Experimental Evaluation of Exoskeletons for Rebar Workers Using a Realistic Controlled Test

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Abstract – Workers in the construction industry are exposed to the risk factors of high forces, repetitive tasks, and awkward postures, and consequently suffer from work-related musculoskeletal disorders (WMSDs). Occupational exoskeletons (OEs) are promising interventions to reduce WMSD rates in the construction trades. Previous work has evaluated the efficacy of OEs in controlled laboratory conditions and semi-realistic test courses; however, there are no standard evaluation methods for the construction industry. Standardizing the methods for evaluating and comparing the efficacy of OEs for construction workers is essential for the adoption of effective OEs in the construction industry. Toward this goal, a realistic, controlled, and repeatable test was implemented to evaluate the efficacy of back-support exoskeletons (BSEs) for the trade of rebar installation. The test was implemented at a steel trades school where nine experienced student participants performed the test course with and without wearing an OE. Objective effects on lower-back muscle activity and subjective effects on discomfort, effectiveness, obstruction, and usability were measured. The study demonstrates the initial implementation of the test, and the results show objective and subjective evidence that the OE reduces loads in the lower back during realistic rebar installation tasks.

Keywords –
Occupational Exoskeleton; Construction; Standard Testing

1 Introduction

Construction workers face considerable health and safety risks on construction sites. For example, reinforcing ironworkers (rebar workers) are exposed to heavy loads, prolonged awkward postures, and repetitive tasks, increasing the risk of significant musculoskeletal stress that leads to work-related musculoskeletal disorders (WMSDs), such as lower back pain and herniated discs [1–3]. These risks can be mitigated by replacing human workers with robots in certain cases, or by supporting the workers with ergonomic tools and wearable technologies. In the case of the rebar trade, workers can be supported by existing devices, such as standing rebar tying tools to reduce the need for bending. The emerging technology of occupational exoskeletons (OEs) has the potential to provide more effective and widely adopted ergonomic tools in the construction industry, compared to existing interventions. OEs have been adopted as tools to reduce WMSD rates in many industries, including construction, with back-support exoskeletons (BSEs) and shoulder-support exoskeletons (SSEs) being the most common designs. OEs can be evaluated in terms of immediate effects in laboratory studies (efficacy) and long-term effectiveness in real-world conditions, but evidence of their impact on WMSD rates is scarce [4–6]. The research community faces the challenge of establishing evidence-based guidelines for the construction industry, necessitating standard testing to compare OE performance and inform large-scale adoption.

To help address this need, and building on prior research [7], the present paper reports the outcomes of implementing a realistic, controlled, and repeatable test to assess BSEs for rebar workers. The main objectives involve implementing a controlled, practical test course and evaluation method designed for a distinct construction trade (rebar workers), a specific type of OE (back-support), and a designated project scenario (horizontal rebar installation). Additionally, the study seeks to extract insights for refining the test in future iterations. The realistic test course and evaluation method is aimed at contributing to future standard tests which will be necessary for large-scale adoption of OEs in the construction industry.

2 Literature Review

In recent years, research on the application of OEs in the construction industry has garnered attention. Guidelines from [8] recommend OE types for specific construction trades based on WMSD statistics from the United States.

Laboratory efficacy studies, such as [9], have assessed the impact of OEs on worker safety, acceptance,

