, Art. no. 2157.

[39] S. De Bock *et al.*, "Passive shoulder exoskeletons: More effective in the lab than in the field?," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, no. 2016, pp. 1–1, 2021.

[40] Horizon2020, "Technology readiness levels (TRL)," European Commission, Luxemburg, Tech. Rep. 2014, 2014.

[41] M. Rossini *et al.*, "Automatic synthesis of arthrokinematically compatible exoskeletons. a. case study on its application on a shoulder occupational exoskeleton," *Mech. Mach. Theory*, vol. 157, Mar. 2021, Art. no. 104186.

[42] S. Grosu *et al.*, "Driving robotic exoskeletons using cable-based transmissions: A Qualitative analysis and overview," *Appl. Mech. Rev.*, vol. 70, no. 6, Nov. 2018.

[43] W. T. Dempster and G. R. L. Gaughran, "Properties of body segments based on size and weight," *Amer. J. Anat.*, vol. 120, no. 1, pp. 33–54, Jan. 1967.

[44] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. Hoboken, NJ, USA: Wiley, 2009.

[45] J. T. McConville *et al.*, "Anthropometric relationships of body and body segment moments of inertia," Aerospace Medical Research Laboratory, OH, USA, Tech. Rep., Dec. 1980.

[46] K. Huysamen *et al.*, "Kinematic and kinetic functional requirements for industrial exoskeletons for lifting tasks and overhead lifting," *Ergonomics*, vol. 63, no. 7, pp. 818–830, Jul. 2020.

[47] S. Toxiri *et al.*, "A wearable device for reducing spinal loads during lifting tasks: Biomechanics and design concepts," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, 2015, pp. 2295–2300.

[48] S. Toxiri *et al.*, "Actuation requirements for assistive exoskeletons: Exploiting knowledge of task dynamics," *Biosyst. Biorobotics*, vol. 22, pp. 381–385, 2018.

[49] R. Adams, "Revised physical activity readiness questionnaire," *Can. Fam. Physician*, vol. 45, pp. 9925–10045, Apr. 1999.

[50] H. J. Hermens *et al.*, "Development of recommendations for SEMG sensors and sensor placement procedures," *J. Electromyogr. Kinesiol.*, vol. 10, no. 5, pp. 361–374, Oct. 2000.

[51] S. J. Baltrusch *et al.*, "The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking," *Ergonomics*, vol. 62, no. 7, pp. 903–916, Jul. 2019.

[52] G. A. Borg, "Psychophysical bases of perceived exertion," *Med. Sci. Sport. Exerc.*, vol. 14, no. 5, pp. 377–381, May 1982.

[53] E. N. Corlett and R. P. Bishop, "A technique for assessing postural discomfort," *Ergonomics*, vol. 19, no. 2, pp. 175–182, Mar. 1976.

[54] J. Brooke, "SUS - A. quick and dirty usability scale," *Usability Eval. Ind.*. New York, NY, USA: Taylor & Franci, 1996, pp. 189–194.

[55] R. Merletti *et al.*, "Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions," *J. Appl. Physiol.*, vol. 69, no. 5, pp. 1810–1820, Nov. 1990.

[56] D. Farina *et al.*, "Assessment of low back muscle fatigue by surface EMG signal analysis: Methodological aspects," *J. Electromyogr. Kinesiol.*, vol. 13, no. 4, pp. 319–332, Aug. 2003.

[57] E. P. Lamers *et al.*, "Low-profile elastic exosuit reduces back muscle fatigue," *Sci. Rep.*, vol. 10, no. 1, Dec. 2020, Art. no. 15958.

[58] Have *et al.*, "Squat lifting imposes higher peak joint and muscle loading compared to stoop lifting," *Appl. Sci.*, vol. 9, no. 18, Sep. 2019, Art. no. 3794.

[59] W. D. McArdle *et al.*, *Energy for Physical Activity*, *7th ed*. Baltimore, MD, USA: Williams & Wilkins, 2015.
[60] T. C. Pataky, "Generalized n-dimensional biomechanical field analysis using statistical parametric mapping," *J. Biomech.*, vol. 43, no. 10, pp. 1976–1982, Jul. 2010.
[61] T. C. Pataky, "One-dimensional statistical parametric mapping in python," *Comput. Methods Biomech. Biomed. Engin.*, vol. 15, no. 3, pp. 295–301, Mar. 2012.
[62] T. C. Pataky *et al.*, "Vector field statistical analysis of kinematic and force trajectories," *J. Biomech.*, vol. 46, no. 14, pp. 2394–2401, Sep. 2013.
[63] T. C. Pataky, "Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis," *J. Biomech.*, vol. 48, no. 7, pp. 1277–1285, May 2015.
[64] A. Bangor *et al.*, "An empirical evaluation of the system usability scale," *Int. J. Hum. Comput. Interact.*, vol. 24, no. 6, pp. 574–594, Jul. 2008.
[65] L. Iuppariello *et al.*, "A novel approach to estimate the upper limb reaching movement in three-dimensional space," *Informat. Med. Unlocked*, vol. 15, 2019, Art. no. 100155.
[66] A. Chapman *et al.*, "Do differences in muscle recruitment between novice and elite cyclists reflect different movement patterns or less skilled muscle recruitment?" *J. Sci. Med. Sport*, vol. 12, no. 1, pp. 31–34, Jan. 2009.
[67] P. S. Glazier and K. Davids, "On analysing and interpreting variability in motor output," *J. Sci. Med. Sport*, vol. 12, no. 4, pp. e2–e3, Jul. 2009.
[68] S. Alabdulkarim *et al.*, "Effects of exoskeleton design and precision requirements on physical demands and quality in a simulated overhead drilling task," *Appl. Ergonom.*, vol. 80, no. May, pp. 136–145, Oct. 2019.
[69] M. S. Cherry *et al.*, "Running with an elastic lower limb exoskeleton," *J. Appl. Biomech.*, vol. 32, no. 3, pp. 269–277, Jun. 2016.
[70] J. Zhang *et al.*, "Human-in-the-loop optimization of exoskeleton assistance during walking," *Science*, vol. 356, no. 6344, pp. 1280–1284, Jun. 2017.
[71] Y. Ding *et al.*, "Human-in-the-loop optimization of hip assistance with a soft exosuit during walking," *Sci. Robot.*, vol. 3, no. 15, pp. 1–9, Feb. 2018.
[72] W. Wang *et al.*, "Improving walking economy with an ankle exoskeleton prior to human-in-the-loop optimization," *Front. Neurorobot.*, vol. 15, pp. 1–12, Jan. 2022.