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Effects of using an active hand exoskeleton for drilling tasks: A pilot study

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ABSTRACT

Introduction: Several studies have assessed and validated the impact of exoskeletons on back and shoulder muscle activation; however, limited research has explored the role that exoskeletons could play in mitigating lower arm-related disorders. This study assessed the impact of Ironhand, an active hand exoskeleton (H-EXO) designed to reduce grip force exertion, on worker exertion levels using a two-phase experimental design. *Method:* Ten male participants performed a controlled, simulated drilling activity, while three male participants completed an uncontrolled concrete demolition activity. The impact of the exoskeleton was assessed in terms of muscle activity across three different muscles using electromyography (EMG), perceived exertion, and perceived effectiveness. *Results:* Results indicate that peak muscle activation decreased across the target muscle group when the H-EXO was used, with the greatest reduction (27%) observed in the Extensor Carpi Radialis (ECR). Using the exoskeleton in controlled conditions did not significantly influence perceived exertion levels. Users indicated that the H-EXO was a valuable technology and expressed willingness to use it for future tasks. *Practical Applications:* This study showcases how glove-based exoskeletons can potentially reduce wrist-related disorders, thereby improving safety and productivity among workers. Future work should assess the impact of the H-EXO in various tasks, different work environments and configurations, and among diverse user groups.

1. Introduction

1.1. Hand-wrist pain and repetitive tasks

The rate of work-related musculoskeletal disorders (WMSDs) or repetitive strain injuries (RSIs) remains a primary concern across all industries globally. According to the U.S. Bureau of Labor Statistics (BLS), 77,800 upper extremity-related WMSD cases in 2020 resulted in days away from work in the United States (BLS, 2022). Approximately 25% of reported upper extremity WMSD cases are associated with workers' hands and wrists (BLS, 2022). In Europe, about three out of every five workers complained of WMSDs in their back, upper arm, and/or hand/wrist in 2015, and approximately 30% reported muscular pains in their hands and wrists (Agency, 2019). Common hand and wrist conditions classified as WMSDs or RSIs include carpal tunnel syndrome (CTS), trigger finger, ulnar tunnel syndrome, tendonitis in the wrist and hand, and bursitis in the wrist. These injuries are primarily caused by over-exertion and repetitive tasks such as hammering, wrenching, and manual handling of vibrating tools (Barr, Barbe, & Clark, 2004). WMSDs of the hand and wrist lead to the longest absences from work, translating to significant losses in productivity and wages (Barr et al., 2004). On average, WMSD injuries like CTS cost companies about $30,000 in medical costs, excluding indirect costs associated with occupational injuries (OSHA, 2017). Strategies to eliminate or reduce the impact of WMSDs include administrative controls (such as job rotation) and engineering controls (such as automation or purchasing equipment with reduced vibration). However, while these solutions have helped reduce WMSDs, significant room for improvement remains. Exoskeletons, an emerging control mechanism, have shown substantial potential for mitigating risks associated with WMSDs in occupational settings.

1.2. Previous studies on exoskeletons for repetitive tasks

Exoskeletons, also known as wearable robots, super suits, or exosuits (EXOs), are a class of robotic devices purposefully designed to be attached to the human body. They facilitate the reduction of physical demand by augmenting force actions during suitable tasks (Kim et al., 2019). According to McFarland and Fischer (2019), EXOs can be either active, powered by an electrical system that measures force output based on feedback mechanisms, or passive, relying on a hydraulic system

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tuned to provide the necessary lift and push when worn. Industrial EXOs typically fall into one of the following categories: arm/shoulder support, back support, leg support, and hand support. Arm/shoulder support EXOs are used to reduce the impact on workers' arms and shoulders during overhead activities (Weston et al., 2022; Kim et al., 2018a), while back support EXOs provide crucial support to workers' lower backs during material handling tasks (Gonsalves, Ogunseiju, Akanmu, & Nnaji, 2021; Kermavnar, de Vries, de Looze, & O'sullivan, 2021). Workers can support their lower limbs using leg-support EXOs while performing tasks that significantly impact their knees and ankles (Pillai, Van Engelhoven, & Kazerooni, 2020; Yan et al., 2021; Viteckova et al., 2018). Hand or glove-based EXOs (H-EXOs) were developed to help reduce the impact of grip-related activities on workers' forearm health (Ferguson, Shen, & Rosen, 2020).

The availability of these and other industrial exoskeletons has led to experimental testing for researchers to confirm the efficacy of using different types of EXOs to prevent or reduce WMSDs. Benefits include increased rest times and lift heights, increased endurance, and improved productivity through enhanced task completion times (Cho, Kim, Ma, & Ueda, 2018; Bock, Linner, & Ikeda, 2012; Gonsalves et al., 2021). A review of EXO studies reveals that arm/shoulder support EXOs have been tested during eye-level and overhead tasks (e.g., Abdulkarim, Kim, & Nussbaum, 2019; Chiaradia et al., 2021; Grazi et al., 2020). In a study conducted by Kim et al. (2018b), participants were asked to complete a drilling task with and without an Ekso Vest—an arm/shoulder EXO. The results suggest that the Ekso Vest reduced shoulder demands by up to 45%. Huysamen et al. (2018) found that muscle activation in the medial deltoid and biceps brachii was reduced by 62% and 49%, respectively, during a static overhead task when using Robomate. Additionally, Yin, Yang, Qu, and Wang (2020) assessed a passive upper-limb exoskeleton (PULE) for use during an overhead task, validating a reduction in muscle activations of 38.5% (anterior deltoid) and 45.1% (posterior deltoid). These studies demonstrate that passive arm-support EXOs could play a significant role in managing WMSDs due to repetitive tasks in various work settings.

1.3. Research needs and objectives

As shown in the review above, several studies have assessed the efficacy of passive EXOs in supporting various tasks; however, knowledge about the efficacy of H-EXOs in repetitive tasks such as drilling is either non-existent or insufficient. Given the significant cost associated with hand and wrist-related RSIs and WMSDs like carpal tunnel syndrome, introducing cutting-edge solutions that could significantly reduce these disorders is essential. Previous studies indicate that providing empirical evidence on the effectiveness of EXOs is critical for adoption (Zhu, Dutta, & Dai, 2021; Okpala, Nnaji, Ogunseiju, & Akanmu, 2022). Moreover, conducting experimental and observation-based studies will yield key information needed to understand potential safety risks introduced or exacerbated by EXOs (Nnaji, Okpala, Gambatese, & Jin, 2023). According to Exoskeleton Reports (https://www.exoskeletonreport.com), only two H-EXOs are available for occupational/industrial use: Ironhand and Daiya Glove. This provides an opportunity for vendors to receive critical user feedback on the perceived effectiveness and value of H-EXOs.

