

Participatory Ergonomics in Construction: Enabling Practice-to-Research-to-Practice via  
the 2SAFE Model

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**ABSTRACT**

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The complicated nature of work-related musculoskeletal disorders necessitates the collective participation of researchers and practitioners in ergonomic interventions. An ideal participatory process should aim to provide mutual benefits that can be achieved via a practice-to-research-to-practice transition; that is, using practical insights to inform the research followed by implementing the research findings in real-world activities. However, researchers are confronted with various behavior-related challenges when participating in ergonomic interventions in the construction industry, in which practitioners are known to have limited knowledge of ergonomics and low levels of motivation for change. These challenges include a lack of worker involvement, weak commitment on the part of management, and poor communication. To improve the research-practice collaboration during a participatory ergonomics program, researchers need to identify ways of influencing construction practitioners' decisions and individual

behaviors, which essentially determine the commitment and participation of practitioners in the program.

This dissertation describes the five-step 2SAFE (Surveillance, Screening, Assessment, Framing, and Evaluation) planning model, which can be used to achieve a practice-to-research-to-practice transition in a participatory ergonomics program. This model was developed by combining the understanding of work-related musculoskeletal disorders, the principles of the health belief model, and the typology of research evidence. This theoretical synthesis enables the model to address the following critical questions: (1) How can data collection processes be designed to capture the nature of ergonomic injuries? (2) How can the collected data be transformed into information that practitioners can use immediately to change their behaviors? (3) What scientific contributions can be made during the participatory process?

This model was tested empirically during a 39-month participatory ergonomics program as a case study at a commercial roofing and waterproofing company in the state of Washington in the United States. The objective of this program was to develop and apply evidence-based solutions to prevent ergonomic injuries resulting from the handling of material carts. In the empirical case study, a research diary was kept to document the program's knowledge production process, which was analyzed to determine whether the implementation of the 2SAFE model contributed to the transition from practice to research. Participant observations, documentary information, and interview data were gathered to examine the changes in the intervention stakeholders' ergonomic motivation and knowledge, the behavioral changes they made, and downstream program outcomes, which were used to verify the model's efficacy in translating research into practice. The

quality of the qualitative data was ensured by data triangulation and member (key informant of the program) checking.

The results of the qualitative analysis show that the 2SAFE model helped to collect, frame, and share information to improve practitioners' perceived susceptibility to risk of injury, perceived severity of an injury, perceived benefits of ergonomic changes, and self-efficacy with regard to ergonomic issues. As a result, practitioner involvement in the program was active and generally voluntary. Decisions regarding the desired ergonomic changes were made by the intervention stakeholders at all levels of the organization. The industry partner's motivation for change was sustained throughout the program and the partner was also pleased to continue the research-practice collaboration as the members from the partner company recognized the benefits of implementing participatory ergonomics program.

Practitioners also contributed to the scientific aspect of the program by providing insights and assistance to co-produce knowledge that enhanced the evidential understanding of how various ergonomic hazards can influence the overexertion risk and productivity during cart handling. The knowledge is immediately transferable and helped construction practitioners make informed decisions when replacing manual equipment and planning material-handling activities. Moreover, practical insights informed the translation of knowledge and improved the actionability, contextually appropriateness, and readability of practitioner-focused ergonomic resources that were created by the program. Lastly, the results of the case study suggested some areas for improvement to develop the model further.

Situated at the intersection of construction ergonomics, behavior change, and health science, this dissertation provides a novel theoretical lens through which one can better understand how research-practice collaboration can be improved during a participatory ergonomics program to achieve a practice-to-research-to-practice transition. The 2SAFE is a business-centric model providing steps that can be implemented to encourage practitioners to embrace ergonomic changes in their organizations and to participate in the scientific inquiry process to strengthen the research enterprise. In the long term, this model will lead to high-quality interventions that combine scientific discovery with the resolution of real-world issues to prevent work-related musculoskeletal disorders, ultimately making construction sites a safer workplace.

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## CHAPTER 1 INTRODUCTION

### 1.1 Participatory Ergonomics: Preventing Musculoskeletal Disorders in Construction

Construction is a physically demanding industry featured by strenuous exertions, awkward working postures, and hand/arm vibrations (Spielholz, Davis, and Griffith 2006; Valero et al. 2016). Exposure to these ergonomic hazards can result in soft tissue injuries and illnesses collectively referred to as work-related musculoskeletal disorders (WMSDs). In 2015, the rate of WMSD injuries in the United States construction industry was 16% higher than the rate of all the industries combined (CPWR 2018a). Within the state of Washington, construction has been ranked as the highest risk industry in terms of WMSDs since 1990s, and a construction worker was 1.9 times more likely to have a WMSD than all the industries combined (Anderson et al. 2015). According to the same report, the average annual economic burden imposed in the state was over \$900 million, the highest among all the industries.

Investigating the root causes of WMSDs and implementing ergonomic interventions are anything but easy in the construction industry. Here, the intervention is defined as “a targeted set of actions, carried out in a workplace, whose purpose was to implement changes directly relating to the work, in order to prevent or curb WMSDs” (Denis et al. 2008). Construction workers can contact with various types of ergonomic hazards as they need to perform a wide range of tasks (Spielholz, Davis, and Griffith 2006). Given that every construction project is unique in its physical and organizational environment, workers may be exposed to different ergonomic hazards even when performing the same task at different projects (Paquet et al. 2005; Buchholz et al. 1996).

Furthermore, construction sites are constantly evolving as projects progress, adding substantial variability to physical environment–related hazards (Hess et al. 2004).

The difficulties of addressing ergonomic issues in the construction industry necessitate the involvement of researchers (Dasgupta et al. 2017). With researchers' technical expertise, practitioners can be equipped with advanced tools and methods to collect robust ergonomic data (Lee et al. 2017; Valero et al. 2016; Yan et al. 2017). On the other hand, worker involvement can provide researchers unique understanding of job to develop practical ergonomic solutions for problem solving (Annelise M de Jong and Vink 2002; Vink, Urlings, and van der Molen 1997; Hess et al. 2004). This model for research-practice collaboration in preventing WMSDs is generally referred to as participatory ergonomics (PE).

## **1.2 Going Beyond Action-Oriented Participatory Ergonomics**

PE can be defined as “the involvement of people in planning and controlling a significant amount of their own work activities, with sufficient knowledge and power to influence both processes and outcomes to achieve desirable goals” (Hignett, Wilson, and Morris 2005). Thus far, PE has been primarily used as an approach for translational research wherein researchers' academic expertise was brought into action to address ergonomic problems (Loisel et al. 2001; Annelise M de Jong and Vink 2002; Jensen and Friche 2010; Tappin, Vitalis, and Bentley 2016; van der Molen, Sluiter, Hulshof, Vink, van Duivenbooden, Holman, et al. 2005) and improve safety culture (Williams et al. 2010; Dale et al. 2016; Brandt et al. 2018; Visser et al. 2018). Such action-oriented programs emphasize the process of research-to-practice translation, with industry partners being the primary beneficiary.

However, the recent decades have witnessed a growing interest in exploring how researchers themselves can benefit from a participatory program (C. L. Balazs and Morello-Frosch 2013; Bach et al. 2017). First, there is a better chance for researchers to propose right research questions to reflect practitioners' needs and interests (C. Balazs et al. 2011). Second, involving populations being affected can enhance the rigor of a research by adding value to study design and data analysis, such as developing culturally sensitive research instrument (Minkler, Salvatore, and Chang 2012) and determining sampling strategies (Brody et al. 2009). Third, research findings produced through a participatory process are more likely to reach to diverse audiences (Campbell, Svendsen, and Roman 2016).

Thus far, promising results have been primarily documented in environmental health (C. L. Balazs and Morello-Frosch 2013; Brody et al. 2009; A. K. Cohen et al. 2016; Campbell, Svendsen, and Roman 2016), health promotion (Minkler, Salvatore, and Chang 2012; Binet et al. 2019), and epidemiology (Bach et al. 2017; Trinidad et al. 2015). There are few examples of success in the discipline of ergonomics. Little attention is given to assess the ways in which practitioner involvement can add value at each stage of an ergonomics research and how to balance new knowledge production and problem solving during a PE program.

### **1.3 Lack of Motivation and Knowledge in Implementing Participatory Ergonomics in Construction**

Active worker involvement, strong management commitment, and effective communication enable close research-practice collaboration and are key elements of a successful PE program (Bolis and Sznalwar 2016; Eerd et al. 2010). However,

researchers are confronted with various behavior-related challenges when initiating ergonomic improvements around these key elements (Yazdani and Wells 2018; Dasgupta et al. 2017).

First, construction practitioners tend to lack motivations of being involved in ergonomic interventions (Glimskär and Lundberg 2013; Boatman et al. 2015). Whysall, Haslam, and Haslam (2007) found that construction workers reported less concerns about WMSDs when compared to employees in other industries. Some workers even perceived WMSDs as an inevitable part of the job and believed there is no way to prevent WMSDs (Choi 2012; Village and Ostry 2010). Managers in the construction industry also place low priority on ergonomic issues due to low awareness of the long-term cost of WMSDs (Village and Ostry 2010; Boatman, Chaplan, and Teran 2012). The time pressure and financial constraints of construction projects can further dampen managers' willingness to invest in ergonomic changes (Dasgupta et al. 2017; Entzel, Albers, and Welch 2007).

Second, construction practitioners typically have limited knowledge of the nature and causation of WMSDs, limiting their involvement in root cause analysis and solution development during a PE program (Yazdani and Wells 2018; Dasgupta et al. 2017). Ergonomic trainings at construction companies were found inadequate and sometimes were instructed simply as “watch your back” (Hess et al. 2004; Eaves, Gyi, and Gibb 2016; van der Molen, Sluiter, and Frings-Dresen 2005; Choi 2012; Entzel, Albers, and Welch 2007). D. M. Kramer et al. (2010) found that more than half surveyed construction workers have no experience of using ergonomic solutions. Construction managers were also reported to lack knowledge and have low confidence in resolving ergonomic issues (D. Kramer et al. 2009).

In a PE program, researchers need to constantly communicate with intervention stakeholders to encourage their commitment and facilitate participation. Stakeholders are defined as “individuals, organizations, or communities that have a direct interest in the process and outcomes of a project” (Deverka et al. 2012), such as managers and workers. This strategy is particularly critical in the construction industry where a majority of practitioners have low ergonomic motivation and knowledge. Researchers need to identify, at the individual level, ways of influencing the intervention stakeholders’ decisions and behaviors that essentially determine their commitment and participation (Zink, Steimle, and Schröder 2008; Haslam 2002; Rost and Alvero 2020; J. Yang et al. 2021).

The recent decades have witnessed a growing interest in the theory and method of PE (Haims and Carayon 1998; Henning et al. 2009; Jaegers et al. 2014; Wells et al. 2003; van der Beek et al. 2017; Punnett et al. 2009). However, the theoretical and methodological advancement were mainly made at the organization level, with a view of offering strategic directions and/or standardized procedures for research-practice collaboration. Little attention is given to understand how to facilitate a PE program at the level of behavioral decision-making so that intervention stakeholders can stay prepared with ‘sufficient’ ergonomic motivation and knowledge to proceed with a PE program. The answers to this question have practical relevance because current PE programs reportedly have trouble engaging individual stakeholders to achieve desirable involvement (Yazdani and Wells 2018). For example, employee representatives dropped expectations as a program progressed (Pehkonen et al. 2009) and became passive in intervention activities (Bolis and Sznalwar 2016). Senior managers did not see needs of

change and ignored ergonomic issues brought up by worker representatives (Dixon and Theberge 2011).

