Evaluating Occupational Exoskeleton Performance in Construction: Towards Standard Testing for the Construction Industry

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Abstract. Occupational exoskeletons (OEs) are wearable devices designed to assist and enable human motion for workers in industries ranging from manufacturing to construction. As with workers in other industries, the opportunity provided by OEs for construction workers is to reduce injury rates for the benefit of worker health and productivity. Potential risks also exist, including discomfort, compromised balance, snags, and increased stress in the unassisted regions of the body. The challenge comes in finding effective OEs for specific construction trades working on specific project types. To meet this challenge, this paper aims to develop a standardized OE efficacy evaluation framework for passive back-support exoskeletons (BSEs) for rebar workers. In-lab efficacy evaluation can lead to in-field effectiveness evaluation giving evidence for practical OE regulations, guidelines, and ergonomic risk indices to be used by the construction industry. The evaluation framework will include the assessment of a BSE's effects on safety, productivity, and acceptability, including a tool for estimating an OE's return on investment. The framework will allow for sensitivity analyses for human attributes, including gender, age, and workers with prior injuries. It is hoped that this work will provide an integral step towards large-scale OE adoption for the construction trades.

Keywords: Occupational Exoskeleton, Construction, Standard Testing

1 Introduction

Construction workers experience large and repetitive forces in the musculoskeletal system of the body, especially in the muscles, tendons, and ligaments of the back and shoulders [1]. The work-related musculoskeletal disorders (WMSDs) that can develop from these forces include lower back pain, herniated discs, rotator cuff injuries, and shoulder impingement [2]. Steel reinforcement bar (rebar) workers are construction workers that fabricate cages of rebar used in reinforced concrete construction. To investigate the risk factors for low back disorders among rebar workers, Antwi-Afari et al. (2018) researched the effects of weight and posture on muscle activity and spinal kinematics, finding that the risk factors of heavier loads and stoop lifting, compared to squat lifting, increase lower back pain and therefore the risk of WMSDs [3]. A survey of approximately 1,000 rebar workers in Massachusetts found that more than half had experienced back injuries during their career, and 14% reported doctor diagnosed ruptured back discs [4].

Since the mid-2010s, occupational exoskeletons (OEs) have been developed as ergonomic tools for workers in manufacturing, particularly the automotive industry, e.g., [5–8]. The purpose of an OE, as opposed to a medical or military exoskeleton, is to reduce the rate of WMSDs in an industry. Passive back-support exoskeletons (BSEs) and passive arm-support exoskeletons (ASEs) are the most common OEs available on the market and are intended to function as ergonomic tools by providing assistive torques about the hip or shoulder joints [9].

There is a limited number of published studies that investigate the longitudinal effects of OEs, including Kim et al. (2021) (18 months) [5], Smets (2019) (3 months) [8], and Ferreira et al. (2020) (4 weeks) [6]. However, there are no longitudinal studies in the literature measuring WMSD rates, and therefore no evidence of OEs reducing WMSD rates in any industry. If this evidence is seen, OEs also have the potential to indirectly increase the productivity of a worker by reducing days away from work cases (DAWCs) due to WMSDs. However, potential risks also exist, including compromised balance, snags, discomfort, increased force in the unassisted regions of the body, and what these undesired effects would imply for long-term health effects [10].

The challenge for the research community is to create practical and evidence-based guidelines for the construction industry that recommend the use of a specific set of OEs for workers from a given construction trade, involved in a certain type of construction project. Acquiring evidence for these guidelines implies large longitudinal effectiveness studies measuring WMSD rates. The value provided by short-term laboratory efficacy studies is in identifying the potential of OEs to be effective in the field before investing in large longitudinal studies. However, the potential effectiveness of OEs cannot be compared if the efficacy evaluation methods are not standardized.

