Semi-Active Exoskeletons for Forearm Muscle Strain Reduction

Chukwuma Nnaji, Ph.D.[1]; Abdullahi Ibrahim[2]; and Ifeanyi Okpala, Ph.D.[3]

[1]Assistant Professor, Dept. of Construction Science, Texas A&M Univ., TX.
Email: cnnaji@tamu.edu
[2]Ph.D. Student, Dept. of Construction Science, Texas A&M Univ., TX.
Email: aaibrahim@tamu.edu
[3]Researcher, Dept. of Civil, Construction, and Environmental Engineering, Univ. of Alabama, Tuscaloosa, AL. Email: iuokpala@crimson.ua.edu

ABSTRACT

Forearm- and hand-related musculoskeletal disorders are increasingly becoming a concern in the construction industry. Emerging solutions such as exoskeletons could play a significant role in reducing the risks associated with exerting forearm muscles. Exoskeletons are designed to reduce musculoskeletal disorders (MSDs) in occupational settings by providing support and reducing the strain on the body. However, there are limited studies focused on assessing the impact of exoskeletons designed to target forearm-related disorders. In response to this need, the present study evaluates the effectiveness of a semi-active glove exoskeleton for a simulated drilling task. The evaluation was conducted through a randomized controlled trial with 10 participants, who performed a drilling task with and without the exoskeleton. The participants' muscle activity was measured during both conditions. The results of the study show that the exoskeleton reduced muscle activity in the forearm, including the flexor digitorium superficialis (5.3%), extensor carpi radialis (5.7%), and flexor carpi ulnaris (0.5%). Additionally, the participants perceived the exoskeleton significantly reduced strains in the hand (36%; p-value = 0.016). The findings of this study suggest that forearm exoskeletons have the potential to reduce the risk of MSDs among construction workers during repetitive tasks. Although the reduction in muscle activation was marginal, the results provide impetus for future studies at the intersection of forearm MSD risk reduction and exoskeletons in the construction industry.

INTRODUCTION

Musculoskeletal disorders (MSDs) are common health issues in the construction industry, affecting the musculoskeletal system and resulting in pain, discomfort, and loss of function in the joints, muscles, tendons, and nerves (Barr et al. 2004). Construction workers are particularly vulnerable to MSDs due to the physical demands and repetitive movements required in their work (Barr et al. 2004), and the prevalence of MSDs in construction can lead to significant productivity loss, work absenteeism, and increased healthcare costs (OSHA 2017; BLS 2020). Moreover, MSDs have been connected to opioid overdose and suicide ideation in the construction industry (Dong et al. 2020). About three out of every five workers complained about MSD in the back, upper arm, and/or hand/wrist in 2015, and approximately 30% of workers reported muscular pains in their hands and wrist (European Agency for Safety and Health at Work 2019). Preventing MSDs in the construction industry is crucial for ensuring the health and well-being of workers and improving the overall efficiency and safety of construction operations (So et al. 2022). Therefore, it is essential that practitioners and researchers explore emerging solutions, such as exoskeletons, that could help reduce the occurrence of MSDs.

Exoskeletons are commonly used in industries that require repetitive or physically demanding tasks, such as construction, manufacturing, and logistics. In the construction industry, exoskeletons are increasingly being used to improve worker safety and productivity. The use of exoskeletons can reduce the risk of workplace injuries and fatigue while increasing worker efficiency and performance (Cho et al. 2018). A few studies have assessed the impact of exoskeletons on workers' exertion and endurance when used to perform typical construction tasks (Cho et al. 2018; Bock et al. 2012; Gonsalves et al. 2021). Back and shoulder support exoskeletons have been widely studied, and their effectiveness in reducing MSDs and fatigue has been validated (Cho et al. 2018; Bock et al. 2012; Gonsalves et al. 2021). However, limited research has been conducted on hand-based exoskeletons (H-EXO), despite their potential to reduce the risk of wrist-related disorders and improve worker comfort during repetitive manual tasks.

Therefore, it is incumbent on researcher to investigate the potential impact of exoskeleton on forearm muscle health and develop recommendations for safe use of exoskeletons for tasks that require exerting hand/wrist muscles. The overarching goal of the present study is to generate useful insight that could support the implementation of hand/wrist support exoskeletons in the construction industry. To achieve this goal, the objectives of the present research are to:

1. Identify and characterize features of hand/wrist exoskeletons.
2. Assess the impact of hand/wrist exoskeleton in reducing activation in relevant muscle groups.
3. Evaluate the perceived effectiveness of hand/wrist exoskeleton.