#### **1.4 Research Objectives**

This chapter raises two important questions remaining understudied in construction ergonomics: how to use practitioners' input to strengthen the scientific inquiry during a PE program (i.e., from practice to research) and how to encourage practitioner participation, at the individual level, to facilitate the translation of research findings into action (i.e., from research to practice). Fundamentally, these two questions concern the ultimate goal of a participatory program: Achieving practice-to-research-to-practice (P2R2P) transition to motivate real-world changes through rigorous research and the application of research findings to action (A. K. Cohen et al. 2016). This dissertation aims at answering these two questions to improve our understanding of how to achieve P2R2P transition in PE programs by adopting a combination of theoretical and empirical approaches.

The theoretical approach is first performed which involves three steps: (1) drawing on health behavior theory to identify the behavior-related factors that should be addressed for facilitating a PE program at the level of decision-making; (2) digging into the typology of evidence in health science to identify various types of research contributions that could be made during a PE program; and (3) integrating the health behavior theory and typology of evidence with the understanding of WMSDs to design a theoretical model on how to achieve the dual goals of PE – advancing both practice and research of ergonomics. The model is called 2SAFE as it involves five essential steps: Surveillance, Screening, Assessment, Framing, and Evaluation.

Then, this dissertation reports on an empirical case study based on a PE program that was developed by the author using the 2SAFE model as guiding principles. The objectives of this case study are twofold: (1) testing the theoretical model and identifying areas of improvement as the model is implemented in practice and (2) demonstrating the value of PE as a scientific inquiry model using an example of success in the construction industry.

This dissertation research is expected to improve the ability of researchers to accomplish P2R2P transition during a PE program. In the long term, this dissertation can lead to more high-quality PE studies to create rigorous research findings that practitioners can immediately adopt to prevent WMSDs. Moreover, this dissertation can enrich ergonomics theory by creating an interdisciplinary model to link ergonomic concepts and methods with those from health behavior science, facilitating transfer of knowledge between ergonomics and health science.

## **1.5 Overview of the Dissertation**

The remaining of this dissertation is organized as follows. Chapter 2 presents a review of literature to identify the shortcomings of existing theoretical frameworks and state-of-the-art practice of PE. In Chapter 3, a novel PE model is constructed by synthesizing ergonomics and health science theories. Chapter 4 describes research methods applied in the empirical case study to test the model, and the results are reported in Chapter 5. Chapter 6 explores the theoretical and practical contributions of this dissertation research, followed by discussions on the limitations and implications for future work. Chapter 7 concludes the dissertation by summarizing key research findings.

## **CHAPTER 2 LITERATURE REVIEW**

Theory is the cornerstone of any ergonomic intervention program (Wijk and Mathiassen 2011). This chapter reviews recent theoretical advancement in participatory ergonomics (PE) and specifically looks into how health behavior theories are applied in ergonomic interventions. Shortcomings in current PE theoretical frameworks are identified. Then, this chapter gives an overview of PE programs that are documents in peer-review outlets and suggests a new path towards achieving a practice-to-research-to-practice (P2R2P) PE program. This chapter is concluded by summarizing knowledge gaps and discussing next steps of this dissertation.

### **2.1 Theoretical Advancement in Participatory Ergonomics**

There is a growing interest in the theory and methods of PE. In an early study by Haims and Carayon (1998), the concept of organizational learning was embedded into PE to allow for the development of a continuous improvement program. The proposed theoretical model emphasizes the roles of feedback and individual learning in achieving a gradual transition from an externally regulated PE program (by researchers) to an internally regulated one (by practitioners themselves). In line with this philosophy, Wells et al. (2003) distinguished between reactive and proactive PE and outlined the successful elements of each model. The authors also suggested that reactive and proactive models are complementary: The objective of the reactive process is to address existing ergonomic issues, whereas the proactive process aims at continuously collecting feedback from the previous changes to develop long-term ergonomic plans.

Furthermore, Henning et al. (2009) and Punnett et al. (2009) suggested integrating PE into an organization's current health initiatives to fully engage employees. Starting with this premise, they outlined a roadmap to show how the desired integration can be achieved within four phases of a PE program, i.e., problem identification, solution design, usability evaluation, and program sustainment. Nobrega et al. (2017) developed a toolkit, including a start-up guide for committee formation and training and a structured workflow, which offered practical resources as a supplemental to this roadmap. A similar PE process was proposed by Hess et al. (2004) who incorporated the conceptual model of the co-operative inquiry into ergonomic initiatives. The authors suggested that a successful PE program should accomplish four strategic goals: reaching an agreement on areas of inquiry, selecting initial solutions, implementing the proposed solutions, and designing and assessing practitioner-initiated modifications.

Haines et al. (2002) proposed nine dimensions to define the organizational structure and strategic directions of a PE program. These nine dimensions include Permanence, Involvement, Level of influence, Decision-making, Mix of participants, Requirement to participate, Topics addressed, Brief, and Role of ergonomics specialist. Moreover, Broberg, Andersen, and Seim (2011) suggested that this framework can be further improved by adding a new dimension Tools and Methods. The authors recommended that the selection of ergonomic tools and methods should depend on whether a PE program aims at modifying a current workplace or designing an entire new workplace.

A review of the literature indicates that recent theoretical advancement has been mainly made at the organization level, with a view of offering strategic directions for

research-practice collaboration during a PE program. However, what is lacking is the ability to identify, at the individual level, ways of influencing the intervention stakeholders' decisions and behaviors that essentially determine what a program can achieve (Zink, Steimle, and Schröder 2008; Haslam 2002; Rost and Alvero 2020). In other words, although organizational-level analysis informs us where a PE program should go, the process of how this can be achieved remains within a black box. This black box can only be unpacked by bringing a behavioral perspective into a theoretical discussion (Rothmore et al. 2017).

## **2.2 Applications of Health Behavior Theory in Ergonomic Intervention**

Health behavior theories seek to explain why a behavior change occurs and how this process can be facilitated by modifying psychological and environmental factors (Glanz, Rimer, and Viswanath 2015). This domain knowledge is not entirely new to ergonomics researchers and has been applied in the form of guiding principles to assess and analyze readiness for change on the part of intervention stakeholders (van der Molen, Sluiter, and Frings-Dresen 2005; Haslam 2002; Whysall, Haslam, and Haslam 2007). Health behavior theories also enrich researchers' tool kits for intervention design. A number of theory-based strategies have been proven to be effective in ergonomic interventions, including goal setting (McCann and Sulzer-Azaroff 1996), social support and feedback (Gravina, Lindstrom-Hazel, and Austin 2007; Sasson and Austin 2004), and tailoring (Oakman, Rothmore, and Tappin 2016; Whysall, Haslam, and Haslam 2007; Rothmore, Aylward, and Karnon 2015). Finally, behavior change theories are helpful for selecting measurement variables for evaluation of an intervention (Greene, DeJoy, and Olejnik 2005; Nieuwenhuijsen 2004; Robertson et al. 2009; Aliakbari et al. 2020).

These attempts have made a promising start towards applying insights from health behavior theories to ergonomic interventions; however, their application is still limited in terms of scope and depth (Wijk and Mathiassen 2011). This is particularly evident if state-of-the-art practice is compared with the constellations of behavior change methods and their best-practice examples in other areas (DiClemente, Salazar, and Crosby 2018; Kok et al. 2016). In an investigation by Rothmore et al. (2017), 44.7% of ergonomics consultants surveyed in Australia were unaware of any type of behavior change theory. This problem is largely ascribed to the isolated theoretical models between two disciplines and a lack of guidance on when and how to use behavior change methods. Therefore, it is critical to fill this gap by creating an overarching intervention model to integrate health behavior science and map out applicable behavior change methods throughout the program.

### **2.3 State-of-the-Art Practice of Participatory Ergonomics**

There have been extensive studies exploring the benefits of PE as an action-oriented model to prevent WMSDs (Burgess-Limerick 2018; Hignett, Wilson, and Morris 2005). PE interventions have been repeatedly proven effective in prioritizing ergonomic problems facing individual organizations and co-producing practical solutions (Annelise M de Jong and Vink 2002; Hess et al. 2004; A. M de Jong and Vink 2000). It is also found that industry participants can develop a sense of co-ownership during the participatory process and are more likely to accept and adopt the co-produced solutions (Loisel et al. 2001; Jensen and Friche 2010). PE approach was also successfully performed at the industry level for developing industrial practice and policy towards WMSDs prevention (Tappin, Vitalis, and Bentley 2016). However, the benefits of

implementing PE programs are mixed when it comes to long-term health outcomes, such as reduction in musculoskeletal symptoms. Cole et al. (2005) reviewed 10 high-quality PE interventions and found that 5 out of 10 of them showed significant effect in reducing musculoskeletal symptoms. In another literature review performed by Rivilis et al. (2008), 12 out of 23 PE programs demonstrated encouraging health outcomes, but the magnitude of effect varies between different programs.

The mixed health outcomes could be largely due to the diversity of program implementation (Burgess-Limerick 2018). Given this, scholarly attention has been recently given to understand how to better plan and implement a PE program. For example, in a randomized controlled trial (RCT) with 10 bricklaying contractors, van der Molen et al. (2005) found that recruiting ergonomics experts in a PE program can significantly improve workers' confidence and ability to use ergonomic solutions. Visser et al. (2018) further suggested that ergonomics experts should have more face-to-face communication with intervention stakeholders. In their RCT with 12 construction contractors, in-person consultations led to higher intervention compliance and greater changes in safety culture and knowledge as opposed to remote consultations. Moreover, Brandt et al. (2018) investigated whether objective ergonomic data collected by wearable sensors and video recorders can bring a PE program closer to success. Unfortunately, no significant beneficial impact was observed in the authors' RCT.

Taken together, PE has demonstrated particular promise for solving ergonomic problems facing individual organizations, and researchers have been gaining a deeper understanding of which implementation methods are effective in facilitating this problem-solving process. What is lacking in the existing body of knowledge, however, is

whether and how PE can be applied as a method of inquiry to strengthen the research quality.

Prior case studies in environmental science (C. L. Balazs and Morello-Frosch 2013; Brody et al. 2009; A. K. Cohen et al. 2016), health promotion (Minkler, Salvatore, and Chang 2012; Binet et al. 2019), and epidemiology (Ansumana et al. 2010) have showcased that the benefits of participatory approach are not confined to problem-solving. Practitioners' input can contribute to a research by widening the study scopes and aims, developing culturally appropriate data collection methods, and making produced knowledge more applicable and relevant to practice (Bach et al. 2017). Similar to these disciplines, ergonomics is an applied discipline whose growth is impossible without the participation of practitioners (van der Beek et al. 2017). Therefore, it is important to examine specific ways in which PE can add values to ergonomics research.

## **2.4 Summary**

Implementing ergonomic interventions in the workplace requires changes in the behavior of the key players. Existing PE theories are limited in addressing behavior-related factors that influence worker involvement and management commitment during a PE program. In view of this, Chapter 3 will create a theoretical model for PE by linking ergonomic concepts and methods with those from health behavior science. The aim is to provide insights on how to communicate with industry partners to promote their better decisions for injury preventions.