Therefore, the objective of the present study was to conduct a pilot test to assess the impact of an active hand exoskeleton on user endurance in both controlled and less controlled environments, and to document user perceptions toward H-EXO. The hypotheses tested were: (H1) using H-EXO can reduce hand and wrist muscle activity, including in the flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), and flexor digitorum superficialis (FDS), during repetitive drilling tasks; (H2) using H-EXO can reduce users' overall perceived exertion; and (H3) using H-EXO will reduce perceived hand strain during repetitive drilling tasks. The results from the current study will provide foundational knowledge on how H-EXOs can potentially reduce wrist and hand disorders and improve user productivity. Additionally, the findings can improve understanding of how H-EXO could impact muscle activity and perceived effectiveness when used for drilling tasks and offer practical recommendations for using and designing H-EXO.

2. Methodology

The research team employed a robust study design that consisted of human-subject experiments to collect relevant pilot data, as well as descriptive and inferential statistical analyses to ascertain the subjective and objective effectiveness of the H-EXOs. Data were collected across two activities as described below in Section 2.2. A convenience sample of 10 healthy, right-handed male participants completed the study. All study participants provided consent before inclusion. The research protocol was approved by the university's Internal Review Board. Fig. 1 summarizes the research process described in this section. The study was approved by the University Institutional Review Board.

2.1. H-EXO

The research team selected the Ironhand 2.0 exoskeleton for the present study (See Fig. 2). While reports suggest that there are two glove-based exoskeletons, to the best of the authors' knowledge, Ironhand is the only commercially available system. Ironhand 2.0 is a device developed by Bioservo in response to the prevalence of hand and wrist injuries and the cost of upper limb disorders. The exoskeleton weighs about 6 lbs., with only 2 oz worn on the hand as a glove. It supplements the end-user's grip force, thereby reducing the effort required by the user. The exoskeleton is designed to apply up to 16 N of additional force to each finger, serving as a fatigue-reducing aid. As an active exoskeleton, it features intuitive functionality and customizable settings accessible through a dedicated app based on internet connectivity through 4G or Wi-Fi. These settings include Force Balance, Sensitivity, Activation Threshold, Locking Tendency, and Quick Grasp, enabling

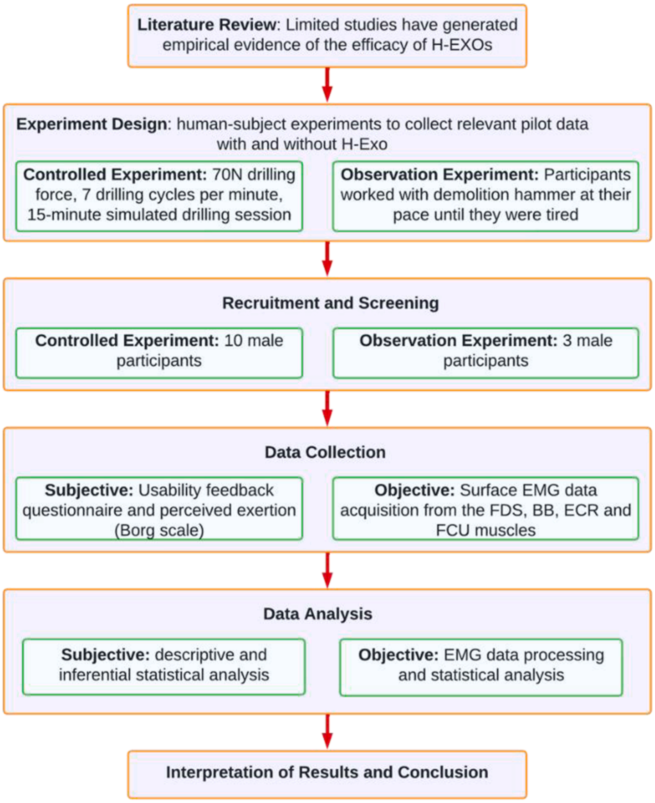


Fig. 1. Research process.

Fig. 2. Bioservo Ironhand 2.0.
Source: Bioservo, 2022

users to tailor the exoskeleton's behavior to their specific needs and preferences.

In this study, participants were given a properly sized exoskeleton glove in small, medium, or large size, and a basic profile was created for each of them. They were given a minimum of two hours on the first day to familiarize themselves with the Ironhand technology while performing various hand tasks, such as repetitive drilling, gripping, and holding, to establish their profiles. The initial settings were adjusted iteratively based on the work situation and feedback from the operator. The force output of the entire hand was set to 100% (through the remote controller), and the force balance for each finger was adjusted according to the feedback from the operator. The sensitivity was set to 3.8, which is the optimal sensitivity, and the activation threshold was set to 0.5 N for all the participants. The locking tendency function was not used since the task did not involve static holding, and the quick grasp function was disabled because it was not required for the task. Finally, the glove features memory storage that saves each participant's profile.

2.2. *Study design*

Study I: Consistent with previous pilot studies (Park, Kim, Nussbaum, & Srinivasan, 2022; Gonsalves et al., 2021; de Vries, Krause, & de Looze, 2021; Huysamen et al., 2018), 10 male students from the university community participated in this study. The participants performed a simulated drilling task (see Fig. 3) on a hollow rectangular rung (sized 1.5″ x 1.5″, 4 ft long) with evenly spaced 6 holes that were 1″ in diameter. The hollow rung was attached horizontally to a vertical structure to hold it firmly in place. All the participants reported that they have no history of joint-related disease, rheumatoid arthritis, upper limb, cardiovascular, or neurological disorders, or any WMSD/ health issues that can impact their ability to stand, move or perform the task. The researchers utilized a within-subjects (repeated-measures) design that includes two conditions — with and without H-EXO. To avoid order effects, the order of conditions was randomized for each participant. The participants made an initial visit to the laboratory to fill out consent forms and be familiar with the workings of the H-EXO. Afterward, the study was completed in two sessions (three separate days) – one session per experimental condition – at least two days apart to reduce the effect of residual muscle fatigue (Abdulkarim et al., 2019). Each session lasted for approximately 1 h. During each session, the participant was asked to participate in a 15-minute simulated drilling task. The setup-up included a drill, rung, and vertical structure propped against the wall (see Fig. 3). Participants positioned their arms at 90-degree angle relative to the biceps area, keeping their elbow at their sides. The duration of 15 min was selected based on the findings of Alabdulkarim and Nussbaum (2019), which showed that 15 min represents an acceptable frequency to detect change in muscle activation for a simulated drilling task. Moreover, previous studies have suggested using a shorter duration experiment when assessing a new exoskeleton to ensure the safety of the participants (Huysamen et al., 2018).

