Roadmap for Exoskeleton Adoption in the Construction Industry: Leveraging Standard Tests and Minimum Criteria

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Abstract –

Occupational exoskeletons (OEs) offer significant potential to reduce the incidence and severity of musculoskeletal disorders (MSDs) in the construction industry. Despite this potential, OE adoption remains low due to unique challenges in this industry. By addressing the limitations of previous OE adoption frameworks and roadmaps, this paper proposes a framework to guide OE design, evaluation, and implementation specifically for the construction industry. The novel elements of the framework are: (1) incorporating sets of general and trade-specific standard OE test methods, and (2) incorporating trade-specific criteria for minimum OE design requirements, sufficient evidence of OE efficacy, and sufficient evidence of OE effectiveness. A roadmap is extrapolated from the proposed framework that recommends future research on trade-specific standard test creation and trade-specific stakeholder surveys to inform minimum criteria. Finally, the results of a pilot field study on a back-support OE for reinforcing ironworkers are linked to the framework as an example of its utility. The goal of this research is to define a process for generating a comprehensive body of scientific evidence that can support large-scale OE adoption in the construction trades.

Keywords –

Occupational Exoskeleton; Construction

1 Introduction

Trade workers in the construction industry suffer from work-related musculoskeletal disorders (MSDs). MSDs in the United States construction industry in 2016 were higher than the average of all other industries combined [1]. 46% of United States construction workers in 2019 self-reported MSD symptoms [2, 3]. Research in Québec, Canada in 2024 suggested that occupational exoskeletons (OEs) had the potential to have addressed 50% of all MSD cases that were observed in a large construction contractor's work force over the three-and-a-half-year study period [4]. The adoption of OEs by the construction industry, however, remains low.

Previous research has investigated the necessary elements for successful industry adoption for any type of occupation intervention. Van der Beek et al. [5] proposed a general roadmap for the adoption of occupational interventions which involves six steps: (1) Quantify MSD incidence and severity, (2) Identify the risk factors associated with MSDs, (3) Investigate the underlying mechanisms relating risk factors to MSDs, (4) Develop an intervention, (5) Evaluate the intervention, and (6) Implement the effective intervention. Step 5 returns to Steps 2, 3, or 4 if there is no evidence of an intervention's effectiveness when evaluated, thereby making the roadmap iterative. Step 6 returns to Step 1, ideally showing a reduction in MSD incidence and severity in a population of workers, making the roadmap circular. As an example-use of their roadmap, Van der Beek et al. [5] presented the hypothetical development of an intervention for bricklayers: change in workstation height.

As the interest in adopting OEs at a large scale has grown since the mid-2010s, frameworks have been proposed specifically for the design, evaluation, and implementation of OEs [6–12]. Pesenti et al. [6], De Bock et al. [7], and Golabchi et al. [8] categorized measures of an OE's effects as either muscular, biomechanical, metabolic, functional, or subjective, and recommended task-specific and posture-specific evaluations. De Bock et al. [7] proposed technology readiness levels (TRLs) to guide the choice of test environments, including laboratory efficacy studies, field effectiveness studies, and simulation studies. Balancing comprehensive evaluation with practicality, Hoffmann et al. [11] recommended standardizing evaluation methods and consolidating measures of OE effects. This has since been exemplified by standard test methods from the ASTM Committee F48 on Exoskeletons and Exosuits (ASTM F48).

To realize such frameworks, roadmaps towards the goal of large-scale OE adoption have also been proposed. Crea et al. [13] proposed a roadmap to facilitate OE adoption in any industry, e.g., manufacturing, logistics, or construction. The goal of the authors was to provide a path toward a holistic body of scientific evidence that is necessary for large-scale OE adoption [13]. A limitation, however, of this roadmap, and of all the above frameworks, is the lack of specific mechanisms or processes by which to generate such a body of scientific evidence.

Clear processes for OE adoption may be especially important for the construction industry because of the unique challenges it faces. Zhu et al. [14] and Nnaji et al. [15] found that, compared to the manufacturing and logistics industries—where OE design and evaluation is more mature—the construction industry is unique because of the inherent variability and intensity of the tasks and conditions that construction workers face within each trade, and because of the variability between trades. These challenges complicate OE adoption in the construction industry [14, 15].