On the other hand, despite a growing literature highlighting the commitment of PE in action-taking, this chapter proposes that PE can become an integral part of the scientific inquiry to transform the way ergonomics study is conducted. Therefore, the

theoretical model to be created in Chapter 3 will also integrate the typology of evidence in health science to classify the scientific contributions that could be made by drawing on practical intelligence throughout a PE program. This overarching model will be empirically tested in the chapters that follow.

## **CHAPTER 3 THEORETICAL FRAMEWORK**

Initiating ergonomic interventions in a business environment to implement changes and prevent or curb WMSDs requires changes in the behavior of relevant actors. When participating in an intervention, researchers need to collect and share information with practitioners to help them make better behavior-related decisions. On the other hand, researchers need to bring practitioners into the scientific inquiry to gain practical insights for improving the relevance, rigor, and reach of research. This chapter describes the five-step 2SAFE (Surveillance, Screening, Assessment, Framing, and Evaluation) planning model, which can be used to guide research-practice collaboration in participatory ergonomics (PE) programs. This model combines the understanding of work-related musculoskeletal disorders (WMSDs) with the principles of the health belief model (HBM) and typology of evidence in health science. This theoretical synthesis empowers the model to address the following critical challenges: (1) how to make data collection processes attuned to the nature of ergonomic injuries; (2) how to transform the data collected into immediately usable information for practitioners to change their behaviors; and (3) how to interact with practitioners to strengthen research quality.

### **3.1 Principles of the Health Belief Model**

In the context of research-practice collaboration, behavior can be defined as anything a practitioner does in response to information shared by researchers that has an impact on changes in ergonomics. Here, the behavior is a broad concept that involves various aspects of a PE program, such as a manager's public commitment to supporting an intervention and active participation of employees in a training session. Understanding

the mechanisms by which behavioral changes are brought about can help researchers prepare and communicate information to achieve a collaborative PE program. The HBM is widely used to explain and predict health decisions and can be useful for this purpose (Glanz, Rimer, and Viswanath 2015). There is a growing recognition of the usefulness of the HBM in addressing workplace health problems (Zhao et al. 2012; Okun, Guerin, and Schulte 2016; DeJoy 1996). The HBM suggests that the key to encouraging health-promoting decisions is to deliver information that can arouse the target population's health beliefs, for which there are five determinants: perceived susceptibility, perceived severity, perceived benefits, perceived barriers, and self-efficacy (DiClemente, Salazar, and Crosby 2018).

### ***Perceived susceptibility***

'Perceived susceptibility' refers to a person's perception of the likelihood of developing a health problem if no change is made. A person with low perceived susceptibility is less likely to take preventative measures (Abraham et al. 2009; Harrison, Mullen, and Green 1992). For example, a worker could refuse to use an ergonomic control by presuming that 'I have done this many times and never been injured, so why bother making a change?'. Injury data, such as the incidence rate and odds ratio (A. L. Cohen 1997), can be used in ergonomic interventions to heighten a stakeholder's perceived susceptibility. A number of behavior change methods can be applied to better communicate susceptibility, such as personalized risk, scenario-based risk, dramatic relief, and fear arousal (Kok et al. 2016).

### ***Perceived severity***

‘Perceived severity’ refers to the degree to which individuals assess the negative outcomes of a health problem to which they are susceptible. A person who worries more about negative outcomes is more likely to embrace preventative measures (Janz and Becker 1984; Orji, Vassileva, and Mandryk 2012). The negative outcomes of a WMSD injury can be discerned from both tangible (lost days, medical cost) and intangible (reduced career longevity, lost productivity, reduced well-being) angles. Note that severity and susceptibility information is packaged together using similar behavior change methods (Glanz, Rimer, and Viswanath 2015), and the awareness campaign usually occurs at the start of a program to ensure adequate stakeholder engagement.

### ***Perceived benefit***

Once aware of the susceptibility and severity of a potential health problem, a person will contemplate taking actions to avoid it. All the while, the belief in the benefits of taking an action will be a driving force, which is called ‘perceived benefit’. Information on benefits can be broader in scope and include health outcomes, behavioral changes, and secondary positive effects, such as earning the respect of co-workers by adopting an ergonomic work schedule. Lack of belief in the benefits can stifle the desire for change (Janz and Becker 1984). For example, a senior manager could purport that ‘A cart is a cart. I don’t see any difference?’ when refusing to invest in ergonomic equipment. Researchers can consider behavior change methods, such as implementation intentions, re-evaluation, shifting perspective, and direct experience (Kok et al. 2016), to frame information for the benefit of persuasive communication.

### ***Self-efficacy***

The HBM refers to a person's perceived confidence in their ability to act upon a decision as 'self-efficacy'. Changes in ergonomics usually involve complicated courses of action. Practitioners who identify themselves as having limited expertise can be discouraged from making any substantive progress, and even worse, could develop a sense of denial ('when it's your time, it's your time!'). Skills-building knowledge and inspirational stories of success provide valuable information that can help intervention stakeholders prepare themselves, both physically and psychologically, for intended changes. Several behavior change methods, such as guided practice, enactive mastery experiences, reattribution, and contingent rewards, can be used to improve self-efficacy (Kok et al. 2016).

### ***Perceived barriers***

There are barriers in the physical and organizational environment that undermine the individual's commitment to health-protective decisions. 'Perceived barriers' refer to the individual's belief in the cost of implementing a decision in the face of barriers or the cost of overcoming those barriers. The HBM posits that one does 'mental math' and decides to make a change only when the perceived benefit outweighs the perceived barriers (Glanz, Rimer, and Viswanath 2015). To ensure the implementation of an ergonomic intervention, researchers should identify barriers and proactively include countermeasures in the intervention. Planning a coping response is an applicable behavior change method for identification of barriers, and facilitation and nudging provide a means for researchers and practitioners to co-brainstorm countermeasures (Kok et al. 2016).

Table 1 summarizes how the HBM can be applied during a PE program. The model implies that developing a PE program requires researchers to change practitioners' health beliefs and help them make a series of optimal decisions as the program progresses. This involves the communication of various health belief information with the help of behavior change methods. Note that different types of information are synergetic with each other and missing any of them could put a program at risk of failure (S. Yang et al. 2016; Orji, Vassileva, and Mandryk 2012). For example, raising practitioners' awareness of the risks and severity of an ergonomic problem should be followed by delivery of self-efficacy information about practical and realistic steps to address the problem. Otherwise the information on susceptibility and severity only creates anxiety that leads to defensive avoidance, instead of good 'fear' to motivate action (Janis and Mann 1977). This points to the need for a model to help researchers systematically collect health belief information as part of a PE program.

Table 1. The application of the health belief model in ergonomic interventions

<b>Behavioral determinants</b>	<b>Intervention objectives</b>	<b>Information needed in intervention</b>	<b>Behavior change methods</b>
<b>Perceived susceptibility:</b> <i>I'm at risk if no change is made</i>	Stakeholders being motivated by good 'fear' to collaborate with researchers	<ul style="list-style-type: none"> <li>• Epidemiological data (incidence rate and odds ratio)</li> <li>• Ergonomic data (frequency of exposure to an ergonomic hazard)</li> </ul>	<ul style="list-style-type: none"> <li>• Personalized risk</li> <li>• Scenario-based risk</li> <li>• Dramatic relief</li> <li>• Fear arousal</li> </ul>
<b>Perceived severity:</b> <i>I can't afford the cost</i>	Stakeholders being motivated by good 'fear' to collaborate with researchers	<ul style="list-style-type: none"> <li>• Epidemiological data (lost days, medical cost)</li> <li>• Ergonomic data (hazardousness of an ergonomic hazard)</li> <li>• Interview/observational data (lost productivity, reduced well-being)</li> </ul>	<ul style="list-style-type: none"> <li>• Personalized risk</li> <li>• Scenario-based risk</li> <li>• Dramatic relief</li> <li>• Fear arousal</li> </ul>
<b>Perceived benefit:</b> <i>I know what to do and why</i>	Stakeholders being committed to the goals co-developed by researchers and practitioners	<ul style="list-style-type: none"> <li>• Ergonomic data (preventative effect when a goal is reached)</li> <li>• Interview/observational data (return on investment, secondary positive effects, change in health beliefs and behaviors)</li> </ul>	<ul style="list-style-type: none"> <li>• Implementation intentions</li> <li>• Re-evaluation</li> <li>• Shifting perspective</li> <li>• Direct experience</li> </ul>
<b>Self-efficacy:</b> <i>I'm confident in getting it done</i>	Stakeholders being skilled in achieving the goals and willing to sustain the changes	<ul style="list-style-type: none"> <li>• Implementation knowledge</li> <li>• Interview/observational data (inspirational stories of success, critical reflection)</li> </ul>	<ul style="list-style-type: none"> <li>• Guided practice</li> <li>• Enactive mastery experiences</li> <li>• Reattribution</li> <li>• Contingent rewards</li> </ul>
<b>Perceived barrier:</b> <i>I have no concerns with changes</i>	Stakeholders' concerns being heard and addressed	<ul style="list-style-type: none"> <li>• Interview/observational/survey data</li> </ul>	<ul style="list-style-type: none"> <li>• Planning coping response</li> <li>• Facilitation</li> <li>• Nudging</li> </ul>

### **3.2 Typology of Evidence in Health Science**

Evidence, generally referred to as a body of information indicating whether a belief or proposition is true or valid, is a bridge between science and decision-making in practice (McKean 2005). Researchers are tirelessly creating evidence to help practitioners make sound judgement in health intervention (Yost et al. 2014; Jewell and Bero 2008). It is widely accepted that three levels of evidence are needed to advance research from pure scientific discoveries to evidence-informed changes (Rychetnik et al. 2004; Brownson, Colditz, and Proctor 2017). Evidence on each level has its distinct roles in a health intervention by providing information on risk-injury relation, the efficacy of an intervention, or the efficacy of an implementation.

Level one evidence describes quantitative relations between a health problem and its contributing risk factors. In other words, it informs which risk factors are related causally to the problem and to what extent. Level one evidence is generalizable because it is typically derived from scientifically rigorous research in highly controlled settings. Although practitioners cannot directly benefit from level one evidence due to low scientific literacy, this type of evidence is already on the “bench” of an intervention program for further interpretation and application (Brownson, Colditz, and Proctor 2017).

Level two evidence describes the efficacy of a specific intervention to address a health problem. This type of evidence can be interpretive (Rychetnik et al. 2004). By situating risk-injury relations within a real setting, one can propose level two evidence to predict the extent to which a health problem could be reduced if an intervention is applied. In doing so, one draws connections between level one evidence and the realm of practice. In a more rigorous form, level two evidence is evaluative which reveals the

efficacy of an intervention by testing it in a controlled environment or real setting. Compared to level one evidence, level two evidence has moved from “bench” to “bedside” by showing practitioners promising solutions and their benefits against a health problem in plain and understandable language.