The proposed method involves developing a standardized test course aimed at a specific construction trade working on a specific type of construction project. Section 3 describes a test course to evaluate the performance of passive BSEs for rebar workers. The chosen project type for the test course is the assembly of rebar cages for horizontal reinforced concrete construction, as in concrete bridge deck construction and concrete slab construction in buildings. The goal in designing a test course is to create a standard evaluation method, verified by short-term field results, for comparing OE performance, as an integral step towards large scale OE adoption in the construction industry.

2 Literature Review

2.1 Evaluating OE Performance for Construction

In recent years, the potential application of OEs for the construction industry has gained interest in the research community. Zhu et al. (2021) created guidelines for implementing OEs in the construction industry by recommending exoskeleton types for specific construction trades [10], informed by WMSD statistics from the United States.

Many efficacy studies, e.g. [11], include general tasks that are applicable to the construction trades. In addition to these studies, a range of literature exists that evaluate OEs for a specific construction trade. A non-comprehensive list of this previous work is shown in Table 1. These studies evaluated the performance of OEs based on increased worker safety, worker acceptance of the OE, and effects on worker productivity. These objective and subjective measures of performance are referred to as efficacy evaluation metrics [12].

Measures of safety include the following: (1) Muscle activity, which is measured by surface electromyography sensors (sEMG). (2) Biomechanical simulation can be used to estimate all the forces in the musculoskeletal system. (3) Perceived work intensity is a construct that serves as an indicator for developing WMSDs. (4) A measure specific to BSEs is lower back disorder (LBD) risk, which is defined as the probability of a job being a high-risk job [13]. (5) Motion capture of joint angles, for example, trunk flexion about the hip joints, and body posture can be used to measure an OE's effect on a muscle group's range-of-motion, and also for estimating safe loads for lifting using the NIOSH lifting index. [14]

Measures of acceptability include: (1) Discomfort, which has been evaluated using the Borg CR 10 scale [15]; the Cornell Musculoskeletal Questionnaire (CMDQ), as in [5]; custom subjective surveys using a Likert scale (from "Strongly Disagree" to "Strongly Agree"), as in [6]; and local perceived pressure (LPP) [16]. (2) Usability, the subjective measure of a product's ease-of-use, can be measured using the system usability scale (SUS) [17]. Custom surveys have also been used to evaluate usability, as in [6]. Productivity can be measured with task completion time. This can be paired with measuring quality, which is task dependent. For the simulated welding task in [18], the quality the of a participants simulated weld seam was measure along with the time to make the weld.

Safety, acceptability, and productivity are interrelated, and some efficacy evaluation metrics may belong to more than one of these three categories. For example, discomfort, as a measure of an OEs usability, may also serve as an indicator of long-term negative health effects from the OE.

In addition to the laboratory evaluation papers in Table 1, surveys and other measures of opinion have been conducted to receive expert and industry opinions on the adoption of OEs into the construction industry, including [19–22], the last being specific to bricklaying, drywall installation, and concrete grinding. These industry surveys note return on investment (ROI) as essential for OE adoption in the construction industry. ROI may therefore be considered an additional measure of acceptability.

After developing OEs as effective ergonomic tools, the end goal of the OE research community is large-scale OE adoption. Crea et al. (2021) created a road map for implementing OEs by defining three eras of OE adoption [9]. (1) The laboratory assessment era is current day and must result in updated standards from regulating bodies like the American Society for Testing and Materials (ASTM) International, and the International Organization for Standardization (ISO), as well as ergonomic risk indices from the National Institute for Occupational Safety and Health (NIOSH) and other occupational health and safety organizations.

Table 1. Examples of explored areas of OE efficacy evaluation for construction trades.