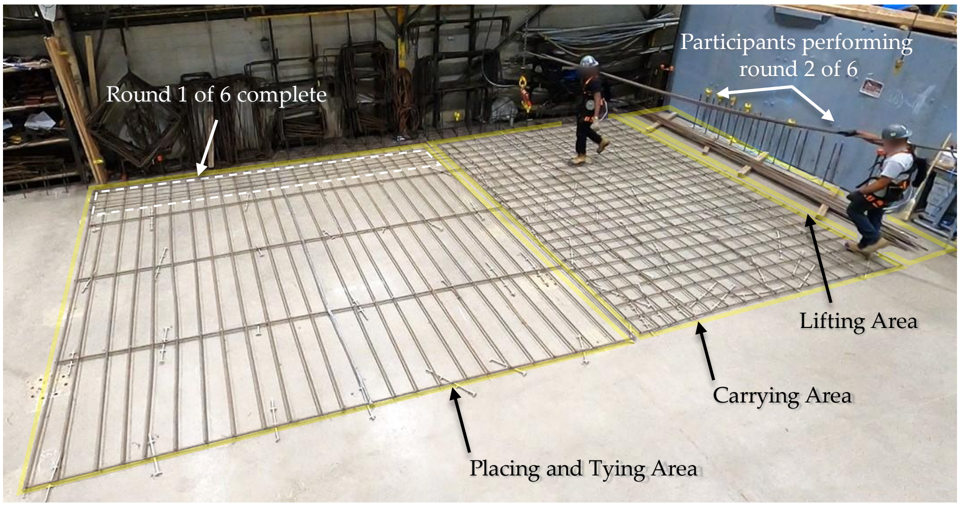

Figure 1. Implementation of the test

and productivity for generic tasks. Measures previously used to assess an OE's effect on health and safety include reductions in muscle activity measured using surface electromyography (sEMG) sensors, biomechanical simulation, and concepts such as lower back disorder risk. Measures previously used to assess OE acceptability include surveys on perceived discomfort, obstruction, and usability. A framework proposed by [10] for evaluating OE efficacy emphasized subjective and objective measures of efficacy, specified target tasks, and specified body postures. De Bock et al. [11] emphasized that the evaluation of the effects of an OE should include realistic tasks and test conditions. Previous work has also investigated the efficacy of OEs for specific construction trades, including rebar installation [12].

However, standard evaluation methods are lacking, as noted by [13] and [14]. Various efforts to standardize OE evaluation methods include the ASTM F48 standards [15], the standard test course for material handling [16], and the *Exoworkathlon* [17]. Ralfs et al. [18] also contributed to the development of generic methodologies and standard tests for OEs.

Crea et al. [19] outlined a roadmap for OE adoption, delineating laboratory assessment, field assessment, and large-scale adoption eras. Within this framework, the authors believe that standard versions of realistic test courses, such as those proposed by [17], will serve as a crucial bridge between controlled laboratory efficacy tests and the large, long-term field studies that will be necessary for the large-scale adoption of effective OEs in the construction industry.

3 The Test and Its Implementation

Our proposed test [7] was designed in consultation with ergonomic experts and implemented in collaboration with the Steel Trades Training Center (STTC) in Montréal, Canada. This collaboration was in line with the recommendations suggested by [20] of working with trade schools and apprenticeship training programs as a potential solution to the barriers to OE adoption.

Figure 1 shows this initial implementation of the test. The test course has three designated areas for the four main tasks of the test, i.e., *lifting* a load of rebars, *carrying* the rebars over an existing matrix, and *placing* and *tying* the rebars. Six *rounds* of the four *tasks* complete the test course and are defined as one *course*, which takes approximately one hour.

Within each *course*, half of the test course (three *rounds*) was completed in the control condition (No OE) and half was completed in the intervention condition (OE). Each participant was asked to complete four *courses* over four consecutive days, defined as one *test*, resulting in four hours of testing, with and without OEs. Figure 1 shows two participants performing the *carrying task* during the second *round* of that *course* in the intervention condition (OE).

A test duration of several hours was recommended by [21] to ensure the stabilization of measures related to back kinematics, pressure perception, and task performance when using a BSE. Similarly, [22] highlighted the advantageous outcomes of training in an experiment involving an ankle exoskeleton, noting that significant reductions in metabolic energy consumption were observed after several hours of training, in contrast to the results following only 12 minutes of exposure to the device. Therefore, each participant in the proposed test completed a one-hour training session and four one-hour test sessions, for a total of three hours of exposure to the OE and two more hours without the OE.