Level two evidence will by no means guarantee the success of an intervention because it only suggests preventative effects of the intervention when it is properly implemented. Practitioners need information on how to effectively design and implement an intervention: who will execute an intervention, what will be done, with whom, and timing and frequency of involved activities (Atkins et al. 2017). Hence, level three evidence is needed to specify the efficacy of an implementation strategy. Such evidence could be specific to the context in which the implementation strategy is tested, but it still represents a valuable source of knowledge that can help practitioners make better decisions in undertaking an intervention under similar conditions. When adapting and evaluating an implementation strategy in multiple different contexts, one can improve the generalizability by understanding how and under which contextual circumstances an intervention will work and reveals mechanisms of why it will work. In this light, level three evidence helps deliver the practical value of research and moves scientific knowledge from “bedside” to “trench”.

### **3.3 Layered Structure of Ergonomic Exposures**

This section presents a layered structure of ergonomic exposures in order to pave the way for creation of an interdisciplinary PE model. The structure was developed by adapting the balance theory of job design (Smith and Sainfort 1989) and the multivariate

interaction theory of musculoskeletal injury precipitation (Kumar 2001). The structure posits that WMSDs are cumulative and multifactorial in nature:

### ***Cumulative nature***

WMSDs can be broadly divided into two groups—traumatic and idiopathic (Kumar 2001). A traumatic injury occurs when a physical load suddenly exceeds the tolerance threshold of a musculoskeletal system and causes immediate structural damage, such as a fibrillar tear (Hauret et al. 2010). In contrast, an idiopathic injury results from repeated exposure to an ergonomic hazard over a prolonged period (Kumar 2001). Cumulative fatigue within a musculoskeletal structure can progressively degrade the tolerance threshold of the structure and ultimately lead to idiopathic injury (Putz-Anderson 2017). The series of tasks performed prior to the injury should be investigated to determine the true nature of an idiopathic injury.

### ***Multifactorial nature***

Performing tasks requires workers to use exertions, make motions, and balance postures, which inevitably place physical loads on the musculoskeletal system. In this regard, physical loads can be categorized into three exposure measures: exertion, motion, and posture. Each exposure measure can be further expressed in three dimensions, namely, intensity, duration, and frequency (Burdorf and Van Der Beek 1999). Given that exposure measures and their dimensional levels can be influenced by the multitude of job elements that exist in the workplace, the development of WMSDs is multifactorial. The job elements of machines (including personal tools), task content, physical environment, materials, and the person interact to determine the exact way in which a task is carried out, thereby determining workers' physical exposures (Smith and Sainfort 1989). The

organizational context in which tasks are carried out usually acts as an effect modifier between physical loads and health outcomes (Putz-Anderson et al. 1997). Finally, different people have different health outcomes in response to the same exposure because of individual differences in body weight, genetically determined predispositions, and lifestyle habits (Costa and Vieira 2010). Therefore, factors related to the individual can modify the effect of physical stress on health outcomes.

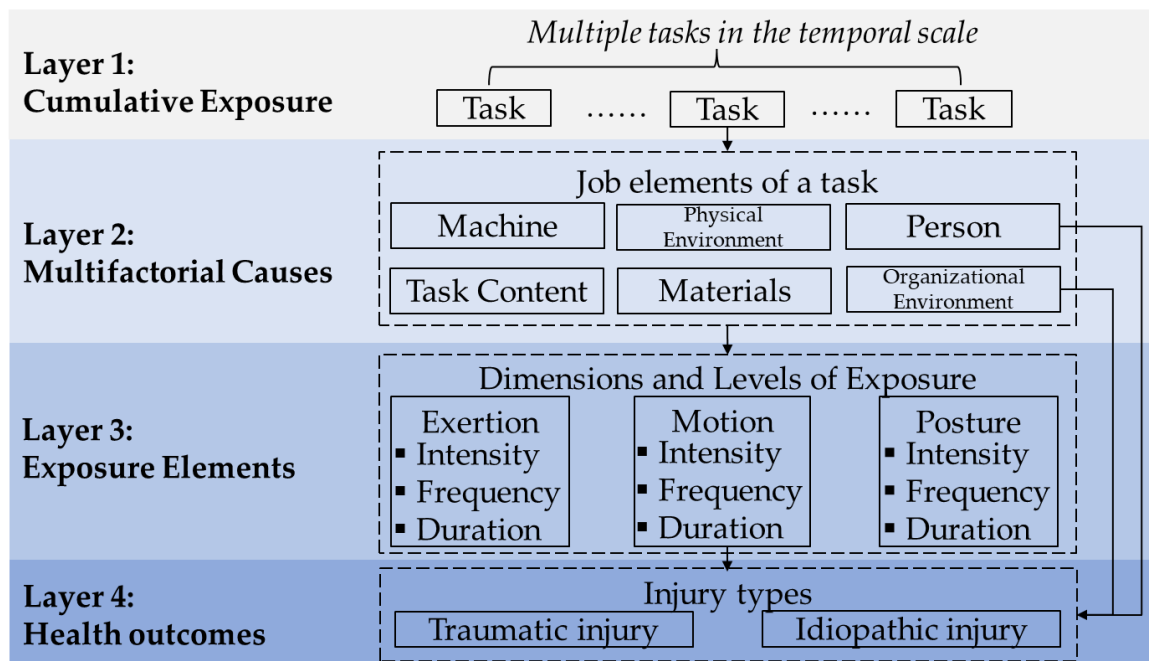


Figure 1. Layered structure for ergonomic exposures.

The layered structure of ergonomic exposures is summarized in Figure 1. The first layer represents the cumulative nature of WMSDs, that is, more than one task in the temporal scale can contribute to a WMSD injury. The second layer shows that each contributing task consists of six job elements that collectively determine ergonomic exposures. Subsequently, ergonomic exposures and their dimensions are specified in the

third layer and the corresponding health outcomes in the fourth layer. This order of layers matches the typical process of job safety analysis adopted by construction practitioners (Rozenfeld et al. 2010) and thereby can help them view and analyze WMSDs exposures during an ergonomic intervention. The cumulative and multifactorial nature of WMSDs should be navigated to reveal the excessive exposures and collect the necessary information in each layer to drive ergonomic behavior changes.

### **3.4 The 2SAFE Model**

#### **3.4.1 Development Process**

The 2SAFE model was adapted from an existing model Elements of Ergonomics Programs (EEP) developed by the National Institute of Occupational Safety and Health (NIOSH) based on its staff's extensive practical experience (A. L. Cohen 2017; A. L. Cohen 1997). The EEP was selected as the basis of the 2SAFE model because it offered an authoritative list of the elements of a workplace ergonomic intervention (left column in Figure 2). The EEP suggests a program start with learning about who is at risk and what qualifies as general ergonomic exposures to find the signs of potential WMSD problems, followed by improving the staff's ergonomic awareness. Then, health and medical evidence should be collected to determine the scope and characteristics of problems and inform the design of solutions. The solutions will be determined and tested in the next step, followed by program evaluation. Promoting worker recovery through healthcare management and return-to-work and maintaining management commitment and employee involvement were the last two steps of the EEP.

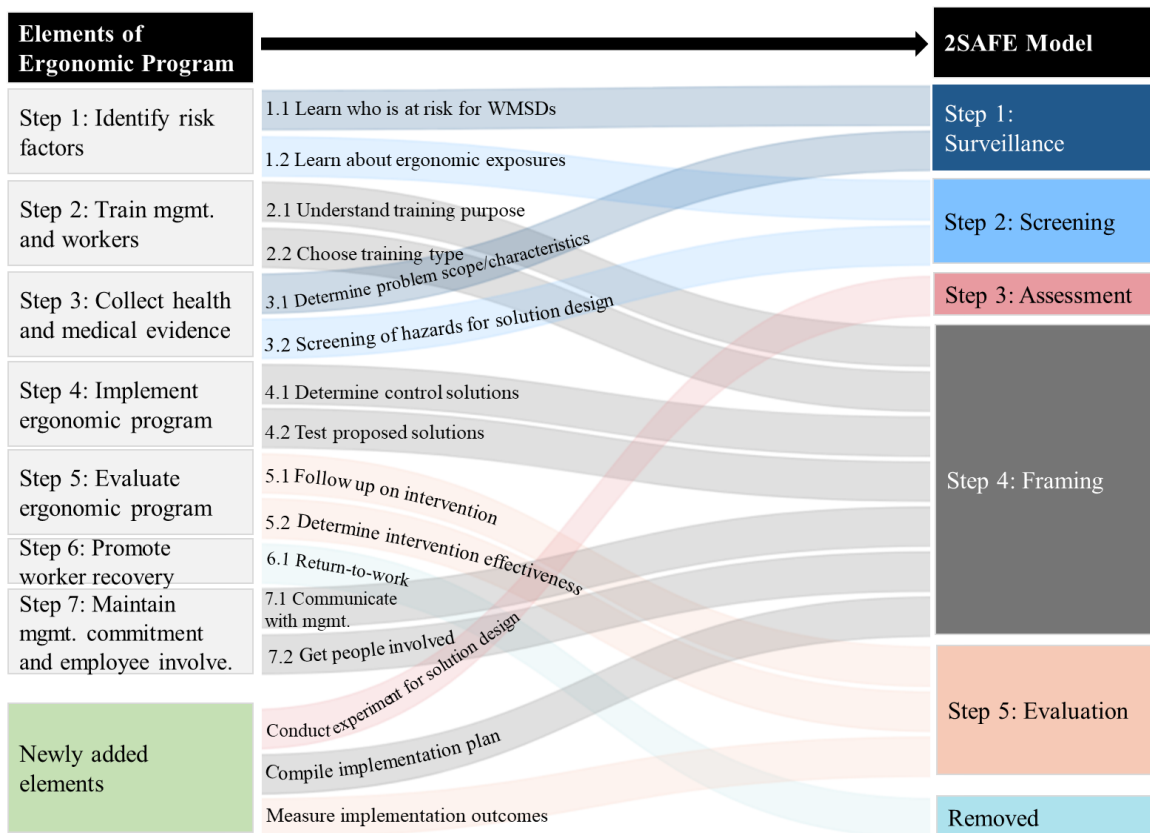


Figure 2. Development of the 2SAFE model: Source model and modifications

As a generic model for ergonomic intervention, the EEP needs to be adapted for several reasons in order to be used for guiding P2R2P during a PE program in the construction industry. The EEP does not explicitly consider how to promote intervention stakeholders' decisions at the individual level. Furthermore, the EEP is designed specifically for practitioners and does not discuss the roles of researchers in a participatory program. Finally, the EEP is not tailored for construction professionals and thus does not consider the industry-specific nature of WMSDs. Given these reasons, the author incorporated the insights from HBM, typology of evidence, and layered structure of ergonomic exposure into the 2SAFE model when adapting the EEP. The modifications

made to the EEP are illustrated in Figure 2, and the underlying rationales are listed below.

- Reversing the step 1.2 ‘Learn about ergonomic exposure’ and the step 3.1 ‘Determine problem scope/characteristics’: Ergonomic problems originate from tasks and constituent job elements that are broad in spectrum and large in magnitude (Figure 1). This is especially the case in the construction industry because of the dynamic nature of construction sites (Paquet et al. 2005; Buchholz et al. 1996) and a multitude of tasks a worker can be involved in (Spielholz, Davis, and Griffith 2006). Therefore, an intervention in the construction industry should start by detecting tasks and job elements that put workers at the highest ergonomic risk. In this way, program implementers can then prioritize risk factors within those problematic tasks and job elements for the sake of efficiency.
- Adding a new element ‘Conduct experiment to assess risk-injury relations for design of solutions’ and inserting it after the step 3.2 ‘Screening of hazards’: Screening tools are generic and simplistic by design, so their results often lack the level of details to explicitly reflect risk-injury relations that are required for design of solutions. This modification highlights the particular contribution that can be made by researchers during a PE program – generating level one evidence to reliably inform practice.
- Inserting the step 2 ‘Train management and workers’ after the new element ‘Conduct experiment to assess risk-injury relations for design of solutions’: According to literature in the health behavior change (Hawkins et al. 2008; Abraham et al. 2009), trainings are more likely to succeed when the materials are

personalized and customized to trainees. This new workflow suggests program implementers first understand the root causes of WMSDs by moving incrementally from layer one to layer four of the structure of ergonomic exposure (Figure 1) and then translate the collected complete information into tailored training programs.