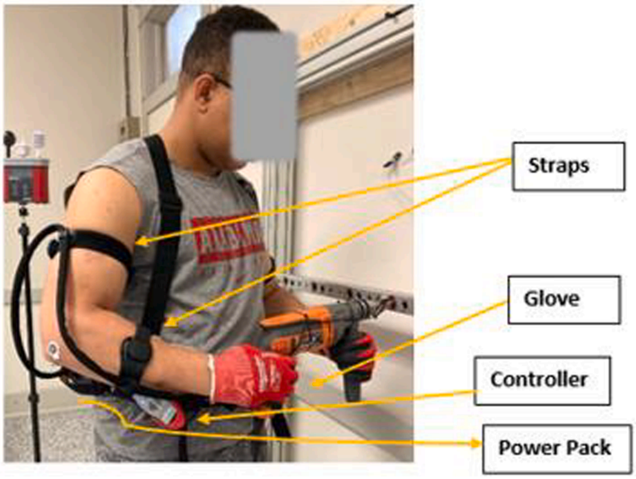


Fig. 3. Ironhand used for a simulated drilling activity.

Similar to previous studies, the rung was equipped with a load cell to determine the amount of force exerted by the drilling tool (Alabdulkarim et al., 2019; Alabdulkarim and Nussbaum, 2019). A commercial drilling tool (Ridgid) weighing approximately 2 kg with two handles was used and a probe representing a simulating drilling bit was attached to the end of the drilling tool. The drill was pressed against the rung, and the trigger was squeezed to simulate drilling; however, the drilling machine was powered OFF throughout the study. Participants received three different audio feedback types: one to indicate when to start drilling for a hole, another to signal the completion of drilling for a hole, and a third to indicate when to start drilling for the next hole. However, if a participant failed to sustain the force for the required 3 s, they did not receive the audio alert, and they were unable to proceed to the next hole on the rung. To assist participants in maintaining the required force, visual feedback was provided in form of an LED light that illuminated when a force of 70 N was reached. The participants conducted the drilling by moving back and forth along the rung in reverse order for each set. After completing a hole, participants were allowed to lower their arms to facilitate recovery.

Study II: This study recruited human subjects to conduct experiments in a less controlled environment to acquire additional relevant data. Four individuals who participated in Study I used a demolition hammer to remove compacted earth and concrete from a soil pit (see Fig. 4). Participants completed a wellness form that was used to screen for conditions that may impair their capacity to carry out the activity effectively, including arthritis, joint-related diseases, lower-limb or upper-limb conditions, cardiovascular or neurological problems, or MSD. The Machine [H-EXO, No H-EXO] was the sole independent variable considered in this investigation. The research team did not control for temperature given that the goal of the second study was to assess how the exoskeleton would perform in less controlled environments. The participants completed the consent forms and practiced using the exoskeleton.

To ensure participants' safety in the soil pit, each one completed the required safety training, which included working at the soil pit, using appropriate personal protective equipment (PPE), as receiving instruction on proper operation of the demolition hammer. Subsequently, participants completed two sessions of concrete demolition task on two different days, spaced roughly a week apart to allow for the dissipation of lingering muscular fatigue (Alabdulkarim and Nussbaum, 2019). In each session, participants were asked to continue working until they became fatigued and could no longer crush concrete. Each grinding session lasted between 40 and 45 min. In each session of the study, the pit was consistently cleared of broken materials before beginning. If broken materials accumulated during the session, the participants only cleared them when necessary. On average, participants took approximately five minutes to clear the broken materials and place them into a bag situated in one corner of the pit. The study utilized a commercial demolition hammer equipped with a SHOCKS Active Vibration Control System® which protects workers against exposure to prolonged vibration (Dewalt MAX L-SHAPE). The same device was used in the with and without an exoskeleton session, hence, the potential effect of vibration exposure is expected to cancel out.

At the end of Studies I and II, participants were provided with a link to a questionnaire survey to assess their perception of exoskeleton use.

Fig. 4. The H-EXO (Ironhand 2.0) used for breaking concrete.

2.3. Data collection

In the first session, after obtaining consent and completing the voiding process, participants' height, weight, and Body Mass Index (BMI) were recorded. These data were collected using the Omron HBF-514C and Seca Digital Column, which estimates human body composition and BMI, respectively. Two Shimmer3 wireless surface electromyography (EMG) devices, each equipped with three sensors, were used to measure the activity of three muscles: Flexor Digitorium Superficialis (FDS), Extensor Carpi Radialis (ECR), and Flexor Carpi Ulnaris (FCU). These specific muscle groups were selected because they are primary contributors to handgrip and drilling operations (Chiaradia et al., 2021; Das et al., 2018; Okafor & Varacallo, 2019). For instance, FCU, one of the superficial flexor muscles of the forearm, is considered the most powerful wrist flexor (Lung & Siwiec, 2022). The ECR is the primary dorsiflexor of the wrist and plays a primary role in grip-related activities (Walkowski & Goldman, 2019). Damage to this muscle leads to paralysis of the wrist extensors, which reduces grip strength significantly (Simoneau, Marklin, & Berman, 2003; Palastanga, Field, & Soames, 2006). FDS is directly linked to trigger-finger, which is a WMSD resulting from performing repetitive tasks using the hand (Barr et al., 2004).

To ensure accurate measurement of muscle activity, the skin surface where the EMG electrodes would be placed was first shaved and cleaned with an alcohol swab. The electrodes were then applied to the same muscle group consistently across all participants and sessions to reduce signal variability caused by differences in electrode placement. To address the interference problem from vibrations during the concrete demolition task, high-quality surface electrodes that stay in place were used. In Study II, where participants had to work with a demolition hammer, the electrodes were further secured in place with arm sleeves worn by the participants. The research team logged each participant's body composition and body mass index (BMI) while they rested for approximately 20 min.

The Maximal Voluntary Contraction (MVC) trial of the hand muscles (FDS, ECR, FCU) with and without H-EXO conditions was performed before the drilling task for subsequent EMG data normalization. The participants were instructed to perform an MVC by power gripping the handle of the drilling machine with their dominant hand while standing and pushing forward the drilling machine on a load cell (for 7 s). This procedure was performed three times, with one minute rest period between each set to allow for optimal muscular recovery and to enhance the reliability of the results (Abdulkarim et al., 2019). According to Finneran and O'sullivan (2013), the highest level of forearm muscle activity during MVC exertions was observed when performing power grip. Moreover, performing this procedure was also an important part of setting up the H-EXO as it uses it to estimate the percentage of the participants' MVC that the participant is using to execute tasks. Before the participants performed their MVC, one of the researchers demonstrated how it is done.