Author (Year) [Reference]	Targeted Trades in Construction	OE Type	Measurements	
			Objective	Subjective
Antwi-Afari et al. (2021) [23]	General construction tasks	BSEs	Muscle activity *(sEMG)*	Discomfort *(Borg CR 10)*, Musculoskeletal pressure *(LPP)*, and Usability *(SUS)*
Ogunseiju et al. (2021) [24]	Flooring installers	BSEs		Discomfort *(Custom Likert survey and Borg CR 10)*, Usability *(Custom Likert survey)*
Gonsalves et al. (2021) [25], and [26, 27]*	Rebar workers	BSEs	Muscle activity *(sEMG)*, Quality *(task completion time)*, Trunk flexion *(IMU)*	Discomfort *(Borg CR 10)*, Ease of Use *(Custom survey)*, Ease of Learning *(Custom survey)*, and Comfort *(Custom survey)*
Kopp et al. (2022) [18]	Welders and prefabricated timber construction workers	ASEs	Muscle activity *(sEMG)*, Cardiovascular load *(Heart rate and impedance cardiography)*, Quality *(task completion time and weld seam quality)*	Perceived exertion *(Borg CR 10)*, Discomfort *(Borg CR 10 and Body Chart)*, and Usability *(SUS)*

*Conference papers on BSEs for rebar workers which are related to [25].

(2) The following field assessment era is currently in its infancy but must eventually validate the findings from laboratory evaluation with data from large and long-term studies. (3) Coming out of the first two eras, the knowledge-based large-scale adoption era will follow.

De Looze et al. (2022) proposed a three-stage approach for OE evaluation which intended to allow for the complexity of studies to increase naturally over time [28]: (1) field observations to identify potential exo use cases and associated tasks, (2) a controlled experiment to compare a task with and without an OE, and (3) a field test to verify the controlled lab results.

2.2 Standardized Evaluation Methods

Past research has investigated standardizing OE evaluation methods. In 2019, the first standards for OE performance on occupational tasks were created by ASTM International, under the name of ASTM F48 [29]. Also in 2019, Bostelman et al. developed one of the first standard test methods for material handling with OEs [30], which was updated in 2022 [31].

De Bock et al. (2022) reviewed 139 studies to investigate OE evaluation methods [32]. Their framework provided recommendations on task design and study design, including the need for randomization and blind experimental conditions, as well as calling for study subjects to be experienced professionals.

Hoffmann et al. (2022) reviewed 74 papers on efficacy evaluation methodologies for OEs and discovered that the methods of the reviewed studies were not consistent nor comprehensive [33]. The authors argued that without consistent and comprehensive methods, researchers cannot iteratively optimize OE designs [33]. An earlier review by Bär et al. (2021) found that most studies lacked the evaluation of non-targeted body areas [34]. Although they found evidence that OEs reduce stress and strain in the intended target areas, they argued that without consistent and comprehensive evaluation methods, the effect on workers' health will be unknown.

Golabchi et al. (2022) reviewed 42 OE evaluation studies and presented a framework for the implementation and assessments of OEs, emphasizing the importance of posture and target tasks [12]. The framework rested on three pillars: (1) subjective and objective efficacy evaluation metrics, (2) the target task in question, and (3) the worker's body posture during the target task.

The "Exoworkathlon" proposed by Kopp et al. (2022) provided a detailed set of test courses relevant to manufacturing, and warehousing, as well as test courses specific to the construction trades, namely the tasks of welding, overhead drilling, and timber beam assembly [18].

The goal of a standard test course, as proposed by Kopp et al. (2022), is to evaluate OE efficacy which can serve as evidence for potential OE effectiveness in the field [18]. However, if the controlled laboratory conditions do not accurately represent the field conditions, efficacy may not be reliable evidence for effectiveness. De Bock et al. (2021) tested two shoulder exoskeletons in laboratory conditions, consisting of isolated movements, and field conditions where workers in a distribution center moved loads between a warehouse shelf and a trailer [35]. In the laboratory conditions, the ASE, "ShoulderX" was found to have the best performance, where performance is defined as reduced muscle activation in the shoulders. In the field conditions, the ASE, "Skelex" was found to have the best performance. The participants' shoulders were seen to be more abducted in the field conditions due to the size of the objects handled. The researchers noted this as a variable that was not represented in the isolated movements of the laboratory conditions, possibly contributing to the discrepancy in OE performance [35]. Considering these findings, short-term field experiments can be used to verify and improve laboratory tests.