Previous work has attempted to addressed these unique challenges in construction by proposing realistic evaluation methods towards the development of standard tests, including the research from Kopp et al. [16] on the welding and timber framing trades. Similarly, Dunson-Todd et al. [17] proposed a realistic test method for evaluating back-support OEs for reinforcing ironworkers (rebar workers), towards a standard test that can be used to generate sufficient evidence of OE efficacy, safety and acceptance, as recommended by [11]. The question remains, however, of how these standard tests for the construction industry can fit within a larger framework for generating the holistic body of scientific evidence required for OE adoption, as proposed by [13].

Informed by the previous work discussed above, the current paper proposes such a framework and uses it to extrapolate a roadmap for future research required in the construction industry. The framework addresses the specific challenges inherent in the construction trades while providing a comprehensive path towards OE adoption. To provide insights into the utility of the proposed framework, the results of a pilot field study on a back-support OE for rebar workers are discussed. The pilot field study is a continuation of previous work toward a standard test for the rebar trade [17]. Examples of real-world construction OE challenges found from the pilot field study are linked to the framework to demonstrate its value. Section 2 presents the framework for OE adoption in the construction industry and the roadmap to realize it. Section 3 presents the results of the pilot field study.

2 Framework and Roadmap for OE Adoption in the Construction Trades

Informed by the previous research described in Section 1, Figure 1 shows the proposed framework for OE adoption in the construction industry. The framework is divided into Steps 1 to 4, and sub-steps, e.g., 2(a), 2(b), etc. Much of the framework has been adapted from previous research: Step 2, Design, is adapted from Van der Beek et al. [5], and Step 3, Evaluation, is divided into short-term and long-term laboratory and field evaluation, as proposed in previous frameworks and roadmaps, e.g., [13]. By convention, long-term can be defined as a study period greater than 3 months, as in [18]. Short- and long-term simulation have been included in Steps 3(a) and 3(b) of the framework. Simulation has been used to estimate an OE's immediate effects on the biomechanical system of the body in previous research, e.g., [19]. Although no methods exist for simulating the long-term effects of an OE, future longitudinal field testing may generate evidence that can be used to verify simulations of an OE's long-term effects.

Two elements of the framework are novel: (1) proposing a set of general and trade-specific realistic standard laboratory tests for each trade, and (2) proposing three minimum requirement decision points informed by a trade-specific industry stakeholder survey, further referred to in this paper as a trade-specific survey (TS). These novel elements are outlined with a bold border in Figure 1. The framework, and a roadmap to realize it, are described in detail in the following subsections.

2.1 OE Design

Van der Beek et al.'s [5] proposed framework for designing an intervention rested on an evidence-based understanding of the mechanisms behind MSDs in a population of workers. As shown in Figure 1, this has been adapted as follows: Step 1, looking to statistics to understand MSD incidence and severity in a construction trade population, (e.g., as in [4]); Step 2(a), conducting epidemiological observational studies to identify the MSD risk factors present in a given trade; Step 2(b), conducting laboratory and field studies to identify the etiological mechanisms linking risk factors to MSDs; and Step 2(c), a research and design process that targets these mechanisms to develop a new OE or modify an existing OE for the benefit of a specific construction trade.

2.2 Set of General and Trade-Specific Standard Laboratory Tests

As recommended by Gutierrez et al. [20], controlled laboratory studies that simulate construction tasks and environments will help identify the most appropriate situations to implement OEs. The Delphi survey from Mahmud et al. [21] identified seven potential solutions regarding policy and regulatory barriers to OE adoption, two of which were (1) scientific data to drive regulation and policy development, and (2) forming industry standard practices. These solutions can be achieved by collecting benchmarking data from a set of both general and trade-specific standard tests.

As an example, the welding trade would benefit from a general standard test to evaluate OE capabilities in confined spaces, and ASTM F48 has already published such a test method: F3523 − 21 [22]. The trade-specific requirements of an OE for a welder, however, cannot be fully met by a set of general standard tests. A realistic trade-specific standard efficacy test for welders, as proposed by Kopp et al. [16], can be used in combination with general standard tests to generate sufficient evidence for OE efficacy. In this case, "sufficient" can be defined by the results of a TS for the welding trade, as will be described in Section 2.3. As a second example, a candidate for a general test method is the evaluation of an OE design's heat retention, which is especially applicable to all construction trades that work in outdoor and non-temperature-controlled environments, such as the rebar trade. The proposed trade-specific test method from Dunson-Todd et al. [17] could be used in combination with general standard tests, including a general test on heat retention, to build a set of test methods that comprehensively evaluates an OE design for the rebar trade.