The aim of the test is to evaluate the short-term efficacy of OEs for the purpose of predicting long-term OE effectiveness. Based on the literature review, a repeatable test that balances experimental control with realistic conditions reflecting site conditions, is well suited for predicting OE effectiveness. The authors are not aware of any similar tests in the area of construction. The following sections will explain about the objective and subjective measures of OE efficacy to predict the potential effectiveness of the OE considering its effects on participants' health and safety, and the acceptability of the OE.

3.1 Lower Back Muscle Activity

Muscle activity of the lower back was recorded throughout the test using sEMG sensors and synchronized to *task* conditions using video reference. Muscle activity was chosen as an indirect but objective measure of the OE's effects on the forces in the lower back during rebar work. Specifically, muscle activity of the erector spinae longissimus thoracis (LT) was measured by placing two sensors on either side of the spinous process of the first lumbar vertebra (L1), as recommended by [23], and as seen in Figure 2.

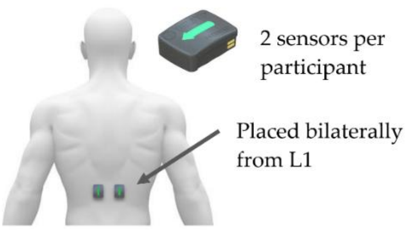

Figure 2. sEMG sensor placement locations

In previous work, different participants experienced reduced fatigue in different lower back muscles, namely the lumbar multifidus (LM), after an OE intervention [24]. Measuring LM activity was not possible in this study because the back pad of the OE covers this muscle group.

Maximum voluntary isometric contraction (MVIC) tests of the LT muscles were used to normalize the data and to compare effects between participants. As recommended by [25], MVIC tests were performed using a roman chair in a 45° position with the hips flexed so that the trunk is parallel to the ground. Participants were asked to contract for three seconds during which non-threatening verbal encouragement was provided. MVIC tests were performed for the LT muscle group two times with at least a 30 s rest in between.

The Delsys Trigno Wireless System was used as sEMG sensor hardware, and data was collected using EMGworks. A minimum sampling rate of 1259 Hz was used for all recordings. Recordings were band pass filtered (20-450 Hz, 4th-order Butterworth), rectified, and a low pass filtered (3-450 Hz, 4th-order Butterworth). During several *courses* in the OE condition, the OE briefly touched one or both sEMG sensors, inducing noise in the sensor data. When OE interference was infrequent, the noise appeared as outliers in the muscle activity data and were successfully removed using a z-score (threshold = 6). *Courses* where sensor noise was not successfully removed were excluded from the analysis.

3.2 Subjective Measures

After participants finished each half of the test course (three *rounds* of *tasks*) in either the control or intervention condition, participants were asked to complete the Discomfort Survey. The survey asks the participants to quantify their perceived discomfort for each area of the body that is in contact with the OE by using the Rating of Perceived Discomfort (RPD) scale [26]. For passive BSEs, there is a concern that the assistive torque of the OE will induce unwanted forces in non-targeted body areas (i.e., in areas other than the extensor muscles of the hip and back). The Discomfort Survey was used as a subjective measure of these potential undesirable effects.

After a participant finishes the *test* (four *courses* over four days), they are asked to complete a Health, Acceptability, and Safety (HAS) Survey developed by the authors. The questions of the survey are shown in Figure 5. This survey uses a 5-point Likert scale allowing participants to agree or disagree with phrases by choosing from five responses: *Strongly Disagree*, *Somewhat Disagree*, *Neutral*, *Somewhat Agree*, and *Strongly Agree*. As the realism of OE evaluations approaches that of field conditions, and the level of experimental control decreases, subjective measures of an OE's effects become more important. The HAS Survey was used as a subjective measure of the OE's effects regarding perceived support, balance, range-of-motion, thermal comfort, obstruction, and usability.

In both the Discomfort and HAS Survey, space for comments is provided after each question. The HAS Survey also asks for comments regarding how the design of the OE can be improved.