3 Standardized Test Course for Rebar Workers

From the findings of the literature review, a standard test course for OE evaluation should be designed based on WMSD statistics, observations of construction sites, and the expertise of construction trade professionals, as described by [10] and [28]. In addition, the results of a standard efficacy evaluation method should be verified by their similarity to the results seen in an associated short-term field study, as in [35].

The goal in designing the standard test course is for it to be representative of the work conditions of rebar workers as well as practical and inexpensive to deploy. A standard test course for rebar workers assembling horizontal reinforcement will include the most common and impactful tasks required by the trade, and the associated co-occurring tasks. These tasks will simulate the activities on a reinforced concrete bridge deck or reinforced concrete slab construction project that most frequently expose rebar workers to the physical risk factors associated with lower back WMSDs. These risk factors are namely: exerting forces, non-neutral postures, and sustained and repeated effort. These risk factors are present in the tasks of lifting rebars, navigating over an existing rebar cage while carrying a load of rebars, placing rebars, and tying rebar intersections [3, 36]. These activities are the main tasks of the test course.

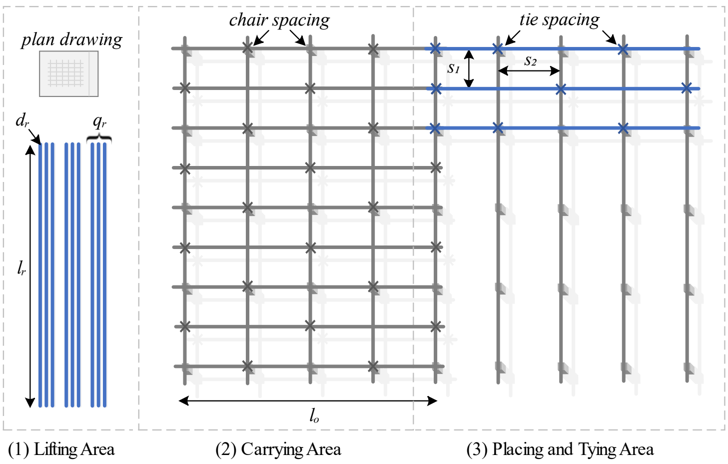

Fig. 1. The plan view of the layout for the proposed standardized test course for rebar workers assembling horizontal rebar.

Side tasks occur during or in between the main tasks and include cutting rebar tie wire to length, ensuring the specified bar spacing using a tape measure, and reading engineering drawings from a stooped posture.

A before-after intervention study design will be used. This study design is selected over a stronger randomized controlled trial design because large sample sizes are typically not available at this stage of OE evaluation research. The test course will be designed for two participants to complete simultaneously, allowing for each of the two participants to wear a different passive BSE, as done by Kopp et al. (2022) [18]. One trial, with or without a BSE, will consist of four rounds of lifting, carrying, placing, and tying rebar.

The test will evaluate the performance of a passive BSE based on its effects on participant safety, participant acceptance of the BSE, and participant productivity. To holistically assess the performance of a BSE, a set of efficacy evaluation metrics will be selected from the range of measures described in Section 2.1. The selection of these measures in future work will be based on evidence from the literature on the most effective efficacy evaluation metrics in past OE efficacy studies.

Fig. 1 shows the layout of the proposed standardized test course which is divided into three areas: (1) the lifting area, a stockpile of rebars, (2) the carrying area, an existing rebar cage to simulate walking over the rebar cages of a slab or bridge deck while carrying a load of rebars, and (3) the placing and tying area, where the carried rebars are placed by the two participants in unison and tied from a stooped posture.