The challenge of creating useful standard efficacy tests is in balancing the comprehensiveness of a set of measurements and conditions with the practicality of implementing them [11]. An example of balancing comprehensiveness of experiment conditions with implementation practicality comes from De Vries et al. [23]. The authors limited the scope of their evaluation for plasterers to three main ceiling and wall plastering activities. In this way, the authors limited test complexity while still capturing most of the ergonomic risk in the

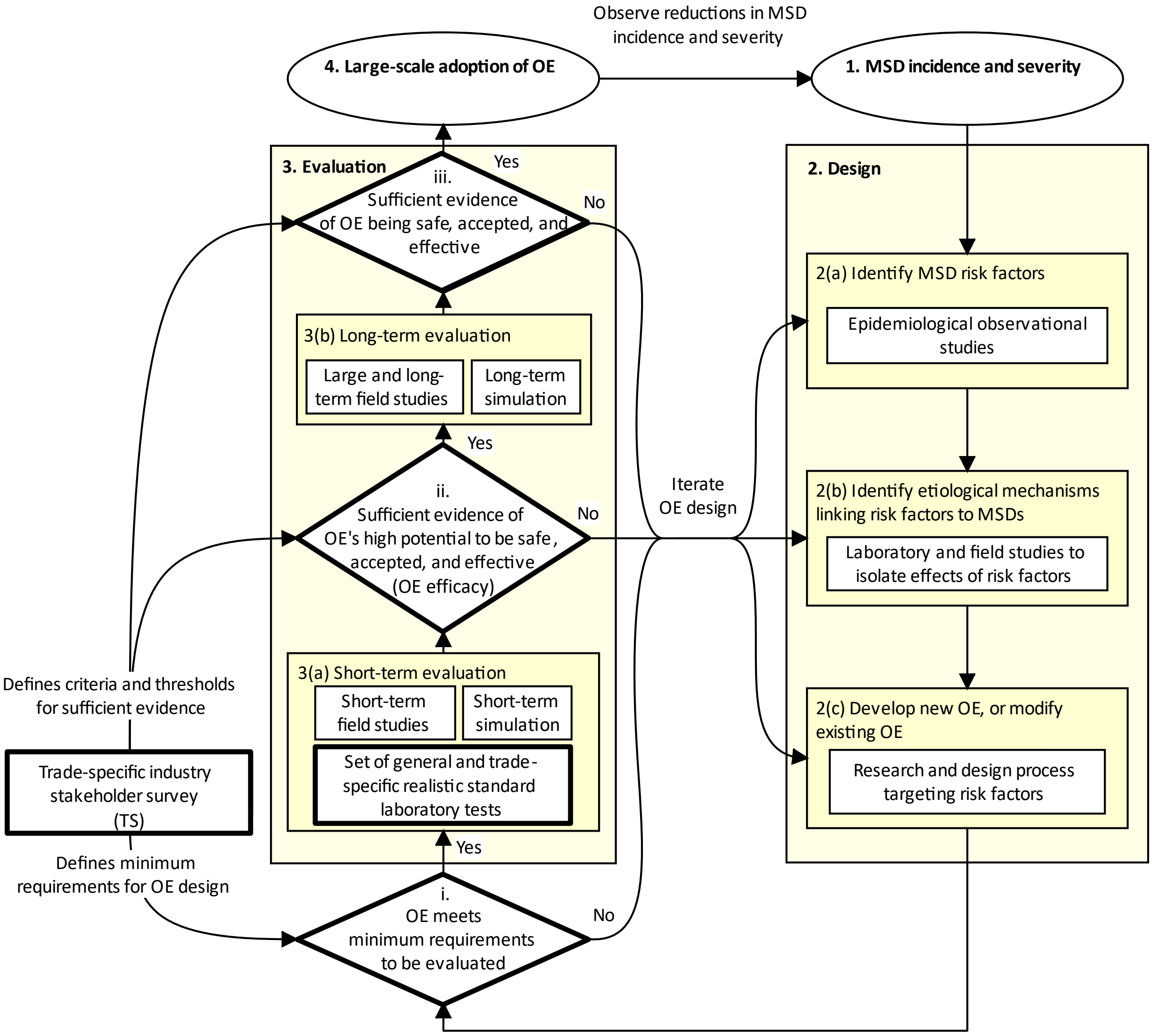


Figure 1. Framework for OE adoption in a specific construction trade

plastering trade. Moreover, the conditions captured the task variability inherent to the trade: results showed a significant reduction in perceived effort during overhead tasks but no significant reduction while applying gypsum to walls, likely due to the variable nature of the latter task. Future work can learn from this example of synthesizing the most important features of the environments and activities of a trade into a realistic efficacy test.

2.3 Trade-Specific Surveys to Define Minimum Criteria Decision Points

The framework shown in Figure 1 includes three decision points: (i) Does the OE meet minimum design requirements to be evaluated? (ii) Is there sufficient evidence of the OE's high potential to be safe, accepted, and effective (i.e., of OE efficacy)? (iii) Is there sufficient evidence of the OE being safe, accepted, and effective? Because of the variation of construction tasks and environments between each construction trade, the criteria for meeting each of these decision points will vary between trades. The criteria for passing each decision point in the framework may therefore be most readily determined through a TS that includes all relevant stakeholders for a given trade. Previous research (e.g., [20, 24, 25]) involved conducting industry surveys to collect construction stakeholders' perspectives. Various survey methods have been used, including Delphi, as in Nnaji et al. [15], in which a panel of experts come to a consensus agreement regarding questions that are important to the construction industry. Similarly, a Delphi TS can be used to inform criteria for passing each decision point in the proposed roadmap in Figure 1.