BACKGROUND

According to the US Bureau of Labor and Statistics (BLS), in 2020, there were 77,800 cases of forearm related MSDs that resulted in days away from work in the United States (BLS 2020). About 25% of these cases are linked to workers' hands and wrists (BLS 2020). These injuries are typically caused by overexertion and repetitive tasks such as hammering, wrenching, and manual handling of vibrating tools (Barr et al. 2004). MSDs of the hand and wrist cause the longest absences from work, leading to significant productivity and wage loss. Strategies such as job rotation and engineering controls have been used to eliminate or reduce the impact of MSDs (So et al. 2022). However, there is still significant room for improvement. Exoskeletons, an emerging control mechanism, have shown considerable potential in mitigating risks associated with MSDs in occupational settings (Gonsalves et al. 2021).

Exoskeletons, also referred to as wearable robots, super suits, or exosuits, are robotic devices designed to be attached to human bodies to reduce physical demand by augmenting force actions during specific tasks (Kim et al. 2019). Exoskeletons come in two types: active exoskeletons, which rely on an electric system to provide force output, and passive exoskeletons, which use a hydraulic system to lift, and push required weights (McFarland and Fischer 2019). Exoskeletons can be either lower-body, upper-body, or full-body (McFarland and Fischer 2019). In the construction industry, exoskeletons have been used to help workers carry out manual handling tasks with minimal impact on the body. Researchers have tested several exoskeleton devices, including the FLx ErgoSkeleton, Hilti EXO-01, Ekso Vest, ATOUN Model Y, Levitate Airframe, Laevo, BackX, SuitX MAX, Flex Lift, and FORTIS (Kim et al. 2019). These devices have been tested in various construction tasks, and benefits reported include increased rest times and lift heights, improved competition times, and reduced incidence of MSDs (Cho et al. 2018;

Bock et al. 2012; Gonsalves et al. 2021). Previous studies have reported that exoskeletons can reduce muscle activation during tasks, such as drilling, overhead tasks, and rebar tasks, by up to 62% and improve worker comfort (Huysamen et al. 2018). However, there have been concerns about discomfort in specific regions of the body, such as the chest region.

While various studies have evaluated the effectiveness of back support, lower-limb support, upper body support, and full-body support exoskeletons in reducing muscle activity and discomfort during physical tasks, few studies have focused on the efficacy of hand exoskeletons (H-EXOs). Conducting experimental studies on the effectiveness and safety of H-EXOs can provide valuable information for users and vendors. Therefore, the objective of the current study is to assess the impact of an active hand exoskeleton on user endurance and perception in a controlled and less controlled environment, with the aim of reducing wrist and arm disorders and improving productivity.

METHODS

The present study utilized a two-phase approach to achieve the research goal. First, the researchers conducted a detailed review of existing research to identify and characterize exoskeletons, including H-EXO, that could be used for construction operations. This review involved searching relevant academic and industry databases. Similar to previous studies (Li and Guldenmund, 2018; Okpala et al., 2020; Zhou et al., 2015), Scopus and Web of Science (WoS) databases were searched to identify and select relevant publications. In addition, industry resources and technological websites such as Engineering News Report, such as exoskeletonreport.com (Exoskeleton Report, 2021), Professional Safety Journal, and Dodge Data Analytics (SmartMarket Report, 2021), were utilized to identify existing and commercially available exoskeletons. The authors relied on multiple key word combinations to ensure that the search was exhaustive. Based on the results from the search, the research team selected one H-EXO to pilot-test in controlled conditions.

In the pilot test, ten male participants from The University of Alabama community were involved in a simulated drilling task, and they reported that they did not have any previous joint-related disease, rheumatoid arthritis, upper limb, cardiovascular, or neurological disorders that could affect their ability to stand, move or perform the task. This study used a sample size of 10 participants, which is within the typical range of 8 to 12 participants for human subject studies (Gonsalves et al. 2021; Huysamen et al. 2018). A platform for simulating the drilling task was developed using a rung propped against the wall (Figure 1a). The drilling tool was equipped with a load cell to capture the amount of force exerted by participants (Figure 1b).