Blue lines depict rebars that must be lifted, carried, and placed. Blue crosses depict intersections to be tied. Solid grey lines depict existing rebars and grey crosses depict tie locations. The rebar mesh will be elevated and supported by plastic or concrete rebar chairs. For a complete test course design, the following variables from the figure must be defined: l_r (length of rebar), d_r (nominal size of rebar), l_o (length of carrying area), $s_1 \times s_2$ (spacing of the existing and placed rebars), *tie spacing*, *chair spacing*, and q_r (the quantity of bars carried in one load).

The realistic cost and size of the test course will be approved by experts in future work by defining the number of bars and other materials required. Tentative recommendations for the test course size, rebar size, length and quantity are as follows: The recommended test course layout is tentatively 4 by 8 meters. The lifting area, carrying area, and placing area are 4 by 1, 4 by 4, and 4 by 3 meters, respectively. The recommended size and quantity of the rebars are tentatively three 4-meter-long #5 bars in the US system (roughly equivalent to 15M bars in the Canadian system, and 16,0 bars in the European system). At 1.556 kg/m, the total load is 18.6 kg, or 9.3 kg per participant. The weight of the load is based on the NIOSH lifting equation, which estimates a maximum safe load of 12 kg per participant, given the postures and repetitions inherent in the test course conditions [14].

The test course allows for variation in the human attributes of the participants. The data analysis will allow for sensitivity analyses for human attributes, including gender, age, and workers with prior injuries. The participants may be men or women, may be of any age typical of rebar workers, and may have prior injuries, including workers in return-to-work programs. As noted in [35], the participants should be able to perform the tasks realistically. The proposed future laboratory study will include students from a trade school learning to assemble rebar cages for reinforced concrete construction. The skill of trade school students can be representative of junior rebar workers.

The sample of participants will be at least gender representative, as an opportunity provided by OEs is equipping women to work in trades where workforces have historically had a low percentage of female workers. For the four rounds of one trial, Participant 1 (P1) will walk in front of Participant 2 (P2) for the first and third rounds, and P2 will walk in front of P1 for the second and fourth rounds. This will ensure that both participants walk roughly equal distances while carrying the load.

Realistic equipment must be used in the test course to assess BSEs' compatibility with the equipment. During the control trials, each participant will be equipped with a tool belt containing tying pliers, cutters, a tie wire reel, and a tape measure for measuring spacing. The participants will wear long sleeve shirts and long pants, safety toe boots, a safety vest, a hard hat, and rubber palm-coated cotton gloves. During the intervention trials, the participants will be equipped with a passive BSE, in addition to the equipment described above.

Following the laboratory experiment, a field experiment will be conducted to verify if the standard test is representative of the real world. The field experiment will be conducted on a reinforced concrete bridge or building project. The workers will perform the same tasks specified in the laboratory experiment with and without a BSE, and the same efficacy evaluation metrics will be used to measure BSE performance. The human attributes of age, gender, experience level, and prior injuries may be considered.

The return on investment (ROI) of an OE is essential for OE adoption in the construction industry [19–22]. With OE performance defined as its effects on safety, acceptability, and productivity, ROI can be included in the evaluation of OE performance as a measure of acceptability. The standard test will therefore include a tool for estimating the ROI of a given BSE on a given project type. This will be based on the potential costs and savings associated with a construction company adopting BSEs. The costs will be estimated by considering initial investments in OEs, OE maintenance and storage, reduced worker productivity from adapting to work with OEs, or readapting to work without OEs, training, and long-term health effects. The savings will be estimated by considering the effects of reduced days away from work cases (DAWCs), reduced worker fatigue, and reduced employee attrition.