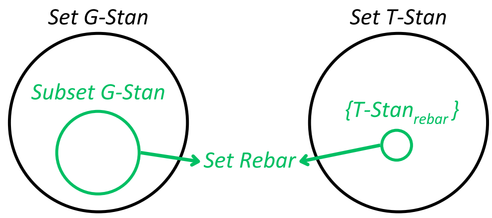
The roadmap from [13] recommended incorporating all stakeholder perspectives into the design and evaluation of an OE and included the following groups to encompass all OE stakeholders: (1) workers, (2) unions and worker associations, (3) corporate management and corporate decision makers, (4) health professionals, including but not limited to ergonomists, kinesiologists, and occupational medical doctors, (5) insurance companies, (6) policy makers, and (7) certifying bodies and standards development organizations (SDOs), e.g., ASTM F48. For the construction industry, two additional stakeholders are trade school instructors and students. These stakeholders can be added for inclusion in a Delphi TS, as they have a strong influence on the future of any major construction trade.

To further leverage the use of minimum criteria for design requirements, and for sufficient evidence of efficacy and effectiveness, a useful tool for OE adoption may be a minimum criteria labeling system. Labels that signify an OE's adherence to minimum design, efficacy, or effectiveness criteria would accelerate OE adoption in the construction industry, shifting the burden of finding suitable OEs away from individual contractors to the evaluation process outlined in Figure 1. This labeling system could be administered by an SDO to provide the industry with clear indicators of the suitability of any given OE for a specific trade.

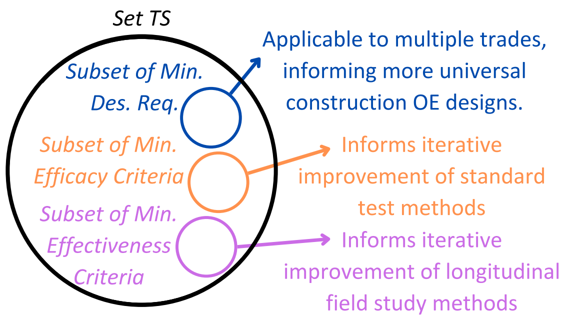
Labels may also be useful for market-neutral OE evaluation. The idea of market-neutral reporting used by Kopp et al. [16] promotes participation in the authors' proposed and implemented *Exoworkathlon*. The authors' reporting of aggregate results from multiple OEs, however, relied on the OEs being relatively similar passive shoulder-support designs with similar torque profiles [16]. This method of market-neutral reporting would therefore be impossible for a group of OEs that have significantly different designs and biomechanical effects. With defined criteria of sufficient OE efficacy and effectiveness—(ii) and (iii) in Figure 1, respectively—multiple disparate OE designs can achieve efficacy and effectiveness labels. Labels could thereby provide market neutrality while encouraging OE design diversity.