The study used a within-subjects design with two conditions, with and without H-EXO, and the order of the conditions was randomized for each participant. The participants visited the laboratory to be familiar with the H-EXO before completing the study in two sessions (one session per experimental condition) with a minimum of two days apart. The study recorded the participants' baseline data, including their height, weight, and body mass index (BMI), using the Omron HBF-514C and Seca Digital Column. The study also collected data on the participants' electromyography (EMG) using the Shimmer3 device, which monitored the physical demand and recorded raw surface EMG signals at 1024 Hz from four muscles. The researchers assessed the maximal voluntary contraction (MVC) for each participant and used it to normalize the EMG when determining peak muscle activity. The study used an Arduino system to control the force and time requirements for each drilling cycle and to provide audio and visual notifications to the participants. The drilling activity lasted for 15 minutes. The participants rated the H-EXO perceived effectiveness using questions designed to elicit useful insight (see Table 1).

(a) (b)

Figure 1. Experimental setup (a) drilling rung (b) drilling tool.

Table 1: Perceived Effectiveness Scale

Q#	Question	Scale	Anchor
Q1	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”
Q2	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”

Next, the research team pre-processed the data before performing statistical analysis by normalizing the EMG data to the MVC and computing the peak values using MATLAB application software (Man et al. 2022; Rose 2011). The data were analyzed in two groups, with and without H-EXO, across the normalized EMG (nEMG) peak muscle activation level, and a similar comparison was made for exertion data using parametric tests such as Paired Samples t-Test for data that met the assumption of normality.

RESULTS AND DISCUSSION

Exoskeleton Identification and Characterization

A detailed review of existing academic and grey literature on exoskeletons revealed several exoskeletons find useful applications within the construction industry, as shown in Table 2. However, only two H-EXOs - Ironhand and Daiya glove – were identified through the review. Unfortunately, Daiya glove is not commercially available for occupational use at the moment. Therefore, the research team acquired the Ironhand exoskeleton for further testing.

Table 2. Identified Exoskeletons Applicable in Construction

S/No	Exoskeleton name	Tasks	Characteristic	Category
1	FLx ErgoSkeleton	Pick and carry	Upper body	Passive
2	Hilti EXO-01	Elevated arms and repetitive arm motions	Upper body	Passive
3	SuitX MAX	Bending, lifting, squatting, elevated arms, and prolonged standing	Full body	Passive
4	Flex Lift	Bending, lifting, and standing	Full body	Passive
5	Ekso Vest	Elevated arms, static arms, and repeated arm motions	Upper body	Passive
6	**Iron Hand**	**Grasping**	**Hand/Wrist**	**Active**
7	FORTIS	Heavy tool and static arms	Semi-full body	Passive
8	ATOUN Model Y	Bending and lifting	Upper body	Active
9	Levitate Airframe	Elevated arms, static arms, and repeated arm motions	Upper body	Passive
10	Laevo	Bending, lifting, and reaching	Upper body	Passive
11	backX	Bending, lifting, reaching, and stooping	Upper body	Passive

Muscle Activation Assessment

Table 3 presents a summary of the Paired T-tests for the EMG data across the different exoskeleton conditions. The Paired T-test was used because all cases met the requirement for a parametric-based analysis, and all p-values have a confidence level > 0.05. Figure 2 shows the mean peak %MVC of muscular effort for the exoskeleton conditions during the drilling task. The error bars indicate the standard deviation of the mean peak %MVC as a measure of variations across all participants. The study found that the use of H-EXO resulted in a 5.34% reduction in FDS muscle activation, a 5.74% reduction in ECR mean peak %MVC, and a 0.48% reduction in FCU mean peak %MVC. However, none of these reductions were statistically significant (FDS p-value = 0.252; ECR p-value = 0.206; FCU p-value = 0.892). Although the activation level of all three muscle groups reduced in the exoskeleton condition, this reduction was not statistically significant. Previous studies with similar experiment duration (less than 20 minutes) showed similar reduction percentage for simulated activities (Cho et al. 2018; Gonsalves et al. 2021; Huysamen et al. 2018;). The marginal muscle activation reduction could be a result of the duration of the simulated drilling task. However, some studies suggest that using EXOs increases biomechanical loads during drilling tasks at waist level, possibly due to the weight and restrictions of the device (Weston et al. 2018; Rashedi et al. 2014). Therefore, future research should test this technology for an extended period.

Perceived Effectiveness

The perception of users towards interventions or practices, rather than their actual effectiveness, has a direct impact on their behavior and intention to use them (Jiang et al. 2017; Nnaji et al. (2022). Therefore, evaluating users' subjective perception is critical to successfully implementing interventions. In Figure 3, it is illustrated that the use of H-EXO resulted in a 36% reduction in perceived sprain by the participants, and this decrease was statistically significant (p-value = 0.016). Users reported a significant reduction in perceived strain levels while using the H-EXO, which is consistent with previous studies that have shown exoskeletons can reduce muscle exertion (Kim et al. 2021; Moyon et al. 2019; Okpala et al. 2022). It is important to note that these findings only apply to drilling activities, and further evaluation is needed to assess the perceived effectiveness of H-EXO for tasks that involve moving other body parts or working in confined spaces.