4 Limitations and Future Work

The proposed method has limitations that must be addressed in future work. Rebar workers are tasked with placing both horizontal and vertical rebars on many types of construction projects and a limitation of the test is that it does not consider vertical rebar installation. The efficacy evaluation metrics for measuring safety, acceptability, and productivity of the OE in the standard test must be chosen, and this selection should be supported by evidence from the literature to ensure a comprehensive evaluation of OE performance. Having trade school student participants has some limitations for the investigation of human factors. Trade school students are less likely to have prior injuries compared to journeyman and senior rebar workers, and the participant sample will be biased towards a younger average age. A limitation of the experiment design is that it does not consider seasonal worker equipment, for example, bulky cold-weather gear. To finalize the experiment design, specific values must be declared for the variables of the test course to determine the cost, ensuring that the standard test should not be prohibitively expensive. Future work involves conducting field observations, conducting the standardized laboratory test course, conducting the associated short-term field experiment, and developing an ROI tool for BSE in rebar construction.

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References

[1] W. Umer, M. F. Antwi-Afari, H. Li, G. P. Y. Szeto, and A. Y. L. Wong, "The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis," *Int. Arch. Occup. Environ. Health*, vol. 91, no. 2, pp. 125–144, Feb. 2018, doi: 10.1007/s00420-017-1273-4.

[2] X. Wang, X. S. Dong, S. D. Choi, and J. Dement, "Work-related musculoskeletal disorders among construction workers in the United States from 1992 to 2014," *Occup. Environ. Med.*, vol. 74, no. 5, pp. 374–380, 2017.

[3] M. F. Antwi-Afari, H. Li, D. J. Edwards, E. A. Pärn, O.-M. De-Graft, J. Seo, *et al.*, "Identification of potential biomechanical risk factors for low back disorders during repetitive rebar lifting," *Constr. Innov.*, vol. 18, no. 2, 2018, doi: 10.1108/CI-05-2017-0048.

[4] M. S. Forde, L. Punnett, and D. H. Wegman, "Prevalence of Musculoskeletal Disorders in Union Ironworkers," *J. Occup. Environ. Hyg.*, vol. 2, no. 4, pp. 203–212, Apr. 2005, doi: 10.1080/15459620590929635.

[5] S. Kim, M. A. Nussbaum, M. Smets, and S. Ranganathan, "Effects of an arm-support exoskeleton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly," *Am. J. Ind. Med.*, vol. 64, no. 11, pp. 905–914, 2021, doi: 10.1002/ajim.23282.

[6] G. Ferreira, J. Gaspar, C. Fujão, and I. L. Nunes, "Piloting the Use of an Upper Limb Passive Exoskeleton in Automotive Industry: Assessing User Acceptance and Intention of Use," In *Advances in Human Factors and Systems Interaction*, Cham, 2020, pp. 342–349, doi: 10.1007/978-3-030-51369-6_46.

[7] 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. Ergon. Hum. Factors*, vol. 7, no. 3–4, pp. 213–221, Oct. 2019, doi: 10.1080/24725838.2019.1573770.

[8] M. Smets, "A Field Evaluation of Arm-Support Exoskeletons for Overhead Work Applications in Automotive Assembly," *IISE Trans. Occup. Ergon. Hum. Factors*, vol. 7, no. 3–4, pp. 192–198, Oct. 2019, doi: 10.1080/24725838.2018.1563010.

[9] S. Crea, P. Beckerle, M. D. Looze, K. D. Pauw, L. Grazi, T. Kermavnar, *et al.*, "Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces," *Wearable Technol.*, vol. 2, 2021, doi: 10.1017/wtc.2021.11.

[10] Z. Zhu, A. Dutta, and F. Dai, "Exoskeletons for manual material handling – A review and implication for construction applications," *Autom. Constr.*, vol. 122, Feb. 2021, doi: 10.1016/j.autcon.2020.103493.

[11] M. M. Alemi, S. Madinei, S. Kim, D. Srinivasan, and M. A. Nussbaum, "Effects of Two Passive Back-Support Exoskeletons on Muscle Activity, Energy Expenditure, and Subjective Assessments During Repetitive Lifting," *Hum. Factors*, vol. 62, no. 3, pp. 458–474, May 2020, doi: 10.1177/0018720819897669.