3.3 OE Characteristics

The OE evaluated during the test implementation was the Biolift [27] passive BSE. Figure 3 shows the OE worn by one of the participants, as well as the integrated tool pouch and tie-wire reel necessary for rebar work. The OE weighs 3.5 kg and the time to put on and take off the OE is approximately 10 seconds each. The time to initially adjust the fit of the OE was approximately 1 minute, depending on the user's familiarity with the device. The OE has three levels of support and was set to the second support level for all participants, which has a maximum torque of 50 Nm during hip and back extension, accounting for hysteresis (energy lost due to friction).

Figure 3. The Biolift passive BSE

3.4 Participant Characteristics

Nine students from the STTC participated in the test. The participants were contacted via their instructor and all interested students signed the provided consent forms after a thorough explanation of the test during a one-hour training session. Eight participants were male, and one participant was non-binary and male at birth. The average age of the participants was 27 yr. with a standard deviation of 10 yr., ranging from 19 yr. to 49 yr.

Larger sample sizes are desirable in order to have statistically significant results regarding interaction effects between measures of efficacy and human attributes, including age, gender, and experience level. The limited sample size during the initial implementation was the result of time limitations and the class size of the school. Despite the small sample size, the authors strived to, as much as possible, have diversity with respect to participant gender and age.

All participants had the same level of experience, as they were all in the process of taking their exams at the end of a seven-month (735-hour) professional degree. As recommended by De Bock et al. [28], the participants had a near professional level of experience in regards to the four tasks of the test course, approximately at the same level as junior rebar workers. During their degree, the participants learned the fundamentals of the steel reinforcing trade, including assembly for reinforced concrete slab construction. Participants were also frequently monitored by their instructor throughout the test. This insured that the participants applied the best practices of the trade, and the authors believed that this improved the realism of the tasks they performed, in addition to the realism provided by the participants' experience levels.

Eight of the participants were divided into four groups of two (G1 to G4), and each participant was named according to their group (e.g., PA1 and PB1 belong to G1). A ninth participant was designated as a replacement in the case of absences (PR). The quantity of data from the test is not consistent among participants due to technical issues with the sensors; however, on average, participants performed each *task* 11 times in the control condition and 10 times in the intervention condition.

4 Test Results

4.1 Muscle Activity Results

Figure 4 compares the average peak (95th percentile) normalized LT muscle activity for each participant in the control (No OE) and intervention (OE) conditions for each *task*. Right and left LT muscle activity is averaged. Error bars show 95% confidence intervals and * marks significant differences ($p < 0.05$) from the control condition (i.e., No OE).

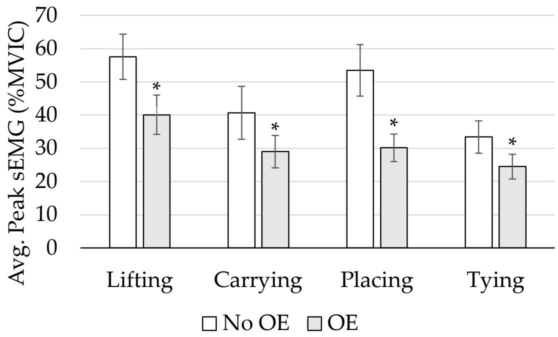

Figure 4. The effect of the OE on average peak normalized LT muscle activity

The average peak (95th percentile) LT muscle activity decreased by 30.4%, 28.7%, 43.6%, and 26.6% for the *lifting*, *carrying*, *placing*, and *tying tasks*, respectively. Average LT muscle activity decreased by 17.1%, 14.2%, 19.5%, and 20.7% for the *lifting*, *carrying*, *placing*, and *tying tasks*, respectively.