This experimental protocol was designed to mimic the operational process for completing a typical drilling task. A cycle consists of pushing the drill against the rung until 70 N is generated (took about 2 s on average), sustaining the generated force for 3 s, and resting for another 3 s. Participants repeat the same process, which leads to completing about 7 drilling cycles per minute.

To ensure consistency, the force and time requirements for each drilling cycle were controlled using an Arduino system. The system was configured to provide audio and visual notifications to participants as they completed the task. Each participant completed a 15-minute simulated drilling session that comprised multiple cycles. At the end of each session, the participants rated their perceived exertion based on the 10-point Borg scale (Gonsalves et al., 2021). A similar process was adopted for data collection in Study II. The primary difference between Studies I and II is that the researchers did not control the cycle; participants were instructed to work at their own pace. The participants provided verbal feedback on their perceived exertion every 5 min since participants were asked to keep going until they were tired. This approach aids in normalizing the rate of exertion across participants.

Finally, participants were asked to provide some feedback on the usability of H-EXO using questions that measured their perception of the use of the exoskeleton. The questions used to assess participants' perceptions were adapted from previous exoskeleton usability studies (Huysamen et al., 2018). Table 1 lists the questions asked to each participant, and the scales and anchors used. Specifically, an 11-point sliding scale (0–10) was used to assess participants' perceptions of the effectiveness and usability of the H-EXO, while a 3-point scale was used to evaluate users' intention to use the H-EXO.

2.3. Data analysis

The present study utilized an objective (surface EMG) and subjective (Borg CR-10 scale) metric for determining muscle fatigue and perceived exertion. In addition, the researchers assessed users' perception of the use of exoskeletons using constructs from established theoretical technology acceptance models. The data were pre-processed before performing statistical analysis.

2.3.1. Pre-processing: Surface EMG, perceived exertion, and perceived effectiveness data

The surface EMG data, which included raw EMG data from the MVC trials, were captured at a sample rate of 1024 Hz with a 20–450 Hz, 4th-order Butterworth bandpass filter (Rose, 2011). The highest Root Mean Square (RMS) EMG value was obtained at a 100 ms moving window through the EMG signals during the three MVC trials. Data processing was performed using Google Colab (Colaboratory, 2023; Larsen, Snow, & Aisbett, 2015). The highest RMS EMG value recorded for each muscle was selected for normalization. The EMG data for muscle activity during drilling tasks were processed in a similar way to the MVC EMG signal analysis for outcome measures. This was done by determining the peak EMG RMS value during a simulated drilling task and dividing it by the corresponding MVC of that muscle for each participant (Man et al., 2022). The resulting values were expressed as a percentage of the MVC (%MVC) (Man et al., 2022). The peak %MVC values were then used to calculate the mean values for each condition (with and without the exoskeleton) for each participant (Man et al., 2022). This allowed for comparisons to be made between the two conditions. In Study II, the task duration was divided into four quarters, and the EMG data for each quarter were used to observe the participants' muscle activation as they moved through the respective quarters (Q1 to Q4). The peak %MVC values for the respective quarters were calculated and the overall peak activation for each session was also computed.

Similar to Huysamen et al. (2018), participants provided an exertion score at the end of the sessions in Study I. Given the longer duration of activity in Study II, the exertion score was provided by the participants every 10 min. The research team extracted the perceived usability survey data from Qualtrics, and the data were cleaned to ensure that only complete responses were used. The data were prepared in Microsoft Excel and entered into SPSS 25 software for statistical analysis.

Table 1
Perceived effectiveness and usability.

Q#	Question	Scale	Anchor
Q1_1	Without the Ironhand: What degree of strain do you believe your hand/arm is put through in this work task?	0–10 sliding scale	“No Strain” to “Most Possible”
Q1_2	When using Ironhand: What degree of strain do you believe your hand is put through in this work task?	0–10 sliding scale	“No Strain” to “Most Possible”
Q2	To what degree do you perceive the glove to be supporting you in this work task?	0–10 sliding scale	“Not at all” to “Most Possible”
Q3	To what degree do you think the Ironhand system is comfortable to wear?	0–10 sliding scale	“Not at all” to “Most Possible”
Q4	To what degree do you perceive the system to be easy to operate?	0–10 sliding scale	“Not at all” to “Most Possible”
Q5	Would you use this exoskeleton in this work task in the future?	Three-point Likert scale	Yes, No, and Maybe

2.3.2. Statistical analysis

First, the processed data were assessed for normality in the SPSS 25 (Huysamen et al., 2018) using widely applied methods such as the Kolmogorov–Smirnov test (Zsoldos et al., 2010) and Shapiro-Wilk test (Hartz, Pires, Moreno, & Bigaton, 2015). The data were analyzed in two groups (with H-EXO and without H-EXO) across the peak percent MVC (% MVC) (H1). A similar comparison was made for exertion data (perceived rate of exertion) at the end of the sessions (H2). For these comparisons, the data that met the assumption of normality were then subjected to a parametric test such as Paired Samples t-Test (Asgari, Phillips, Dalton, Rudl, & Crouch, 2020; Tong, Wu, & Nie, 2014), wherein a T statistic (Lim, Kim, Song, Cynn, & Yi, 2014) is calculated alongside the effect size (Semciw, Green, Murley, & Pizzari, 2014). Moreover, when the assumption of normality was not met, the Wilcoxon signed-rank test, a non-parametric test, was utilized (Sandberg et al., 2020; Huysamen et al., 2018).

Finally, the researchers assessed perceived usability using a combination of descriptive (mean, standard deviation, etc.) and inferential statistics. To determine if participants believed that H-EXO is useful, the research team conducted a paired sample *t*-test and Wilcoxon Signed-rank test. Similar to previous research (Nnaji et al., 2023), the mid-point of the scale was used as the test mean (mid-point of an 11-point scale = 5). A mean value significantly higher than the mid-point (5.0) confirms that participants believe the H-EXO is useful. Wilcoxon Signed-rank test was used to assess the difference in perceived strain – with and without using the H-EXO. All statistical analyses in this study were performed at a 95% confidence level. The null hypothesis for H3 is as follows: *The perceived population mean effectiveness of H-EXO (η) is less than or equal to the hypothesized mean rating (η0).*

3. Results

The following subsections present the results of data analyses of (1) muscle fatigue for two exoskeleton conditions (with and without H-EXO), in the controlled and uncontrolled environment (Hypothesis 1), (2) users' perceived exertion for two exoskeleton conditions (with and without H-EXO), in the controlled and uncontrolled environment (Hypothesis 2), and (3) users' overall assessment of exoskeletons perceived effectiveness (Hypothesis 3).