2.4 Roadmap Toward Standard Tests and Minimum Criteria

To realize the framework for construction OE adoption shown in Figure 1, a roadmap, the goals of which are shown in Figure 2, is proposed as follows.



(a) Goal of standard testing research effort.



(b) Goal of TS research effort.

Figure 2. Roadmap goals toward OE adoption

As outlined in the introduction, previous research has designed OEs for construction trades and has evaluated their efficacy in laboratory studies. In coming years, ongoing longitudinal field studies on construction OEs may be published. The non-novel steps of the framework (without a bold outline in Figure 1) have therefore been touched upon by previous or ongoing research, with varying degrees of success, and for a limited number of construction trades. Future research may increase the probability of success for construction OE adoption by focusing on the novel components of the framework, which are outlined in bold in Figure 1 and described in Sections 2.2 and 2.3.

The set of general standard tests (*G-Stan*) and trade-specific tests (*T-Stan*) described in Section 2.2 can be represented visually, as shown in Figure 2(a). A set of standard tests for each construction trade can come from the union of a subset of tests from *G-Stan* with a subset of tests from *T-Stan*. As an example for the rebar trade, Figure 2(a) shows *Set Rebar* as the union of multiple general tests, *Subset G-Stan*, and one trade-specific test, $T\text{-}Stan_{rebar}$.

Set G-Stan, *Set T-Stan*, and *Set Rebar* can also be represented as equations, as shown in Equations (1), (2), and (3), respectively:

$$Set\ G\text{-}Stan = \{G\text{-}Stan_1, G\text{-}Stan_2, \dots, G\text{-}Stan_n\} \quad (1)$$

$$Set\ T\text{-}Stan = \{T\text{-}Stan_1, T\text{-}Stan_2, \dots, T\text{-}Stan_{nt}\} \quad (2)$$

$$Set\ Rebar = Subset\ G\text{-}Stan \cup \{T\text{-}Stan_{rebar}\} \quad (3)$$

In Equation (1), *n* is the total number of general standard tests. In Equation (2), *nt* is the total number of construction trades. Zhu et al. [14] classified 16 separate construction trades and their potential for OEs. An *nt* greater than 16 may be necessary, however, as some trade categories from publicly available occupational statistics are too broad. For example, "ironworker" encompasses rebar assembly and steel beam assembly—arguably two sub-trades involving significantly different tasks, environments, and ergonomic risk factors.

The set of trade-specific industry stakeholder surveys (*Set TS)* described in Section 2.3 can also be represented visually, as shown in in Figure 2(b). *Set TS* would provide a benchmark for minimum OE design requirements and useful measures of an OE's efficacy (i.e., evidence for Decision Point ii in Figure 1), and effectiveness (i.e., evidence for Decision Point iii in Figure 1). As represented in Figure 2(b), subsets of *Set TS* can be used as benchmarks to guide the design of future OEs that optimize capabilities and features to meet the requirements of multiple trades. Research conducting TSs would therefore support the development of OEs that are more universally applicable in the construction industry.

Set TS can also be represented as an equation, as shown in Equation 4:

$$Set\ TS = \{TS_1, TS_2, \dots, TS_{nt}\} \quad (4)$$

As in Equation (2), *nt* in Equation (4) is the total number of construction trades. To efficiently use the resources dedicated to researching OEs for the construction industry, the largest construction trade populations with the highest MSD incidence and severity should be prioritized in the pursuit of the goals shown in Figure 2.

3 Pilot Field Study on Rebar Installation

As discussed in Section 2.2, Dunson-Todd et al. [17] proposed a realistic trade-specific efficacy test method for evaluating back-support OEs for rebar workers. The proposed test method from [17] is currently under review by ASTM F48 to potentially contribute to a new standard. Following this research, a pilot field study was conducted to evaluate the same OE as in [17] in field conditions.