- Merging the step 2 ‘Train management and workers’ and the step 4 ‘Implement ergonomic program’ because training is usually considered as one type of intervention methods (Molen et al. 2018; Westgaard and Winkel 1997).
- Merging the step 7 ‘maintain management commitment and employee involvement’ with the steps 2 and 4, because these three steps share the core activity: framing ergonomics-related data as health belief information for communication and intervention.
- Adding a new element ‘Compile implementation plan’ and merging it with the steps 2, 4, and 7: The typology of evidence emphasizes the significant role of the efficacy of an implementation in moving science to practice. There is a need to create an implementation plan, as it can determine whether the intervention can get management commitment and employee involvement to be implemented faithfully.
- Adding a new element ‘Measure implementation outcomes’ and merging it into the step 5 ‘Evaluate ergonomic program’: This modification aims to emphasize the evaluation of implementation efficacy, which is missing in the EEP.
- Removing the step 6 ‘Promote worker recovery’ because it is not directly relevant to the objectives of a PE program.

In summary, the principles of HBM, the typology of evidence, and the layered structure of ergonomic exposure are integrated to adapt the EEP, which leads to the 2SAFE model. The model plans a route for advancing both research and practice during a PE program. There are five fundamental steps in the model: surveillance, screening, assessment, framing, and evaluation. The schematics of the 2SAFE model is shown in Figure 3.

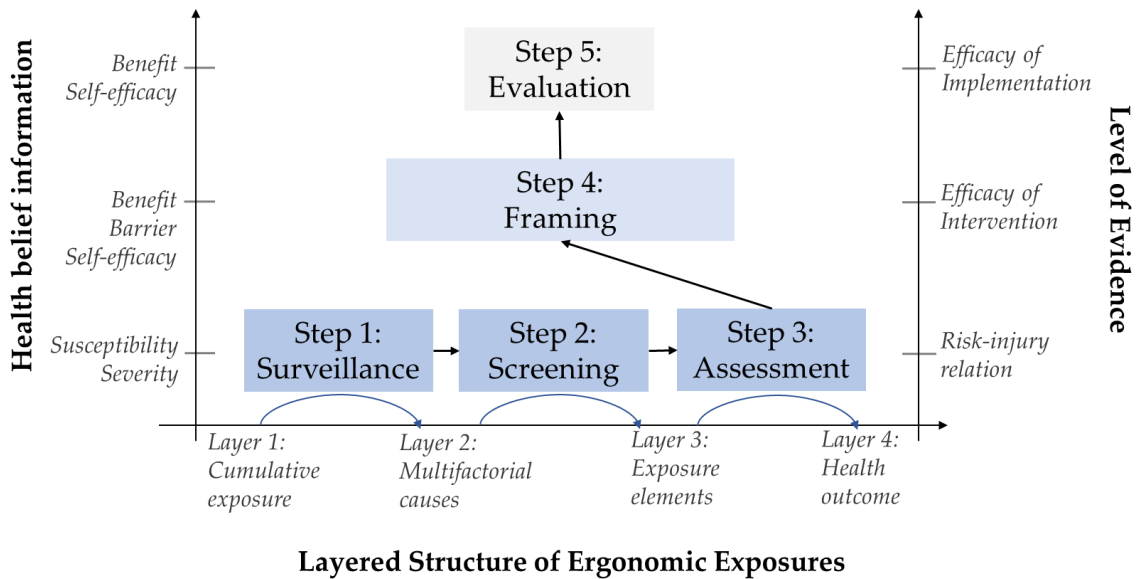


Figure 3. 2SAFE model: synthesis of the layered structure of ergonomic exposure, the health belief model, and the typology of evidence in health science.

Overall, the 2SAFE model breaks down a PE program into five steps to navigate the cumulative and multifactorial nature of WMSDs (X-axis of Figure 3) and to highlight both the level of evidence that can be generated at different phases of the program (right Y-axis) and the corresponding health belief data critical to ergonomic decision-makings (left Y-axis). In the first three steps, users of the model need to incrementally move from

layer 1 to layer 4 of the layered structure of ergonomic exposure (X-axis) to generate level one evidence (right Y-axis) for describing quantitative relations between a WMSDs injury and its contributing risk factors. The level one evidence will be presented in the form of susceptibility and severity information (left Y-axis) to provide explicit problem statements.

The results from the first three steps will then be framed as intervention solutions in step four. The solutions will be tested to generate level two evidence (right Y-axis) which can be translated into information on benefits to reveal preventative health, behavioral, and secondary effects (left Y-axis). In this step, an implementation plan will also be proposed to convey a contextual understanding of implementation barriers (information on barriers along left Y-axis) and express a competency in addressing these barriers (information on self-efficacy along left Y-axis).

The implementation plan will be evaluated in the last step of the 2SAFE model to generate level three evidence (right Y-axis). As a result, two types of health belief information (left Y-axis) can be generated to gauge the return on investment of the whole program and support the deliver the practical values of scientific evidence: benefits to reveal outcomes and impacts of program implementation, and self-efficacy to communicate knowledge about ‘know-how’.

### **3.4.2 Workflow of the Model**

The detailed workflow of the 2SAFE model is elaborated below:

#### ***Step 1: Surveillance***

The first step is detection of areas of concern that deserve closer attention. Injury data that contains information on susceptibility and severity can serve as a barometer for this purpose. The medical data held by industry partners is more contextually relevant and can be more compelling in raising stakeholders' health awareness (Hawkins et al. 2008; Abraham et al. 2009). As a supplemental to medical data, researchers can also interview at-risk individuals to determine their feelings about specific tasks and job elements and share them with organizational decision-makers to influence their perceived susceptibility and severity. A combination of these injury and interviewing data can drive both reflective and impulsive motivations to better facilitate behavioral changes (Presseau et al. 2014).

When collecting injury data, researchers should determine the work tasks that contribute to WMSDs and then break them down into constituent job elements to identify the problematic ones that are closely associated with WMSDs. Note that this step focuses solely on associations to allow rapid identification of cues indicating safety problems. The causal relationship will be examined in the following steps. The product of this step is the ranking of problematic job elements. This ranking contains information on susceptibility and severity that should inspire 'good' fears on the part of intervention stakeholders towards WMSDs and problematic job elements. The first step can be considered successful if stakeholders have been persuaded not to engage in 'exceptionalism', that is, being of the opinion that severe WMSD incidents will not happen to them. This step can set the stage for a PE program that has commitment from top management and encourages employee involvement.

Surveillance is a starting point for creating level one evidence that can reveal the underlying causes of problematic job elements. Researchers and practitioners should reach a consensus regarding which problematic job elements should be focused as joint research directions. Practitioners tend to focus on their urgent needs that are indicated by their company's injury and interviewing data, while researchers could be more interested in widespread problems captured by national or regional injury data. Shared goals should be achieved through collective discussion and negotiation to reflect interests and needs of both parties. Last but not the least, interviewing data could provide valuable insights into organizational factors to reveal structural determinants of ergonomic issues. Researchers should scrutinize this field data and pay special attention to at-risk populations when defining study aims.

### ***Step 2: Screening***

The purpose of screening is to understand how ergonomic concerns arise by revealing excessive exposures within problematic job elements. As shown in Figure 1, job elements can influence exposure in three ways, namely exertion, motion, and posture; each of these three dimensions need to be considered in terms of their intensity, duration, and frequency. Any measurement with a high value could give rise to a WMSD. However, it is too difficult to collect detailed data on all measurements for every problematic job element. Therefore, a screening process is needed that allows rapid identification of measurements indicating excessive risk levels. Many observational/interview tools have been developed for this purpose (AIHA Ergonomic Committee 2011).

Screening results for a problematic job element can be summarized in a nine-cell matrix to denote the intersections of three exposure measurements and three dimensions. A statement is provided in each cell to indicate susceptibility (i.e., how often a measurement exceeds the at-risk threshold) and severity (i.e., how excessive it is). The most prevalent and hazardous measurements can be selected as the focus in the following steps. Compared to the surveillance results that focus on tasks and job elements, this step moves one layer down to obtain information on the susceptibility and severity of ergonomic exposures. For one, the screening results can help researchers formulate research questions by pinpointing what exact exposure-injury relations (i.e., level one evidence) should be investigated. On the other hand, the screening results can be compiled into educational materials to inform stakeholders about the causes of WMSDs and alert them about the potential health consequences if excessive exposures are not addressed. Researchers can move on to the next step when consensus is reached with practitioners regarding the exposures that need to be reduced.

### ***Step 3: Assessment***

This step is an extension of screening and aims to develop level one evidence for fostering a deeper understanding of excessive ergonomic exposures. Scientifically rigorous experiments are needed to explicitly assess causal relationships between the identified excessive measurements and health outcomes. The core process is to involve practitioners and intentionally select experimental variables and their ranges, so that the results can be contextually relevant and applicable. Note that literature review should be conducted at the beginning of this step, and this step can be omitted if applicable evidence already exists.

The product of this step is a statistical analysis table showing how various problematic job elements of a task can interact to influence an ergonomics measurement. At this point, researchers have generated a detailed problem statement, critical review of literature, and level one evidence describing root causes of a problem. This provides a basis for researchers to write a peer-review paper to disseminate milestone research findings. On the other hand, because of the contextually relevant study design and rigorous process, the results of this assessment are more persuasive and could avoid potential distrust between researchers and practitioners. The quantitative data will be applied in the following steps to formulate solutions and set up the objectives of an intervention.

#### ***Step 4: Framing***

The results of the assessment are level one evidence and are not easily intelligible to a lay audience, which should be framed in plain language within the context of the intervention. In general, assessment results describe the magnitude of the effect of the various job elements on an exposure measurement by holding or averaging out all other experimental variables. However, in this step, researchers and practitioners should collectively examine how the magnitudes of effect vary under all possible working circumstances by deliberately varying the experimental variables to represent the working circumstances. Only by doing this can researchers create interpretive level two evidence to suggest to what extent a hazardous exposure should be reduced, what possible solutions can be applied, and what preventative health effects can be expected. An increase in perceived benefit can prompt stakeholders to perceive a need to embrace changes in ergonomics and co-develop a provisional list of solutions with researchers.

When brainstorming solutions, researchers should proactively interact with stakeholders, as well as other ‘organizational insiders’ who have experimental knowledge of the organizational and physical working environments, to pinpoint the barriers that could impede the intended changes in ergonomics. Although the solutions suggested by the level two evidence would be effective in an ideal environment, some may not be possible to implement and others could have unacceptable spill-over effects for stakeholders. Information concerning barriers helps researchers to understand the context of implementation, identify ways to remove barriers and increase stakeholders’ control of the process of change, and implement solutions that are realistic and organizationally appropriate to adopt. This is a key process in which researchers can demonstrate to practitioners that their concerns have been understood and addressed.