3.1. Muscle activation

3.1.1. Controlled experiment

The demographics of participants are summarized in Table 2, and Table 3 presents a summary of the Paired T-tests (mean, standard deviation, *p*-value, and effect sizes *d*) performed for the EMG data, across the exoskeleton conditions. The Paired T-test was used because all cases met the requirement for a parametric-based analysis. All *p*-values had a confidence level greater than 0.05.

Fig. 5 shows the overall mean peak %MVC of their muscular efforts for the exoskeleton conditions during the drilling task, and the error bars indicate the standard deviation of the mean peak %MVC as a measure of

Table 2
Summary of participant demographic information (N = 10).

Participant	Mean	Standard Deviation	Minimum	Maximum
Age (years)	23.7	5.33	18	31
Height (in)	70.2	3.16	65	74
Weight (lb)	187.76	48.33	143	276

Table 3
Summary of peak muscle activation level for the drilling task with and without Exoskeleton for muscles: FDS, ECR, FCU (N = 10).

Muscles	FDS Peak %MVC		ECR Peak %MVC		FCU Peak %MVC	
Statistic	H-EXO	No H-Exo	H-EXO	No H-Exo	H-EXO	No H-Exo
Mean	21.24	26.58	31.29	37.03	22.94	23.42
SD	6.80	11.02	8.33	9.80	10.32	9.65
Mean Pair differences	5.34		5.74		0.48	
SD Pair differences	13.78		13.32		10.93	
t-value	1.225		1.362		1.40	
P-value	0.252		0.206		0.892	
Effect size	0.387		0.431		0.044	

Where FDS = Flexor Digitorium Superficialis; BB = Biceps Brachii; ECR = Extensor Carpi Radialis; FCU = Flexor Carpi Ulnaris; SD = Standard deviation

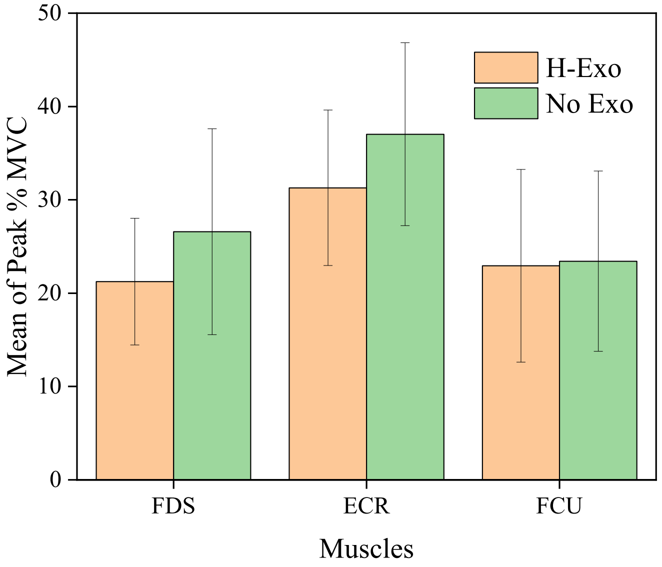


Fig. 5. Mean of peak percent MVC across the three muscle groups for the drilling task in both conditions: with and without the H-EXO; The bars show the standard deviation.

variations across all participants. During the drilling task, no significant statistical effects of the exoskeleton were observed on muscle activation. Results show a 5.34% reduction in the FDS muscle activation due to the introduction of H-EXO, however, there was no significant difference in FDS mean peak %MVC (*p*-value = 0.252). The ECR and FCU mean peak %MVC also reduced by 5.74%, and 0.48%, respectively. However, none of these reductions were significant (ECR *p*-value = 0.206; FCU *p*-value = 0.892).

3.1.2. *Uncontrolled observed experiments*

A summary of the results of the dependent samples test conducted on the peak %MVC data is shown in Table 4. Of the four participants who completed the task, the research team only utilized data from three participants because the EMG sensor malfunctioned for one of the participants. Initial analysis assessing data normality indicated that the mean peak %MVC was normally distributed; therefore, paired sample *t*-test was conducted to assess if activation levels differed, with or without the exoskeleton. When comparing the 'H-Exo' and 'No H-Exo' conditions, muscle activation was lower in the 'H-Exo' condition. H-Exo had a significant impact on the ECR muscle activation (*p*-value = 0.036) but there was no significant difference between the two Exo conditions for the FDS and FCU muscle. For both conditions, there was a slight increase in muscle activation as the participants perform the demolition task from the beginning (Q1) to the end (Q4).

Table 4
Results of the Wilcoxon Signed-Rank Test for the Demolition Task for Muscles: FDS, ECR, FCU (N = 3).

Muscle	Time	Mean	SD	t	*p*-value	Effect size (d)
Flexor Digitorium Superficialis	Q1	−6.07	29.30	0.359	0.754	−0.207
	Q2	7.41	7.96	1.613	0.248	0.931
	Q3	2.22	6.68	0.574	0.624	0.332
	Q4	7.17	6.93	1.793	0.215	1.035
	Total	3.35	8.03	0.723	0.545	0.418
Extensor Carpi Radialis	Q1	19.75	11.18	3.059	0.092	1.766
	Q2	26.12	21.50	2.104	0.170	1.215
	Q3	14.55	7.60	3.316	0.080	1.915
	Q4	12.91	12.20	1.833	0.208	1.058
	Total	20.44	6.94	5.100	0.036	2.945
Flexor Carpi Ulnaris	Q1	1.79	32.32	0.096	0.932	0.055
	Q2	27.07	29.82	1.572	0.257	0.908
	Q3	21.44	50.15	0.740	0.536	0.427
	Q4	7.52	13.76	0.946	0.444	0.546
	Total	17.11	28.54	1.038	0.408	0.599

Where t = t-value; *p*-value = significant value; Mean % = Pair differences for peak %MVC mean; SD = Pair differences for peak %MVC standard deviation; FDS = Flexor Digitorium Superficialis; ECR = Extensor Carpi Radialis; FCU = Flexor Carpi Ulnaris.