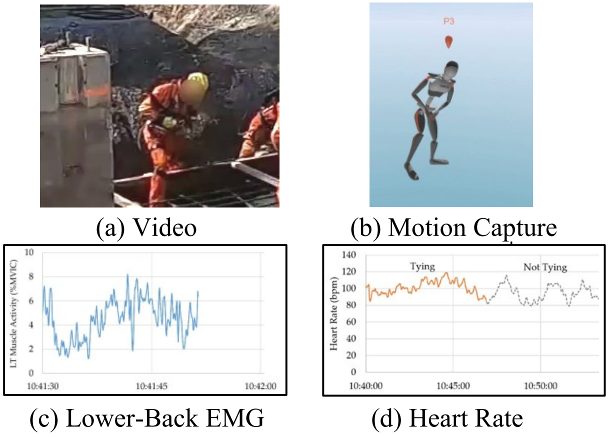
Three male construction workers participated in the pilot study, with an average (standard deviation) age of 45.7 (4.0) years, and an average (standard deviation) of 21.0 (2.6) years of experience in construction. The Research and Ethics Unit at Concordia University approved all ethics documents and surveys. The participants constructed a reinforced concrete slab foundation over the course of five days at an electrical substation construction site. Their tasks included assembling rebar, assembling formwork, and pouring and consolidating concrete. Figure 3 shows the construction site conditions and an example of a participant tying rebar while wearing the Biolift back-support OE. Although the sample size of participants was small, the pilot field study was aimed primarily at providing suggestive results on challenges regarding OE design and evaluation in construction. To that end, the following subsections discuss insights from the pilot field study regarding the utility of the design and evaluation framework proposed in Section 2.

(a) Construction site (b) Tying task

Figure 3. Pilot field study conditions.

3.1 Challenges with Measuring OE Effects

As in Dunson-Todd et al. [17], electromyography (EMG) was used to record muscle activity of the lower back, electrocardiography (ECG) was used to record heart rate as a measure of physiology, and inertial measurement units (IMU) were used to record full-body motion capture (i.e., joint angles and segment positions). Figure 4 shows the three sensor data types synchronized to video reference of a participant tying rebar.



(a) Video (b) Motion Capture

(c) Lower-Back EMG (d) Heart Rate

Figure 4. Synchronized sensor data from the pilot field study.

Although the small number of participants and quantity of objective data was too low to be statistically significant, insights were gained regarding using these measures of OE effects in the field. The lack of control over when and for how long each task was performed created challenging conditions for collecting data in both the control (No OE) and intervention (With OE) conditions for each participant.

Data collection was also challenging due to environmental conditions, where hot days delayed construction, induced noise in muscle activity data, and made frequent readjustment of sensor placement necessary due to the participants sweating. Future field studies would benefit from more practical measures, and from measures that are more directly correlated with safety, acceptance, and effectiveness. The criteria created by a TS for the rebar trade could provide insight into what is sufficient evidence of efficacy and effectiveness, and therefore, what objective measures of an OE's effects are required.

3.2 Iterative Design Process

As examples of the iterative design process shown in Figure 1, the OE manufacturer has implemented design improvements informed by [17] and by internal studies, including: (1) providing a suitable replacement for a rebar worker's tool belt, (2) lowering the position of the lower-back pad and dividing it into two pieces on either side of the spine to improve comfort, and (3) providing more secure thigh strap fixtures to prevent strap misalignment.

The pilot field study exposed other potential OE design requirements that were not anticipated in the study from Dunson-Todd et al. [17]. Figure 5 shows participants' responses to a 5-point Likert survey adapted from [17]. Although opinions on support and on balance in the steep environment were positive, all participants found the heat retained by the OE uncomfortable. As discussed in Section 2.3, low heat retention—achieved through integrated cooling, low contact area, or other features—is a promising minimum design requirement for many trades.

Two unanticipated design requirements stemmed from the concept of OE acceptance: (1) A design that allows for both men and women to use the restroom without removing the OE, and (2) A design that allows for maintenance to be possible in field conditions without the need for specialized tools. Two additional design requirements stemmed from the safety measures necessary at an electrical substation: (1) fire resistant materials, and (2) covering all metal parts to eliminate the risk of electrical arcing. A further unanticipated design requirement was the OE's compatibility with a kneeling posture while tying, as one participant commented they were uncomfortable while kneeling with the OE activated. This difficulty, however, may stem from the pilot study's ad-hoc conditions. The design of the OE [26] evaluated in the pilot field study was informed by subjective feedback from experienced rebar workers on large slab construction sites, collected with surveys internal to the manufacturer. The pilot study field conditions were fundamentally different compared to large-slab construction sites, as the conditions involved a relatively small concrete slab with no need to carry rebars. Moreover, although the participants were experienced construction workers, they did not specialize in the rebar trade. As noted in [17], difference in experience in the rebar trade is correlated with significant differences in posture while tying.