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

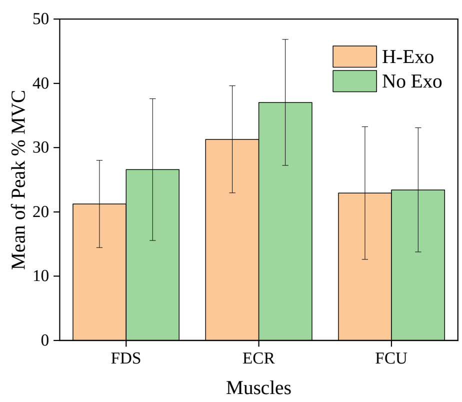

Figure 2. Mean of peak %MVC across the three muscle groups: with and without the H-EXO

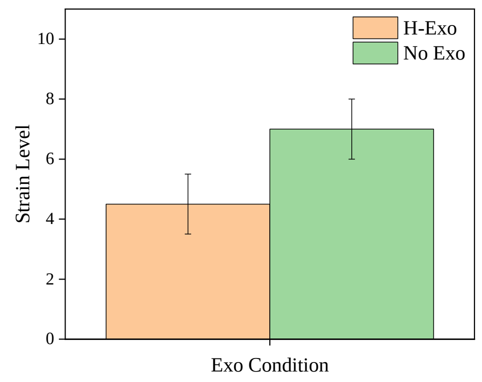

Figure 3. Participants' perception of H-EXO effectiveness

CONCLUSION

Musculoskeletal disorders (MSDs) are a growing concern in the construction industry, and exoskeletons offer a promising solution to reduce their risk. This study evaluated the effectiveness of a semi-active glove exoskeleton for a simulated drilling task and found that it reduced muscle activity in the forearm, including the Flexor Digitorium Superficialis (5.34% reduction), Extensor Carpi Radialis (5.74% reduction), and Flexor Carpi Ulnaris (0.48% reduction). It also reduced perceived exertion (36%) during the task, and participants perceived a reduction in hand strains. Although the reductions in muscle activation were marginal, the study provides impetus for future studies at the intersection of forearm MSD risk reduction and exoskeletons in the construction industry. The findings suggest that exoskeletons have the potential to reduce the risk of MSDs among construction workers during repetitive tasks, and future studies should explore the use of exoskeletons in larger samples and with more complex tasks. One of the limitations of this study is that the sample size (n = 10) may affect the generalizability of the results. Future research should consider larger and more diverse populations to validate findings.

ACKNOWLEDGEMENT

This work was supported by the Pilot/Small Project Research Training Grant #T42OH008436 from the National Institute for Occupational Safety and Health (NIOSH) and support from Bioservo. Bioservo loaned the exoskeleton and provided information that contributed to the design of the study. However, they were not involved in the data analysis/interpretation. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH or Bioservo.

REFERENCES

Barr, A. E., Barbe, M. F., and Clark, B. D. (2004). Work-related musculoskeletal disorders of the hand and wrist: epidemiology, pathophysiology, and sensorimotor changes. *Journal of orthopaedic & sports physical therapy*, 34(10), 610-627.

BLS (Bureau of Labor Statistics). (2020). Injuries, Illnesses, and Fatalities. IIF Home. Available via https://www.bls.gov/iif/home.htm [Accessed: February, 2023].

Bock, T., Linner, T., and Ikeda, W. (2012). Exoskeleton and humanoid robotic technology in construction and built environment. *The future of humanoid robots-research and applications*, 111-144.

Cho, Y. K., Kim, K., Ma, S., and Ueda, J. (2018, April). A robotic wearable exoskeleton for construction worker's safety and health. In *Construction Research Congress 2018* (pp. 19-28).

Dong, X. S., Brooks, R. D., and Brown, S. (2020). Musculoskeletal disorders and prescription opioid use among US construction workers. *Journal of Occupational and Environmental Medicine*, 62(11), 973-979.

European Agency for Safety and Health at Work. (2019). Work-related musculoskeletal disorders: prevalence, costs and demographics in the EU. Available via https://osha.europa.eu/en/publications/msds-facts-and-figures-overview-prevalence-costs-and-demographics-msds-europe [Accessed: February, 2023].

Gonsalves, N. J., Ogunseiju, O. O., Akanmu, A. A., and Nnaji, C. A. (2021). Assessment of a passive wearable robot for reducing low back disorders during rebar work. *J. Inf. Technol. Constr.*, 26, 936-952.