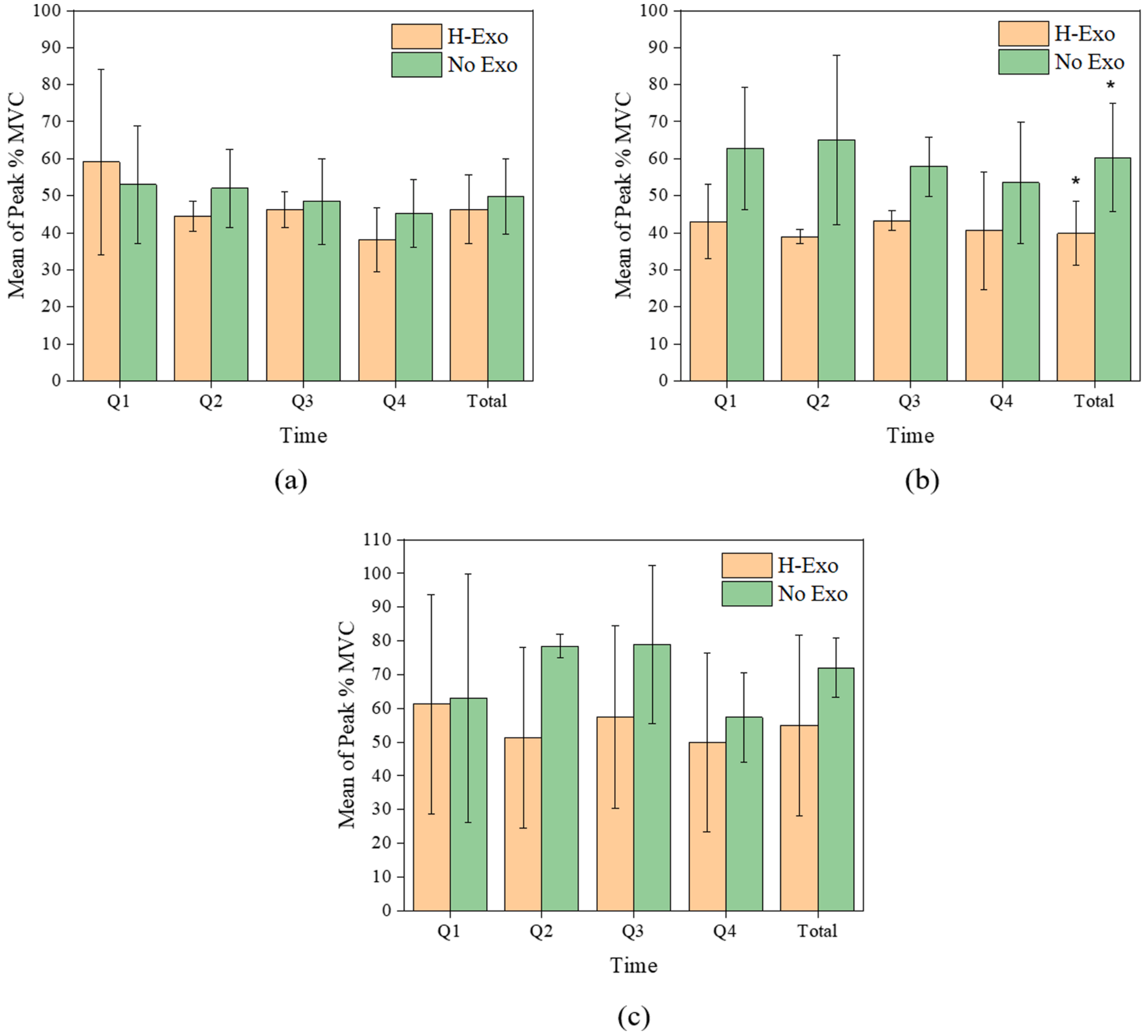
Fig. 6 show the overall mean peak % MVC for the muscular efforts in each quarter, comparing the H-EXO and No H-EXO conditions during the demolition task. H-EXO reduced FDS muscle activation in three out of the four quarters. Overall, the result showed a 3.35% reduction in the mean peak %MVC of FDS muscle activation when H-EXO was used for the demolition task. The effect of the H-EXO on the FDS muscle activation varied from weak to large (Cohen's d ranges from −0.207 to 1.035) during the task but the overall effect was small (Cohen's d = 0.418). H-EXO statistically significantly reduced the overall ECR muscle activation during the demolition task by about 20.44% (*p-value* = 0.036). The effect of H-EXO on ECR mean peak %MVC was large (Cohen's d = 2.945). The statistical test also showed that there was an insignificant difference but with a moderate effect (Cohen's d = 0.599) in the FCU mean peak %MVC muscle activation during the demolition task before and after the introduction of H-EXO. When H-EXO was used, the mean peak %MVC muscle activation decreased by about 17.11%, but the reduction was not significant (*p-value* = 0.599).

The result demonstrates that the ECR muscle experienced a significant experimental effect from H-EXO, whereas the FDS and FCU muscle experienced some experimental effect from the H-EXO. Overall, the results from the uncontrolled observation with H-EXO showed muscular activation across all muscles investigated in this study, consistent with some previous EXO studies that reported a decreased muscle activity in the arms and shoulder regions (Grazi et al., 2020; Huysamen et al., 2018; Theurel, Desbrosses, Roux, & Savescu, 2018).

3.2. *Perceived exertion*

3.2.1. *Controlled experiment*

The Shapiro-Wilk test indicated that the participants' perceived rate of exertion (Borg CR-10) met the assumption for normality (p-value > 0.05). Therefore, a paired samples *t*-test was conducted to assess the impact of the exoskeleton conditions on their perceived exertion. As shown in Fig. 7, the statistical analysis revealed that the level of perceived exertion was insignificantly different for the H-EXO and No H-EXO conditions (t (9) = -0.818, *p-value* = 0.434). The observed insignificant difference in perceived exertion during the H-EXO condition is consistent with existing literature. For instance, Kim et al. (2018b) suggested that the perceived pain and discomfort felt by workers during drilling operations remained largely the same for both conditions (with and without exoskeletons).



(a) (b) (c)

Fig. 6. Mean peak % MVC for (a) FDS (b) ECR (c) FCU muscle activation across 4 quarters for the demolition task in both exoskeleton conditions.

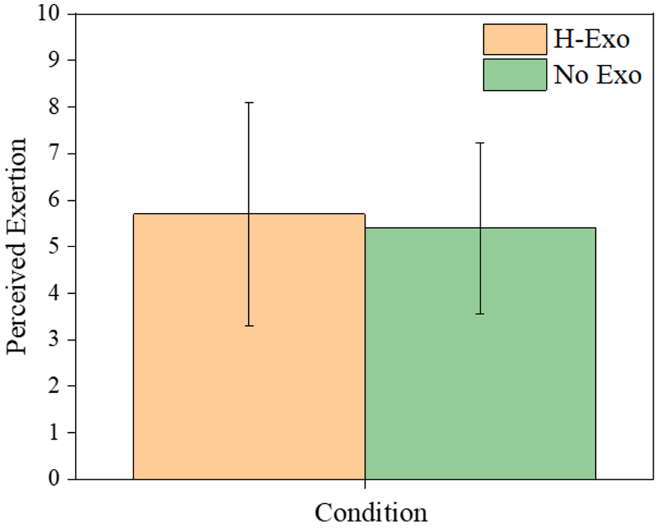


Fig. 7. Mean perceived exertion, using the Borg CR 10 scale, for the drilling task with and without H-EXO (n = 10).