[12] A. Golabchi, A. Chao, and M. Tavakoli, "A Systematic Review of Industrial Exoskeletons for Injury Prevention: Efficacy Evaluation Metrics, Target Tasks, and Supported Body Postures," *Sensors*, vol. 22, Apr. 2022, doi: 10.3390/s22072714.

[13] W. S. Marras, W. G. Allread, D. L. Burr, and F. A. Fathallah, "Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks," *Ergonomics*, vol. 43, no. 11, pp. 1866–1886, Nov. 2000, doi: 10.1080/00140130050174518.

[14] T. R. WATERS, V. PUTZ-ANDERSON, A. GARG, and L. J. FINE, "Revised NIOSH equation for the design and evaluation of manual lifting tasks," *Ergonomics*, vol. 36, no. 7, pp. 749–776, Jul. 1993, doi: 10.1080/00140139308967940.

[15] G. Borg, *Borg's Perceived exertion and pain scales*. Champaign, IL: Human Kinetics, 1998.

[16] M. P. Van der Grinten and P. Smitt, "Development of a practical method for measuring body part discomfort.," *Adv. Ind. Ergon. Saf.*, vol. 4, no. 635, pp. 311–18, 1992.

[17] A. Bangor, P. T. Kortum, and J. T. Miller, "An Empirical Evaluation of the System Usability Scale," *Int. J. Human–Computer Interact.*, vol. 24, no. 6, pp. 574–594, Jul. 2008, doi: 10.1080/10447310802205776.

[18] V. Kopp, M. Holl, M. Schalk, U. Daub, E. Bances, B. García, *et al.*, "Exoworkathlon: A prospective study approach for the evaluation of industrial exoskeletons," *Wearable Technol.*, vol. 3, ed 2022, doi: 10.1017/wtc.2022.17.

[19] S. Kim, A. Moore, D. Srinivasan, A. Akanmu, A. Barr, C. Harris-Adamson, *et al.*, "Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions," *IISE Trans. Occup. Ergon. Hum. Factors*, vol. 7, no. 3–4, pp. 185–191, Oct. 2019, doi: 10.1080/24725838.2018.1561557.

[20] D. Mahmud, S. T. Bennett, Z. Zhu, P. G. Adamczyk, M. Wehner, D. Veeramani, *et al.*, "Identifying Facilitators, Barriers, and Potential Solutions of Adopting Exoskeletons and Exosuits in Construction Workplaces," *Sensors*, vol. 22, no. 24, Dec. 2022, doi: 10.3390/s22249987.

[21] N. Gonsalves, A. Akanmu, X. Gao, P. Agee, and A. Shojaei, "Industry Perception of the Suitability of Wearable Robot for Construction Work," *J. Constr. Eng. Manag.*, vol. 149, no. 5, May 2023, doi: 10.1061/JCEMD4.COENG-12762.

[22] C. Nnaji, I. Okpala, J. Gambatese, and Z. Jin, “Controlling safety and health challenges intrinsic in exoskeleton use in construction,” *Saf. Sci.*, vol. 157, Jan. 2023, doi: 10.1016/j.ssci.2022.105943.

[23] M. F. Antwi-Afari, H. Li, S. Anwer, D. Li, Y. Yu, H.-Y. Mi, *et al.*, “Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers,” *Saf. Sci.*, vol. 142, Oct. 2021, doi: 10.1016/j.ssci.2021.105382.

[24] O. Ogunseiju, N. Gonsalves, A. Akanmu, and C. Nnaji, “Subjective Evaluation of Passive Back-Support Exoskeleton for Flooring Work,” In *EPiC Series in Built Environment*, Jun. 2021, vol. 2, pp. 10–17, doi: 10.29007/3jk9.