The above observations highlight the challenge of designing OEs that accommodate a wide range of workers and use cases, and the challenge of ensuring field conditions that provide generalizable results. Identifying useful minimum design requirements, as described in Section 2.3, can help strike a balance between OEs that are versatile enough to support diverse trades while remaining cost-effective for widespread adoption.

4 Summary and Conclusions

Improving the design and metrology of construction OEs can accelerate the successful adoption of OEs in the construction industry. Informed by previous research, this paper provides a framework by which the OE research community may generate the holistic body of scientific evidence required for OE adoption while addressing the unique challenges faced by the construction industry. By aligning OE design and evaluation processes with trade-specific requirements, incorporating comprehensive stakeholder input, and by leveraging standard tests and minimum criteria, the roadmap offers a specific pathway for accelerating the adoption of safe, accepted and effective OEs.

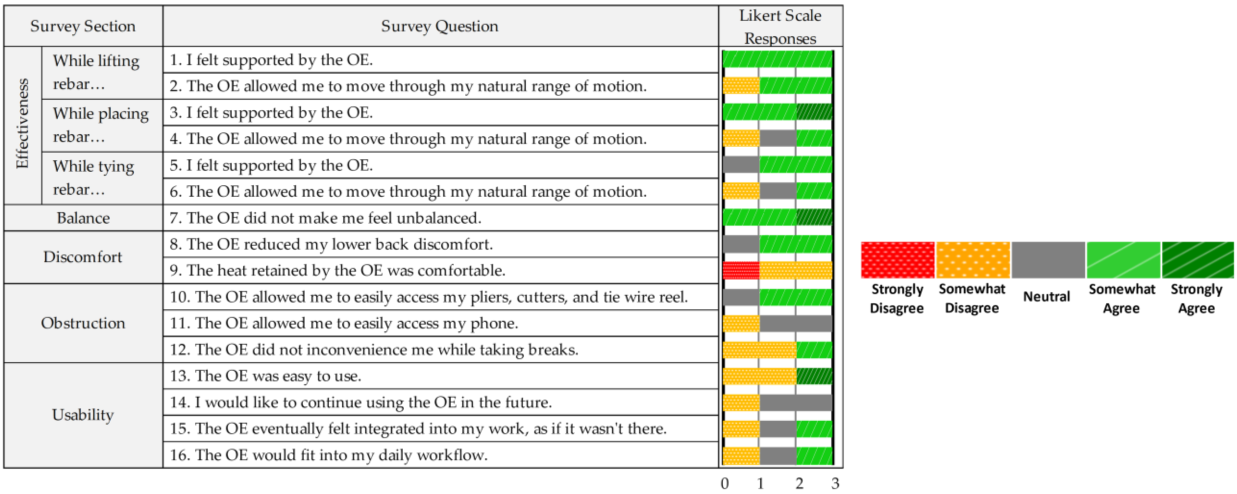


Figure 5. Subjective data from the pilot field study.

The framework outlines significant research initiatives, and this paper argues that investment in these initiatives is justified by the benefits they may bring to the construction industry: mitigating the unique challenges of OE design and evaluation which prevent large-scale OE adoption. To demonstrate the value of the framework with real-world examples of these design and evaluation challenges, the paper presented a pilot field study on a back-support OE for construction workers. The challenges identified in the study included choosing suitable measures for field evaluation, choosing representative field conditions in which to evaluate an OE, the difficulty of accounting for minimum design requirements in unpredictable environments, and other specific design challenges like heat retention. All these challenges can be mitigated by insights gained from a trade-specific industry stakeholder survey, and by this survey informing the other novel aspects of the proposed framework.

As described in the roadmap in Section 2.4, future work can focus on conducting trade-specific industry surveys to establish a consensus on the criteria for each decision point in the framework, eventually leading to benchmarks for minimum design requirements and useful measures of OE effects.

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