During the test, it was observed that some participants took on a narrower stance while tying as compared to the traditional wide stance. Rebar workers use a wide stance to tie the maximum number of intersections before having to move to a new area. Moving to a new area is done either by standing up to move or by shifting positions while maintaining a forward leaning position. Both ways of changing position engage the muscles of the lower back. A narrower stance therefore necessitates more frequent use of the lower-back muscles for tying the same number of intersections. In addition, when a worker's hands are in a working position near the ground, the wider stance will allow him or her to have less back flexion compared to the narrow stance.

Using video reference, each of the eight main participants was classified into using either a wide or narrow stance while tying. This classification was done subjectively and did not rely on objective joint angle data. The average decrease in peak (95th percentile) muscle activity for the two groups of wide and narrow stance was -18.6% and -38.4% respectively. The larger decrease in muscle activity in the narrow stance group compared to the wide stance group may suggest, as explained above, that the traditional wide stance allows workers to rely less on their LT muscles while tying. As recommended by Golabchi et al. [10], posture must be considered while assessing OE efficacy, and future iterations of the test can record joint angles to objectively measure tying posture.

4.2 Subjective Survey Results

Table 1 shows the results of the discomfort survey as mean levels of discomfort at the OE contact areas for all participants. The minimum and maximum values of the Rating of Perceived Discomfort (RPD) scale are 0, and 10, respectively [26]. The mean discomfort for all contact points was at or below level 1, defined as “Minor Discomfort.” Although the standard deviations for each contact area are large compared to the mean, the deviations are relatively small compared to the range of the RPD scale.

Figure 5 shows the results of the HAS Survey. Questions three and nine were originally written “While carrying rebar, the OE made me feel unbalanced” and “The heat retained by the OE was uncomfortable.” However, these questions have been rewritten in the positive sense to visually unify the data. Green responses represent positive opinions regarding the OE and orange and red responses represent negative opinions. The survey results on perceived support, OE heat retention, obstruction, and usability were generally positive.

Table 1. Discomfort at the OE contact points

Contact Area	Discomfort [Mean (SD)]
OE Shoulder Straps	0.5 (0.4)
OE Chest Strap	0.6 (0.6)
OE Belt	1.0 (1.2)
OE Thigh Straps	0.7 (0.8)

The two oldest participants PA3 and PA4 (49 and 36 years old, respectively) both strongly agreed that the OE made them feel unbalanced while carrying rebars. PA3 commented that he also felt more unbalanced while tying. All other participants strongly disagreed or were neutral regarding the OE making them feel unbalanced. The average age of all other participants, excluding PA3 and PA4, was 23.1 yr. (SD 3.3 yr.). The third oldest participant, PB4 (27 years old) commented that the OE “… did not interfere with my balance.” PB4 commented that at times, his movements were restrained while carrying rebars with the OE activated and that this was not a problem when the OE was deactivated while walking during breaks. The OE designers recommend deactivating the OE if the wearer is walking more than 100 meters. The distance of the carrying task is small enough that all participants left the OE activated while carrying. For PB4, the average and average peak (95th percentile) LT muscle activity showed no significant change ($p < 0.05$) between the No OE and OE conditions during the *carrying task*, suggesting that the activated OE had little to no effect on the LT muscles during the *carrying task*.