3.2.2. Uncontrolled observed experiments

The results of the Wilcoxon-Sign rank test are displayed in Table 5 and Fig. 8. The perceived rate of exertion during the demolition task was observed to be greater in the H-EXO condition compared to the ’No H-EXO’ condition in the first 10 min, Z = -1.414; however, the difference was both insignificant (*p-value* = 0.157) and moderate (Effect size, r = 0.577). This could be because participants were still acclimating to the combined use of a vibration impact demolition hammer and H-EXO. After another 10 min, their perceived exertion was lower with the use of H-EXO relative to when it was not used (Z = -1.633), but the difference was not statistically significant (*p-value* = 0.102) and was moderate (r = 0.667). This reduction in their perceived exertion with H-EXO continued until the end of the task (I4), Z = -1.414, and the differences were strong (r = 0.577) but insignificant (*p-value* = 0.157). By the end of the task, there was an 11.1% reduction in perceived exertion level, and the large effect size indicated that the difference was noteworthy. This decrease in perceived exertion is comparable to the finding of other research showing that exoskeleton use over an extended period decreased users’ perceived exertion (de Vries et al., 2021; Grazi et al., 2020; Spada et al., 2019).

Table 5
RPE difference for demolition task, with and without the exoskeleton (N = 3).

Duration	Z	df	*p*	r
Pair I1	−1.414	2	0.157	0.577
Pair I2	−1.633	2	0.102	0.667
Pair I3	−1.414	2	0.157	0.577
Pair I4	−1.414	2	0.157	0.577

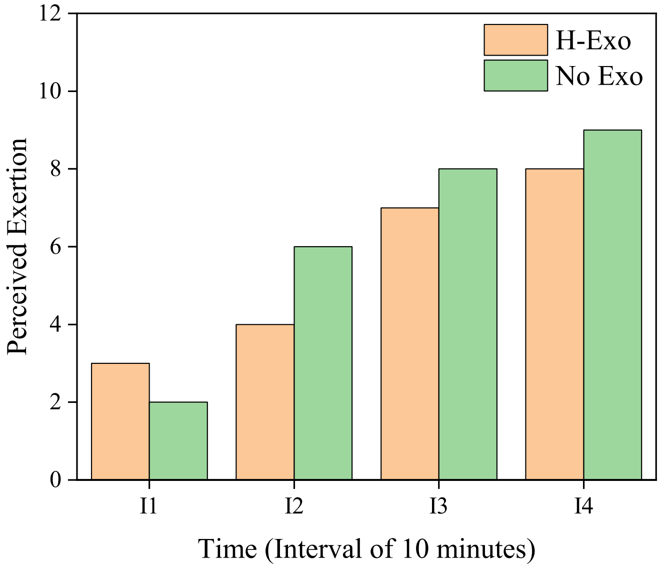


Fig. 8. Median perceived exertion at different intervals, with and without the Exoskeleton (n = 3).

3.3. *Perceived effectiveness and usability*

As depicted in Fig. 9a, participants perceived sprain reduced by about 36% when using the H-EXO, and this reduction was statistically significant (*p-value* = 0.016). Regarding participants' perceptions of the support, comfort, and ease of use provided by H-EXO, the results indicate that, on average, they believe H-EXO to be supportive, comfortable, and easy to use (Fig. 9b). Specifically, participants rated comfort and ease of use significantly above the test mean of 5 (comfort *p-value* = 0.04; ease-of-use *p-value* < 0.00), suggesting that they perceive H-EXO to be very useful. Eight out of 10 participants indicated that they would use H-EXO to perform drilling activities in the future if given the opportunity.

5. Discussion

The present study aimed to examine the effectiveness of H-EXO in terms of its impact on reducing end-users' fatigue. Overall, the results suggest that using H-EXO (Ironhand) could provide multiple benefits to end-users.

5.1. *Muscle activation*

The effects of using Ironhand on muscle activation are very interesting considering that there is limited data on the use of active glove exoskeletons in industrial/occupational settings. Moreover, considering that some passive upper-body exoskeletons have already been shown to reduce muscle activity in the arms and shoulder areas (Kim et al., 2018a; Asgari et al., 2020), the results from this study specifically reinforce the crucial role that exoskeletons can play in reducing worker fatigue. The use of H-EXO appears to be beneficial to reducing muscle activation at the Flexor Digitorium Superficialis, Extensor Carpi Radialis, and Flexor Carpi Ulnaris during drilling operations. Specifically, using H-EXO reduced peak nEMG values in these muscles by between 0.48% and 27.07% across the two experiments (controlled and observational), respectively. Interestingly, a higher percentage of muscle activation reduction was recorded in Study II (Observation) for FCU and ECR. This result suggests that prolonged use of H-EXO could offer greater benefits to end-users. Therefore, additional studies should explore deploying H-EXO for a prolonged period to assess the true effect of H-EXO on workers. Furthermore, practitioners should encourage workers to use H-EXO for extended periods to maximize return on investment through increased effectiveness.

In contrast to our findings, some studies suggest that using EXOs increases biomechanical loads during simulated drilling tasks at the waist level (Weston, Alizadeh, Knapik, Wang, & Marras, 2018; Rashedi, Kim, Nussbaum, & Agnew, 2014). Previous studies suggest that this increase in biomechanical load is likely associated with the weight of the device and certain restrictions it imposes (Weston et al., 2018; Kim et al., 2018a).