Huysamen, K., Bosch, T., de Looze, M., Stadler, K. S., Graf, E., and O'Sullivan, L. W. (2018). Evaluation of a passive exoskeleton for static upper limb activities. *Applied ergonomics*, 70, 148-155.

Jiang, K., Hu, J. I. A., Liu, S., and Lepak, D. P. (2017). Understanding employees' perceptions of human resource practices: Effects of demographic dissimilarity to managers and coworkers. *Human Resource Management*, 56(1), 69-91.

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D. M., and Nussbaum, M. A. (2019). Potential of exoskeleton technologies to enhance safety, health, and performance in construction: Industry perspectives and future research directions. *IISE Transactions on Occupational Ergonomics and Human Factors*, 7(3-4), 185-191.

Kim, S., Nussbaum, M. A., Smets, M., and Ranganathan, S. (2021). Effects of an arm-support exoskeleton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly. *American Journal of Industrial Medicine*, 64(11), 905-914.

Man, S. S., Nordin, M., Cheng, M. C., Fan, S. M., Lee, S. Y., Wong, W. S., and So, B. C. L. (2022). Effects of passive exoskeleton on trunk and gluteal muscle activity, spinal and hip kinematics and perceived exertion for physiotherapists in a simulated chair transfer task: A feasibility study. *International Journal of Industrial Ergonomics*, 90, 103323.

Moyon, A., Petiot, J. F., and Poirson, E. (2019, October). Investigating the effects of passive exoskeletons and familiarization protocols on arms-elevated tasks. In *Human Factors and Ergonomics Society Europe Chapter 2019 Annual Conference*.

Nnaji, C., Okpala, I., Gambatese, J., and Jin, Z. (2023). Controlling safety and health challenges intrinsic in exoskeleton use in construction. *Safety science*, 157, 105943.

Okpala, I., Nnaji, C., and Karakhan, A. (2020). "Utilizing emerging technologies for construction safety risk mitigation" *ASCE PPSDC*.

Okpala, I., Nnaji, C., Ogunseiju, O., and Akanmu, A. (2022). "Assessing the Role of Wearable Robotics in the Construction Industry: Potential Safety Benefits, Opportunities, and Implementation Barriers." *Automation and Robotics in the Architecture, Engineering, and Construction Industry*. Springer, Cham.

OSHA (Occupational Safety and Health Administration). (2017). Estimated Costs of Occupational Injuries and Illnesses and Estimated Impact on a Company's Profitability Worksheet, Available via https://www.osha.gov/safetypays/estimator, [Accessed: February, 2023].

Rashedi, E., Kim, S., Nussbaum, M. A., and Agnew, M. J. (2014). Ergonomic evaluation of a wearable assistive device for overhead work. *Ergonomics*, 57(12), 1864-1874.

Rose, W. (2011). Electromyogram analysis. *Online course material*. The University of Delaware. Retrieved July 5, 2016.

So, B. C. L., Cheung, H. H., Liu, S. L., Tang, C. I., Tsoi, T. Y., and Wu, C. H. (2020). The effects of a passive exoskeleton on trunk muscle activity and perceived exertion for experienced auxiliary medical service providers in cardiopulmonary resuscitation chest compression. *International Journal of Industrial Ergonomics*, 76, 102906.

Weston, E. B., Alizadeh, M., Hani, H., Knapik, G. G., Souchereau, R. A., and Marras, W. S. (2022). A physiological and biomechanical investigation of three passive upper-extremity exoskeletons during simulated overhead work. *Ergonomics*, 65(1), 105-117.

COMPUTING IN CIVIL ENGINEERING 2023

RESILIENCE, SAFETY, AND SUSTAINABILITY

SELECTED PAPERS FROM THE ASCE INTERNATIONAL CONFERENCE ON COMPUTING IN CIVIL ENGINEERING 2023

June 25–28, 2023
Corvallis, Oregon

SPONSORED BY
Computing Division of the
American Society of Civil Engineers

EDITED BY
Yelda Turkan, Ph.D.
Joseph Louis, Ph.D.
Fernanda Leite, Ph.D., P.E.
Semiha Ergan, Ph.D.

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

Published by the American Society of Civil Engineers

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia, 20191-4382
www.asce.org/publications | ascelibrary.org

Errata: **Errata, if any, can be found at https://doi.org/10.1061/9780784485248**

ISBN 978-0-7844-8524-8 (PDF)
Manufactured in the United States of America.