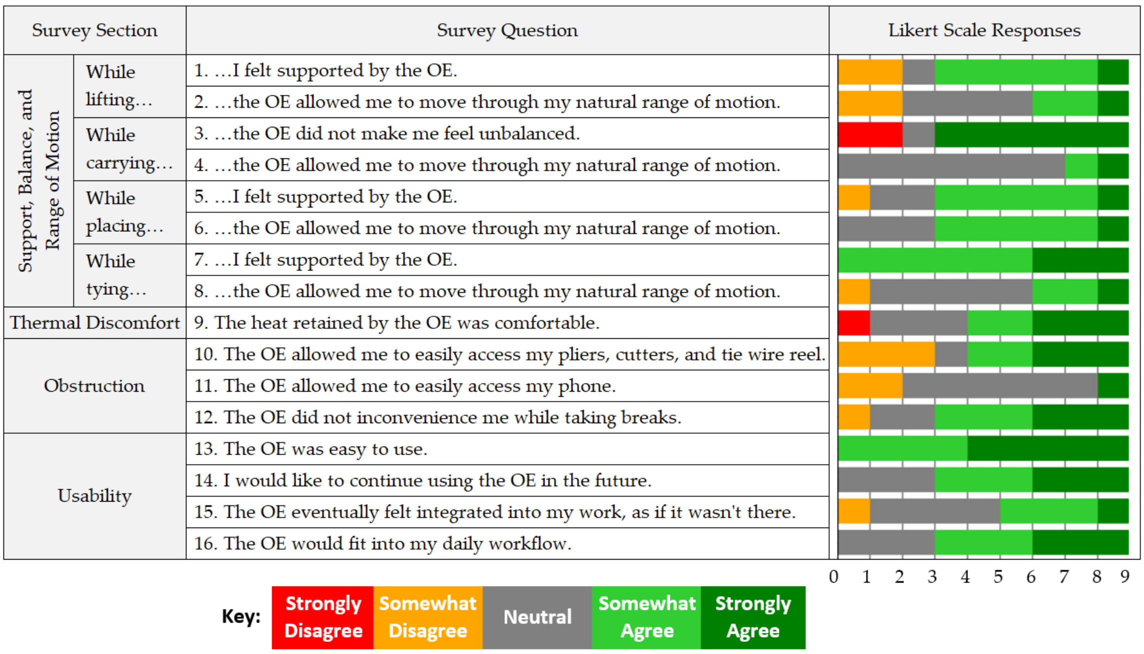

Figure 5. Responses of the nine participants on a 5-point Likert scale from the HAS Survey

5 Conclusions and Future Work

Standard testing of OE efficacy for the construction trades is an integral step from laboratory efficacy evaluation to field effectiveness evaluation, leading to large-scale adoption of effective OEs in the construction industry. This study demonstrated the initial implementation of our previously proposed test for evaluating the effects of BSEs on workers installing horizontal rebars [7]. The potential benefits of the Biolift BSE were evaluated using realistic testing conditions and tasks. The nine participants from the collaborating professional school were at the end of their programs and had the level of experience of junior rebar workers. The study revealed significant reductions in lower-back muscle activity for the main tasks of *lifting*, *carrying*, *placing*, and *tying*. Suggestive differences in muscle activity were found when investigating and comparing participants' tying postures. Subjective results from the surveys showed low levels of discomfort from using the OE and positive opinions regarding OE support, obstruction, and usability.

Future work using the proposed test involves comparing multiple OEs for the trade of rebar assembly. However, the test has limitations that can be addressed in future work. First, conducting the test with a larger sample size with diversity regarding participant age and experience level, as well as having a gender balanced sample, will allow for statistically significant analyses of interaction effects between measures of OE efficacy and human attributes. The manual process of labelling sEMG data led to an unexpected reduction in muscle activity during the *carrying task*, as peaks in muscle activity belonging to the *lifting* and *placing tasks* may have been incorrectly labelled. Future work will involve inertial measurement units (IMUs) for full-body motion capture. Full-body motion capture can ensure accurate task labelling of the muscle activity data and gives an objective measure of an OE's effect on posture. Some loss of data occurred due to technical difficulties with the sEMG sensors. As novel methods of estimating OE assistance mature, for example, combining IMUs and pressure-sensing insoles [29] and simulating spine loading [30], the test may benefit from measures of efficacy that are more practical than sEMG-based measures. Introducing practical measures would be beneficial in two ways: (1) the test would be easier to reproduce, and (2) long-term field studies could implement the same measures of performance as the test, allowing for the results of both types of studies to inform the other, and iteratively improve. The authors hope this research works towards standard testing of OEs for construction trades that balances the factors of implementation repeatability, realism of the testing conditions, and experimental control.

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