[25] N. Gonsalves, O. R. Ogunseiju, O. Ogunseiju, A. Akanmu, and C. Nnaji, “Assessment of a passive wearable robot for reducing low back disorders during rebar work,” *J. Inf. Technol. Constr.*, vol. 26, pp. 936–952, Nov. 2021, doi: 10.36680/j.itcon.2021.050.

[26] N. Gonsalves, O. Ogunseiju, A. Akanmu, and C. Nnaji, “Influence of a Back-Support Exoskeleton on Physical Demands of Rebar Work,” In *EPiC Series in Built Environment*, Jun. 2021, vol. 2, pp. 1–9, doi: 10.29007/5rg3.

[27] N. J. Gonsalves, M. Khalid, A. Akinniyi, O. Ogunseiju, and A. Akanmu, “Subjective Evaluation of Passive Back-Support Wearable Robot for Simulated Rebar Work,” In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, Waterloo, Canada, 2022, vol. 39, pp. 430–436.

[28] M. de Looze, A. de Vries, F. Krause, and S. Baltrusch, “Three-Stage Evaluation for Defining the Potential of an Industrial Exoskeleton in a Specific Job,” In *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)*, Cham, 2022, pp. 235–241, doi: 10.1007/978-3-030-74614-8_28.

[29] B. D. Lowe, W. G. Billotte, and D. R. Peterson, “ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits,” *IISE Trans. Occup. Ergon. Hum. Factors*, vol. 7, no. 3–4, pp. 230–236, Oct. 2019, doi: 10.1080/24725838.2019.1579769.

[30] R. Bostelman, Y.-S. Li-Baboud, A. Virts, S. Yoon, and M. Shah, “Towards Standard Exoskeleton Test Methods for Load Handling,” In *2019 Wearable Robotics Association Conference (WearRAcon)*, Scottsdale, AZ, USA, Mar. 2019, pp. 21–27, doi: 10.1109/WEARRACON.2019.8719403.

[31] A. Virts, R. V. Bostelman, S. Yoon, Y.-S. Li-Baboud, and M. Shah, “A Peg-in-Hole Test and Analysis Method for Exoskeleton Evaluation,” *NIST*, Mar. 2022, Accessed: Oct. 24, 2022. [Online]. Available: https://www.nist.gov/publications/peg-hole-test-and-analysis-method-exoskeleton-evaluation

[32] S. De Bock, J. Ghillebert, R. Govaerts, B. Tassignon, C. Rodriguez-Guerrero, S. Crea, *et al.*, “Benchmarking occupational exoskeletons: An evidence mapping systematic review,” *Appl. Ergon.*, vol. 98, Jan. 2022, doi: 10.1016/j.apergo.2021.103582.

[33] N. Hoffmann, G. Prokop, and R. Weidner, “Methodologies for evaluating exoskeletons with industrial applications,” *Ergonomics*, vol. 65, no. 2, pp. 276–295, Feb. 2022, doi: 10.1080/00140139.2021.1970823.

[34] M. Bär, B. Steinhilber, M. A. Rieger, and T. Luger, “The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton – A systematic review and meta-analysis,” *Appl. Ergon.*, vol. 94, Jul. 2021, doi: 10.1016/j.apergo.2021.103385.

[35] S. De Bock, J. Ghillebert, R. Govaerts, S. A. Elprama, U. Marusic, B. Serrien, *et al.*, "Passive Shoulder Exoskeletons: More Effective in the Lab Than in the Field?," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, pp. 173–183, 2021, doi: 10.1109/TNSRE.2020.3041906.

[36] W. Umer, H. Li, G. P. Y. Szeto, H. S. An, and A. Y. L. Wong, "Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders during Manual Rebar Tying," *J. Constr. Eng. Manag.-Asce*, vol. 143, no. 1, Jan. 2017, doi: 10.1061/(asce)co.1943-7862.0001208.