Ideally, solutions should be practiced and tested on a small scale to generate evaluative level two evidence before rolling out in a full-scale program. For example, practitioners can be requested to rehearse an interventional activity, discuss the experience, and build confidence and expertise before the program is implemented.

Once solutions are determined, an implementation plan should be generated to specify who will implement the solutions, what will be done, understand the precise circumstances in which they need to be implemented and with whom, and the timing and frequency of the activities involved. The goal of this plan is to improve intervention stakeholders’ personal ability to undertake the intended changes. The more detailed an implementation plan is, the more self-efficacy stakeholders will need to fulfil it.

### ***Step 5: Evaluation***

The final step is to evaluate the proposed implementation plan to capture the actual benefit of a PE program. Health outcomes have traditionally been emphasized when evaluating such a program. However, the HBM suggests that changes in behavioral determinants and outcomes should also be recorded. The measurement variables and scales for behavioral determinants and outcomes can be determined by referring to the HBM measurement framework (Glanz, Rimer, and Viswanath 2015). Researchers can use these types of benefit information as indicators to monitor intervention efforts and progress at the level of behavioral decision-making (Cervai and Polo 2018). Equally important, changes in behavioral determinants and outcomes can be achieved relatively rapidly, so that researchers can bring these immediate benefits to stakeholders' attention to continually strengthen their motivation to proceed with the program. For the same reason, stakeholders' subjective feedback on secondary positive effects is also a valuable source of information on benefits. Overall, the information concerning benefits collected in this step can help practitioners to recognize ergonomic interventions as a rewarding process and promote their adherence to changes.

Self-efficacy information should also be accumulated in this step. For example, researchers can ask stakeholders to reflect on their experience of participation in an intervention and explain the reasons for its successes and/or failures. Inspirational stories and successful mastery experiences can then be summarized and shared with other stakeholders to reinforce their competence in fulfilling the intervention. Such self-efficacy knowledge can also be passed on to other researchers and program planners for successful design of PE programs in the future. Self-efficacy information is critical for sustainability of a program because it determines whether or not stakeholders have

developed sufficient motivation, expertise, and confidence to sustain the program after the researchers leave.

When a rigorous evaluation process is conducted, obtained benefit and self-efficacy information can be synthesized and converted into level three evidence to describe the efficacy of an implementation plan. Researchers should carefully document the contextual circumstance in which a program is implemented, so that potential users will understand the applicability and limitations of the implementation plan in their own settings. A journal paper and industry report can be written based on the evaluation results. In an ideal situation, practitioners could be actively engaged in the marketing and dissemination of the level three evidence to industry after fully recognizing its benefits.

### **3.5 Discussions and Next Steps**

This chapter discusses the 2SAFE (Surveillance-Screening-Assessment-Framing-Evaluation) model. By bridging the disciplines of ergonomics, health behavior theory, and health science, this model combines an understanding of the nature of work-related musculoskeletal disorders with the principles of the HBM and the typology of evidence. It has been developed to allow researchers to isolate the information they need to facilitate practitioners' decision-making for desired changes and claim scientific contributions during a participatory process. A real-world application will be demonstrated in the following chapters to illustrate how it works and identify areas for improvement as it is implemented in the real world.

## **CHAPTER 4 RESEARCH METHOD**

In the research for this dissertation, an empirical case study was conducted to provide a step-by-step example of using the 2SAFE model in an actual participatory ergonomics (PE) program and illustrate how the model works. The case study is also a formative prototyping process, wherein this theoretical model was tested in a real-world context for the purpose of improvement. This chapter begins by presenting the rationale for and the overall design of the case study. A brief description of the participatory process is then provided, followed by an introduction to the measurement methods and qualitative data used to evaluate the performance of the PE program.

### **4.1 Study Design**

Case study is an appropriate method to evaluate a theory within real-world contexts (Yin 2017). Its closeness to real-life situations allows researchers to obtain a wealth of evidence for the crucial examination of how and why a program theory works (Rogers et al. 2000; Veerman and van Yperen 2007). In the previous chapter, the author supplied the key theoretical attributes of ergonomic information that could promote better decision making in both problem solving and in research inquiries, as well as a workflow (Section 3.4.2) of collecting such information during a PE program. In the case study presented in the remainder of this dissertation, the author paid particular attention to areas of improvement for the 2SAFE model as it was implemented in practice. Taking the notion of ethnographic method, this case study reflects the author's personal experience as the lead researcher in a multiple-year PE program at a commercial roofing and waterproofing company. By following the 2SAFE model, this program aimed to prevent

WMSD injuries resulting from material cart handling, with an embedded research project that provided scientific evidence for the design of intervention solutions.

Qualitative data were gathered to track the decisions made by researchers and practitioners, the contexts in which these decisions were made, and the actions and downstream program outcomes. The data sources included participant observations, documentary information, interviews, and a research diary. The performance of the 2SAFE model in facilitating the R2P translation was examined by mapping the ergonomic information provided by the program against each intervention stakeholder's decisions and the downstream program outcomes. The performance of the 2SAFE model in strengthening the quality of the research was analyzed by summarizing how participatory inputs shaped the scientific process in the PE program using the three Rs (rigor, relevance, and reach) framework provided by C. L. Balazs and Morello-Frosch (2013). The validity of the qualitative data analysis was ensured via data triangulation and member (key informants in the program) checking.

In addition to the evaluation of theory, the author aimed to refine the operability of the 2SAFE model via feedback from the participants during the case study. At this stage, the model was presented in the form of general rules and tactical planning with little concern about operational details, such as where to find key information and which tools to use. The praxis of operationalizing a theory cannot be accomplished by examining the theory on paper, as they will only emerge when putting the theory into practice in real-world settings (Schram 2012). In line with this research philosophy, the author derived experiential knowledge from the case study and translated it into operational guidelines as a complement to the theory-informed model. The ultimate goal

is to extend the 2SAFE model to produce an instruction manual to inform efforts to achieve P2R2P transition during a PE program. In fact, many frameworks and approaches have been developed by adopting this hands-on method, such as Intervention Mapping (Bartholomew, Parcel, and Kok 1998) and the Promoting Action on Research Implementation in Health Services (PARIHS) framework (Kitson, Harvey, and McCormack 1998), to name just two.

The empirical case study is also presented for demonstration purposes. The author anticipates that the contextual details and step-by-step illustrations will make the theoretical model easier for potential users to understand. Furthermore, as suggested by Flyvbjerg (2001), narrative accounts can assist readers to relate to the specific context in which the operational details of the model were developed to better understand their practical rationale and the potential limitations that are subject to future improvement. Finally, this empirical case showed promising results with regard to achieving P2R2P during a PE program and could thus serve as an inspirational success story to encourage more PE programs that could strike a balance between research enterprises and real-world problem solving.

## **4.2 Case Selection**

The industry partner selected for this case study was a family-owned, privately held commercial roofing and waterproofing company. Located in the Pacific Northwest of the United States, the company is one of the largest of its kind in this region, with more than 150 employees delivering full service for more than 30 projects of various sizes and types every year. Most of its business involves large construction projects, such as light rail stations, retail centers, university stadiums, commercial complexes, and so

on. The company is dedicated to safety and has consistently been rated among the top five safest construction contractors in the Washington State during the study period. As it is motivated to continuously improve its safety records, this company had a strong interest and prior experience in safety research at the time of the program's inception.

According to the diffusion of innovation theory (Dearing 2009), this company can be categorized as an early adopter with low resistance to innovation. In this regard, this case constituted a critical case: If the 2SAFE model were to be invalid in this case, it would be unlikely to be effective in other cases (Flyvbjerg 2006). However, as satisfactory results were achieved, this single-case study can reveal insights regarding how to use the 2SAFE model to engage other construction contractors that are included in the category of early adopters (Yin 2017).

This PE program was an embedded research project (Vindrola-Padros et al. 2017), as the author was employed by the industry partner while pursuing a Ph.D. at the University of Washington. The partnership began when the author worked as an Environment, Health and Safety (EHS) intern/assistant at the company. The author was directly involved in the company's routine safety operations, which provided opportunities for collecting participant observations and interview data. The "insider" experience also allowed the author to gain familiarity with the company's management system and to identify all the archival documents that could possibly be used to inform the research. Furthermore, the author and his research team were given direct access to all the company's records, as well as to jobsites and workers, which provided an excellent opportunity to explore the implementation of the 2SAFE model empirically.

Similar to other single-case studies, the research process was susceptible to the particular context of the study, and the research findings may not be generalized to other settings (Sultan 2018). The author must acknowledge the potential influence of such individual knowledge and experience. However, this does not undermine the contribution of this study or its empirically proven model that is subject to further improvement, adaption, and extension to broader applications. For example, the experientially produced Intervention Mapping (Fernandez et al. 2019) and PARIHS frameworks (Harvey and Kitson 2016) mentioned previously have been evolving consistently since their inception via feedback from empirical testing in various settings.

#### **4.3 Participatory Process**

The PE program was led by a research team at the University of Washington between June 2018 and September 2021. The author of the dissertation worked as the lead research coordinator in the program. Individuals employed at different levels by the industry partner were involved in the program, including managers, site supervisors, and field workers. Specifically, the EHS director and the EHS manager were the two key informants who functioned as the author's primary point of contact at the industry partner. The program was divided into two major phases (Figure 4) as the 2SAFE model was repeated twice, which were a preliminary phase and a detailed phase.

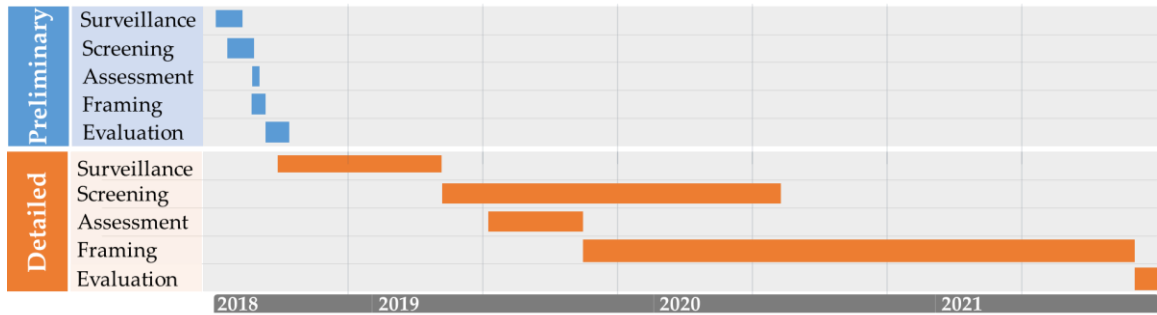


Figure 4. Timeline of the PE program

In the preliminary phase, the 2SAFE model was implemented for a short period between June 2018 and August 2018. The original intention was to develop data-driven ergonomic awareness training, but the author and the company extended the collaboration and embarked on a longer-term ergonomic initiative after observing the success of the preliminary phase. The detailed phase was implemented between September 2018 and September 2021, wherein the 2SAFE model was used extensively in order to jointly develop evidence-based solutions to prevent cart handling injuries. The overall goals of the two phases, as well as objectives and activities of each step are summarized in Table 2.