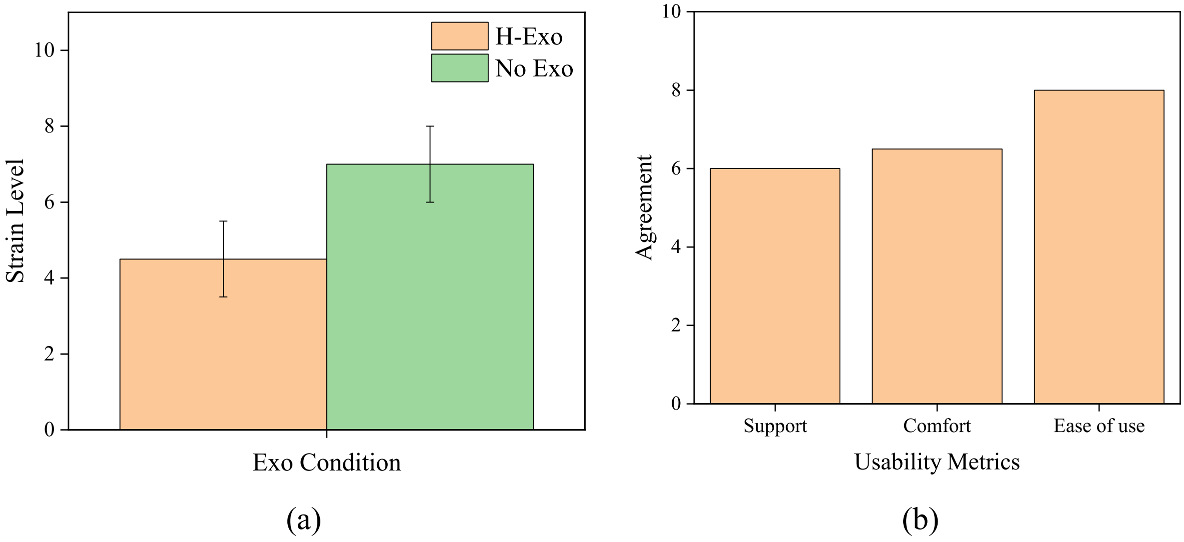


Fig. 9. Participants' perception of (a) H-EXO effectiveness and (b) usability (n = 10).

5.2. Perceived exertion

The results indicated that H-EXO did not have a significant effect on users' perceived rate of exertion (RPE) during the controlled experiment (Study I). A close examination of the results from Study I indicates that users felt fractionally more discomfort due to the exertion when using H-EXO. However, the increase in RPE (0.30) is not critical since the minimally clinically important difference (MCID) in exertion level using Borg CR 10 is 1 unit (Ries, 2005; So et al., 2020) and the difference is statistically insignificant (*p-value* = 0.38). This result is consistent with findings from previous studies that suggested exoskeletons may increase RPE (So et al., 2020; Gonsalves et al., 2021; Kim et al., 2018a). These results regarding perceived exertion and muscle activity in the hand/wrist region thus appear slightly contradictory. Specifically, the use of the H-EXO reduced FDS, ECR, and FCU muscle activity, yet perceived exertion increased a bit. One likely explanation for this discrepancy is that the duration of the drilling tasks was not long enough to cause significant exertion.

While the RPE score was higher in the Exo condition during the controlled experiment, the score was lower during the longer, observation-based study. Interestingly, RPE reported by participants in the first 10 min of the observation-based study (Study II) also suggested an increase in exertion when using the exoskeleton. However, after the initial 10 min, participants consistently reported lower RPE scores while using the exoskeleton. Although the reduction in RPE at the end of Study II was statistically insignificant (*p-value* = 0.157), the reduction was relevant based on MCID (difference of 1 unit). This finding suggests that in real-world applications, where workers are expected to use the exoskeleton for extended periods in less controlled environments, they may perceive less exertion when using H-EXO.

5.3. Perceived effectiveness and usability

According to Jiang, Hu, Liu, and Lepak (2017) and Nnaji, Jin, and Karakhan (2022), a worker's perception of the role of interventions or practices, and not the actual effect of these practices, directly impacts the worker's behavior (i.e., intention to use H-EXO). Therefore, assessing the perception of users, while subjective, is critical to the successful implementation of interventions.

Participants perceived the H-EXO to be a useful device to support drilling activities. Most (80%) participants indicated that they would use the H-EXO again if given the opportunity. Users also reported a significant reduction in perceived sprain levels when using the H-EXO (36% reduction; *p-value* = 0.016). Previous studies support this finding. For instance, Okpala et al. (2022) reported that workers perceived that exoskeletons could reduce forceful exertions of muscles by 40%. In addition to reporting reduced strain levels, users also found H-EXO to be comfortable and easy to use. This finding suggests that the Ironhand H-EXO is well-designed, making it easy for users to don and doff, and limiting the interference the device could have with work activities. However, it is important to note that while this assertion may be true for drilling activities, it is crucial to evaluate the perceived effectiveness of H-EXO when used to execute additional tasks that may require moving other body parts or those performed in confined spaces.

6. Limitations and future research

One possible limitation of this pilot study is that the small sample size (n = 10) may affect the generalizability of the results. Although the sample size is within the range used in previous exoskeleton studies (Park et al., 2022; Gonsalves et al., 2021; de Vries et al., 2021; Huysamen et al., 2018), future efforts should consider larger sample sizes, especially for observation-based analysis. Furthermore, there is a need for case studies to assess the exoskeleton's performance in real-world applications. Another possible limitation is the 15-minute duration of the simulated drilling task. Given that exosuits are expected to be used for extended periods on job sites (Huysamen et al., 2018), future experiments should consider longer task durations to more accurately measure perceived exertion and trends in muscle activation levels. In addition, future research should consider increasing the length of the session where participants are trained on how to use the exoskeleton for the task. Future research using different vibration tools should log trigger time to quantify the vibration exposure, and measure and graph the vibration of the tools to account for its impact during EMG analysis. Alternatively, non-vibrational tools could be considered for testing the H-Exo. This can help the participants better appreciate and understand the force augmentation pressures produced by the device – before using it during the main task sessions.

7. Conclusions

Within the present study, the research team assessed the effectiveness of an active hand exoskeleton, *Ironhand 2.0*, which was developed in response to the prevalence of hand and wrist injuries in occupational settings. Ten male participants performed a 15-minute simulated drilling task, while three participants completed a concrete grinding task. As an objective measure, electromyography (EMG) signals were monitored for three muscle groups (Flexor Carpi Ulnaris (FCU), Extensor Carpi Radialis (ECR), and Flexor Digitorum Superficialis (FDS)) while the perceived exertion scale (C-Borg scale) was used to subjectively monitor user exertion during the tasks. When considering both the controlled and uncontrolled studies, the H-Exo led to a notable decrease in peak muscle activation across the three target muscles, ranging from 1% to 27%. In the uncontrolled experiment, the H-EXO significantly reduced ECR peak muscle activation. Findings from the present study showed that although using the H-EXO did not significantly influence the perceived exertion levels, users confirmed that H-EXO was a valuable technology, and they would use it if allowed to complete tasks using H-EXO in the future. This study contributes to the existing exoskeleton safety knowledge by characterizing the impact of using an active glove-based exoskeleton for drilling and demolition tasks. Organizations now have objective data that highlights the efficacy of H-EXO and can consider incorporating H-EXO (not just the Ironhand 2.0) during operations. Furthermore, the results of the present study can be utilized in the development of an assessment protocol for improving human-robot (exoskeleton) interaction and optimizing the selection of robotic aid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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