Table 2. Objectives and activities of the two phases in the case PE program

	<b>Preliminary phase</b>	<b>Detailed phase</b>
<b>Practical goal</b>	Initiated data-driven ergonomic training	Developed solutions to reduce cart handling injuries
<b>Research goal</b>	N/A	Created level one evidence to support the design of the solutions
<b>Objectives for each step</b>		
Surveillance	Analyzed company injuries between 2017 and 2018 to find problematic tasks and job elements	Analyzed company injuries between 2015 and 2018 to increase credibility of surveillance results
Screening	Conducted 2-month field observations to identify ergonomic hazards and propose solutions	Conducted survey and field observation tracking cart use for 15 months to identify related hazards; and reviewed literature to propose research questions whose answers can support design of solutions
Assessment	Measured and compared the forced required to operate new and old four-wheel carts	Perform experiments to understanding of the effects of cart condition, tire type, environment-related factors, and load on ergonomics and productivity of cart handling
Framing	Created and rehearsed training presentation	Translated experiment results into intervention resources and compiled implementation plan
Evaluation	Collected feedback on the training presentation	Designed an evaluation plan for the program to be implemented from June 2021 to June 2023

#### 4.3.1 The Preliminary Phase

The partnership began with the author’s employment as an EHS intern at the industry partner in June 2018. Because WMSDs had been a concern at the company for an extended period, the author’s main responsibility was to prepare an ergonomic training program.

### ***Step 1: Surveillance***

The author and the EHS director first analyzed the company's incidents of WMSDs between 2017 and 2018. The data sources included workers' compensation records, nursing triage reports, and incident investigation reports. The author interviewed five injured workers/witnesses at the company office to obtain supplementary information. Injured workers' medical diagnoses and timecards were also scrutinized to track job elements that contributed to WMSDs; the number of incidents and the sum of the medical and indemnity costs were acquired from the workers' compensation system and the company's annual financial reports for each of the problematic job elements.

### ***Step 2: Screening***

In June and July of 2018, the EHS director and the author conducted field observations to identify excessive ergonomic hazards posed by problematic job elements, with two jobsites being observed every week. The Physical Job Evaluation Checklist (Washington State Department of Labor and Industries 2016) and the screening tool for four-wheel hand carts recommended in the book *Kodak's Ergonomic Design for People at Work* (Chengalur 2004) were used to analyze the observational data. OSHA's screening tool was applied as a complement to include additional numerical thresholds concerning postures and durations (Hament 2001). The screening results were discussed with the EHS director and the research team to brainstorm possible measures that could decrease the identified hazards.

### ***Step 3: Assessment***

The screening results regarding material cart handling did not convince the program team because the referenced acceptable cartload appeared to be too low; due to

having large wheels, a roofing cart could require less operating force compared to other industrial carts. In addition, the screening tools did not consider malfunctions of old carts as a contributor to WMSDs. These limitations indicated a need to explicitly assess the effect of cartloads on the risk of WMSDs posed by roof carts, and to examine whether the effect would be amplified as a cart became older. To accomplish this, a digital force gauge was used to assess the force required to sustain the movement of such carts in July 2018. A brand-new cart and a poorly maintained cart that had been in service for more than five years were tested in the industry partner's warehouse. By referencing the Liberty Mutual Manual Materials Handling Table (Snook and Ciriello 1991), the force data were converted into the capability percentage to understand the psychophysical severity of cart operation. Data to be entered in the Liberty Mutual Manual Materials Handling Table, including the operating posture, the travel distance, and the frequency of use; these were obtained from the field observations that were conducted in the previous phase.

#### ***Step 4: Framing***

The surveillance, screening, and assessment results were distilled and converted into presentation slides, which not only illustrated the prevalence and severity of WMSDs injuries at the industry partner's company, but also provided data-informed solutions. The presentation was rehearsed at the company's safety committee meeting to gain an understanding of the industry partner's attitude toward and knowledge about the presentation topic, as well as the expectations, and to make stylistic and content choices. The committee consisted of 15 representatives from both the administration and the fieldwork teams. The modified presentation was then rehearsed at a top management

team meeting. The attendees included the company's CEO, the president, two superintendents, and one senior project manager. The purpose of this presentation was to gain management's commitment and to obtain feedback. Finally, a 20-minute awareness training presentation was created, and was presented at an All-Hands meeting at the end of July 2018.

#### ***Step 5: Evaluation***

The company's CEO, the president, two foremen, and five workers were requested to evaluate the effectiveness of the training presentation.

#### **4.3.2 The Detailed Phase**

The preliminary findings assisted the research team and the industry partner to determine the focus for the detailed phase, namely the prevention of injuries caused by handling carts. In the detailed phase, the five-step workflow was implemented again but in a more thorough manner. A research grant application was jointly prepared, which resulted in an award to continue the P2R2P collaboration.

#### ***Step 1: Surveillance***

This step was an extension of the surveillance in the preliminary phase. The same surveillance approach and data sources were used to analyze the company's historical WMSDs incidents between 2015 and 2017. The intention was to increase the sample size and the credibility of the surveillance results.

#### ***Step 2: Screening***

A longitudinal trial to track how material carts were operated in the field began in April 2019. The company's foremen were recruited to complete a daily survey and to return in together with the company's timesheets. The author and the EHS director also visited jobsites to gather observational data, with one jobsite being observed each month. The repeated surveys and site observations followed the sampling strategies proposed by Buchholz et al. (1996) and Paquet et al. (2005), and ensured the validity of the screening results.

The program team discussed the screening results in June 2019 with the aim of identifying excessive ergonomic measurements for cart handling and co-defining intervention objectives and research focuses. As a result, the team identified the potential for modifying work procedures and processes to prevent overexertion in pulling and pushing (OPP) resulting from cart handling. Possible intervention measures included preventative cart maintenance, tire selection, the workplace layout, and task pre-planning (e.g., load restriction and teamwork). The author then conducted a literature review to find scientific evidence that could support the design of the solutions. The following four knowledge gaps were identified:

(1) How does the risk of OPP increase and productivity decrease as carts age and develop structural problems?

(2) How do tire types (solid versus pneumatic tires) impact on the risk of OPP and on productivity?

(3) What are the main interaction effects of factors related to the physical environment, (i.e., obstacle height, ramp slope, and space constraints, on cart operation?

(4) How do the risk-injury relations mentioned above change under different loads?

After determining the research focuses, the surveys of cart use and the field observations were extended for a further 12 months (June 2019 to June 2020). The results were used in the assessment step as a required entry for the Liberty Mutual Manual Materials Handling Table (Snook and Ciriello 1991) to convert force exertion into the capability percentage, and to understand the risk of OPP when operating carts.

### ***Step 3: Assessment***

To answer the proposed research questions and to inform the design of the intervention measures, a series of research experiments was designed and conducted via a collaborative process. Field observations were conducted by the EHS director and the author between June and August 2019, with two jobsites being observed each month. This was done to observe and record the working circumstances in which cart operations were performed, which helped to determine the degree of interaction between various experimental parameters and the range of each experimental parameter. Four foremen were surveyed for further confirmation of the design choices. Furthermore, two field workers assisted us to determine the pulling techniques adopted in the experiment, and provided training and observational feedback to an experiment subject in the practice trials. The EHS manager and two workers set up tracks in the laboratory to simulate a real construction site. All the experiments were conducted in the industry partner's warehouse with the assistance of warehouse personnel and the EHS manager.

### ***Step 4: Framing***

The author took the lead in analyzing the experimental data, and the industry partner was subsequently involved in the interpretation of the results. Data analysis reports were developed to specify the extent to which exposure to hazards could be decreased and the ergonomic changes that were needed. Individual meetings were then scheduled with the EHS director, the EHS manager, two foremen, and four workers, during which actionability for each change was discussed. As a result, the author developed numerical guidance to illustrate the intervention measures (that is, preventative cart maintenance, tire selection, workplace layout, and task pre-planning) and the corresponding benefits of prevention. The author developed a one-hour long ergonomic training session based on the numerical guidance in collaboration with the EHS director and the EHS manager; the session was presented at the All-Hands meeting in August 2021. The guidance was then expanded to produce different program products, including a five-page training handout, a planning tool, and two animated videos. An implementation plan was also developed.

The creation of the products involved two rounds of iterations and were advanced through another successful grant co-application. In the first round, the products were sent to the EHS director and EHS manager for review. Individual meetings were then schedule with them to solicit feedback and refine the products. Specifically, the discussions focused on examining if the scientific results were framed into plain language that construction workers can understand and if there is any barrier to the implementation of the intervention measures. Refinement was primarily made in content and visual design.

In the second round, the refined products were presented to 12 safety trainers from the United Union of Roofers, Waterproofers & Applied Workers. Individual interviews were conducted to receive feedback regarding whether the scientific information included in the products was conveyed clearly. A \$50 gift card was provided to each participant. In addition, the safety animations were presented to three focus groups at the industry partner's company, and a total of 31 field workers participated in rating the quality of the animations and provided feedback. A \$25 gift card was offered to each participant. Finally, the animations were tested in the industry partner's safety orientations and foremen's meetings, and a total of 45 new hires and 20 foremen were involved in rating and refining the program's products. Positive feedback obtained during the iteration process was shared with the EHS director and the EHS manager to increase their self-efficacy in applying these products in a long-term intervention program.

### ***Step 5: Evaluation***

The author and the EHS director co-formulated an evaluation plan to gauge the effectiveness of the implementation plan. Following another successful research grant application, the plan was eventually converted into a different PE program that focuses on evaluating the efficacy of the implementation plan. This program is scheduled to be implemented from June 2021 to June 2023.

## **4.4 Methods for Examining Program Performance**

Various forms of qualitative data were collected to examine the achievements of the PE program. Special attention was paid to reflecting on the role of the 2SAFE model in the program's successes and failures with a view to improving the theoretical model.

Given the dual function of the 2SAFE model, the performances of the program were measured according to the following two perspectives: R2P translation and the strengthening of P2R. Methods for examining the R2P and P2R performance are briefly described below, respectively, and more technical details can be found in Appendix A.

#### **4.4.1 R2P Translation**

The first function of the 2SAFE model was to provide researchers with insights into how to encourage practitioner participation at the behavioral level to facilitate the translation of research into practice. Here, the behavior is a broad concept that involves various intervention stakeholders at different levels of the organization, such as top managers, the EHS team and other middle-level managers, site supervisors, and field workers. Given that the participants' behavior could be driven by changes in any health belief such as perceived susceptibility to risk of injury, perceived severity of the injury, perceived benefits of implementing the program, self-efficacy with regard to ergonomic changes, and perceived barriers to implementation, a total of five outcome measures were defined based on the HBM (DiClemente, Salazar, and Crosby 2018; Glanz, Rimer, and Viswanath 2015) for each type of intervention stakeholder in the PE program, as shown in Table 3.

Table 3. Program objectives for R2P translation

<b>Intervention stakeholders</b>	<b>Outcome measures</b>
Top Managers (the company's CEO and the president)	<b>R2P-TM1:</b> perceived susceptibility <b>R2P-TM2:</b> perceived severity <b>R2P-TM3:</b> perceived benefit <b>R2P-TM4:</b> self-efficacy <b>R2P-TM5:</b> perceived barrier
EHS Team (the EHS director and the manager)	<b>R2P-ET1:</b> perceived susceptibility <b>R2P-ET2:</b> perceived severity <b>R2P-ET3:</b> perceived benefit <b>R2P-ET4:</b> self-efficacy <b>R2P-ET5:</b> perceived barrier
Middle-level Managers (the estimator, the warehouse manager, and project managers)	<b>R2P-MM1:</b> perceived susceptibility <b>R2P-MM2:</b> perceived severity <b>R2P-MM3:</b> perceived benefit <b>R2P-MM4:</b> self-efficacy <b>R2P-MM5:</b> perceived barrier
Site Supervisors (the superintendents and foremen)	<b>R2P-SS1:</b> perceived susceptibility <b>R2P-SS2:</b> perceived severity <b>R2P-SS3:</b> perceived benefit <b>R2P-SS4:</b> self-efficacy <b>R2P-SS5:</b> perceived barrier
Field Workers	<b>R2P-FW1:</b> perceived susceptibility <b>R2P-FW2:</b> perceived severity <b>R2P-FW3:</b> perceived benefit <b>R2P-FW4:</b> self-efficacy <b>R2P-FW5:</b> perceived barrier

To determine the success of the PE program in achieving the R2P outcomes defined in Table 3, qualitative data were gathered using an ethnographic method with participant observations as the primary source of data. Participant observations allowed the author to capture intervention stakeholders' spontaneous responses and generate contextual understanding of the program implementation and outcomes. Rapport with stakeholders can be developed through repeated interactions to encourage open communication (Tong, Sainsbury, and Craig 2007).

As an intern at the industry partner (June 2018 – April 2019) and as the lead researcher in the PE program (May 2019 – September 2021), the author was able to

observe the PE implementation process closely. Field notes and photographs were taken to record conversations and discussions among practitioners and between practitioners and myself while visiting jobsites, attending company meetings, and conducting experiments in the warehouse. The secondary observation by the EHS director was used for the weekly senior managers' meetings, routine safety training, and safety inspections. The EHS director had frequent and close interactions with other intervention stakeholders whose observations represented a company insider's perspective. Taken together, the participant observations from the author and the EHS director provided a complete narrative account of the program activities, the stakeholders' decisions, and the underlying changes in health beliefs.

Observational evidence was triangulated using archival data and formal interviews to generate confidence in the credibility of evidence and add a richer understanding to the implementation of the program (Farmer et al. 2006). Textual analyses of corporate policy documents, emails, and meeting notes were performed to examine how the intervention stakeholders' decisions revealed during the participant observations were translated into written documents. Key intervention stakeholders, including the EHS director and the company's president, and two foremen were interviewed following the completion of the PE program. Each interview was semi-structured and lasted for approximately 20 minutes. The interviewees discussed their personal experiences within the program, with an emphasis on how their health beliefs had changed during the program and how this had shaped the decisions that they made.

The qualitative data were sorted by the author based on the involved intervention stakeholders and then coded using a coding scheme that was generated inductively. The

themes related to changes in health belief were categorized deductively based on the measurement framework presented in Table 3. The relationships among themes about program outputs, health belief, stakeholders' decisions, and influence on the program were also coded. The emphasis was on mapping the ergonomic information provided by the program against intervention stakeholders' changes in health beliefs, the actions they carried out to facilitate the problem-solving process, and the downstream program achievements. The interpretation of the results eventually generated a contextual understanding of how the use of the 2SAFE model contributed to the program's achievements. The preliminary results were frequently discussed within the research team, and the EHS director and the EHS manager performed a member check to ensure the credibility of the analysis.

#### **4.4.2 Strengthening P2R**

The second function of the 2SAFE model was to provide researchers with insights regarding how to use practitioners' input to enhance the scientific inquiry during a PE program. In this case study, the industry partner was engaged in each stage of the research process. A research diary documenting the original research plan, the participatory feedback, and revisions to the research process was kept. Research diary is used as a common method to record the research trajectory and important decisions (Engin 2011) and to assist researchers in practicing reflexivity (Nadin and Cassell 2006).

The evolution of the research project was tracked by comparing the planned and the actual ways in which the research was conducted. This enabled the identification and summary of the benefits of practitioner participation in terms of P2R objectives that are outlined in Table 4. The objectives were determined by referring to the framework

created by C. L. Balazs and Morello-Frosch (2013), which is one of the few that summarize the benefits of participatory research in strengthening research enterprises. This framework was deemed appropriate for this case study because it is sufficiently broad to include every aspect of the research process. Moreover, although the framework was derived from the examination of case studies in environmental science, it is general and can also be applied in a PE program.

Table 4. Program objectives for strengthening P2R

<b>Category</b>	<b>Objectives</b>
Relevance	<b>P2R-1:</b> Relevance of the research goals <b>P2R-2:</b> Relevance of the study design
Rigor	<b>P2R-3:</b> Rigor of the study design <b>P2R-4:</b> Rigor of the data collection <b>P2R-5:</b> Rigor of the data analysis
Reach	<b>P2R-6:</b> Reach of the results

## **CHAPTER 5 IMPLEMENTATION PROCESS AND OUTPUTS**

The 2SAFE model provides a five-step workflow to plan and implement a participatory ergonomics (PE) program: surveillance, screening, assessment, framing, and evaluation. The step-by-step example and practical usefulness of this theoretical model was demonstrated via the adoption of a case study, as it was implemented in a PE program at a commercial roofing and waterproof contractor. In what follow (Chapter 5 and 6) the author presents the results of the case study. This chapter describes the implementation and main outputs for each step of the program, while the next chapter will examine the 2SAFE model's role in program achievement.

### **5.1 Surveillance**

The contractor's historical injuries between January 2015 and January 2019 were reviewed. There are 115 incidents during the selected time period, comprising 72 workers' compensation claims and 43 self-care cases (i.e., the incidence that was only reported to nursing triage because no medical care was needed). Injury narratives were then reviewed to determine if ergonomic hazards (e.g., awkward postures, repetitive motions) played a role in the occurrences of incidents. As a result, 68 of the 115 incidents were classified as WMSDs, including 40 workers' compensation claims and 28 self-care cases. Medical diagnosis was subsequently used as the primary reference to differentiate between idiopathic and traumatic injuries. 17 incidents that were potentially caused by cumulative ergonomic exposures were categorized as idiopathic injuries. These incidents meet one of the following criterion: diagnosed as an occupational injury; caused by non-specific reasons; or chronic pains reported prior to injury. The remaining 51 were classified as traumatic injuries. To track the tasks aggravating the idiopathic injuries,

diagnosis documents and timecards were further scrutinized, in conjunction with interviewing data. Finally, 13 tasks were founded that contributed to the development of WMSDs. Strikingly, 40 out of 68 WMSD incidents happened during three types of manual material handling (MMH) tasks: lift/carry materials, operate hand carts to transport materials, and push/pull materials. Full attention was then directed to these MMH tasks to prioritize data collection efforts.

Task information of historical WMSDs injuries were then broken down into constituent job elements to explore their multifactorial causes. The most frequently-reported job elements of these three MMHs were obtained and summarized in Table 5. The association relationships between job elements and health outcomes were identified to look for cues of problems. The number of incidences and the sum of medical and indemnity costs, acquired from the workers' compensation system and the company's annual financial reports, were used as the indexes to indicate susceptibility and severity of each WMSD injury. A ranking of problematic job elements was provided to inform which job elements are more prevalent and severe that should be resolved.

Table 5. Ranking of problematic job elements of material handlings tasks

<b>Contributing Task</b>	<b>Problematic Job Element</b>	<b>Number of cases (Prevalence)</b>	<b>Economic cost (Severity)</b>	<b>Ranking</b>
<b>Carry/lift materials</b>		<b>27</b>	<b>\$171,480</b>	
	Workers employed less than 1 year	12	\$69,341	1
	Up/down stairs	6	\$44,305	3
	Asphalt roll membrane	10	\$43,260	5
	Demolition trash	3	\$32,702	8
	Insulation board	3	\$31,201	9
<b>Operate cart to transport materials</b>		<b>7</b>	<b>\$65,405</b>	
	Aged four-wheel hand cart	5	\$64,333	2
	Workers employed less than 1 year	6	\$44,011	4
	Obstacles/ramp along the route	4	\$42,156	6
	Slippery floor	1	\$21,999	11
<b>Push/pull materials</b>		<b>6</b>	<b>\$42,051</b>	
	Bundles of Insulation Material	4	\$38,482	7
	Workers employed less than 1 year	5	\$24,832	10

Note: the sum of sub-items (i.e., problematic job elements) exceeds the value of an item (i.e., contributing tasks). For instance, an overexertion injury occurred when the worker lifted bags of demolition trash upstairs. The economic cost will be counted twice on two demolition trash and up/down stairs.

The job element of operating hand cart to transport materials drew special attention by the industry partner and researcher team and was selected as the intervention target of the PE program. Although the job element of hand cart was only involved in seven (17.5%) WMSDs and caused \$65,405 (23.4%) economic costs, its average lost time and average cost per claim are 21.2 days and \$9,430, respectively, both of which were the highest among all injury types. Equally importantly, interviewed workers consistently perceived cart operation as strenuous and attributed low morale and reduced productivity to the malfunctions of aged carts. A relevant quote from a field worker is as follows: *“This material cart is too old and impossible to pull. Rusted bearings. Warped axles. I would rather borrow a cart from other trades. Can you ask them [employer] to get us some new carts?”*

## 5.2 Screening

After the problematic task and job elements were prioritized, the next question coming into the spotlight was what the root causes are at the level of exposure measures. As input into the selective screening tools (Hament 2001; Chengalur 2004), field data was obtained through repeated site observation and survey at seven jobsites from April 2019 to June 2020. The jobsites include two new constructions and five renovations, and the average project duration was two months (Table 6). All seven projects were large in physical size and relied on four-wheel carts for materials transportation. The needs of carts varied between projects, as the deployment numbers ranged widely from 1 to 6. Carts were fully loaded with an average load range between 455 and 907 kg (1000 – 2000 lbs), which is close to cart design capacity of 907 kg. The utilization of carts was fairly extensive: for six out of seven projects, carts were used for more than 4 hours every day. Carts were also maneuvered over a tiresome distance: longer than 31 meters on average and at a high frequency: three to four minutes every pull.

Table 6. Survey results for cart operating conditions

Project type	Project duration (month)	Number of carts (n)	Cart Operating Condition			
			Load weight (kg)	Duration (hour per day)	Frequency (minute every pull)	Travel distance (meter)
1 School building renovation	1.5	1	455 - 907	> 4	3 – 4	16 – 30
2 Industrial building tear-off	1	3	0 - 454	> 4	> 4	> 31
3 Industrial building renovation	5	6	455 - 907	> 4	3 – 4	> 31
4 New manufacturing plants	3.5	3	455 - 907	> 4	0 – 2	16 – 30
5 Government building renovation	0.5	1	455 - 907	3 – 4	3 – 4	< 15
6 Government building renovation	1	2	0 - 454	> 4	> 4	> 31
7 New commercial building	1	2	455 - 907	> 4	> 4	< 15
<b>Weighted Average (by project duration)</b>	<b>2</b>	<b>2.6</b>	<b>455 - 907</b>	<b>&gt; 4</b>	<b>3 – 4</b>	<b>&gt; 31</b>

By comparing field data against corresponding safety thresholds, screening results were obtained and displayed in the format of a matrix (Table 7) to suggest susceptibility and severity of excessive exposures. A total of five excessive exposures were unveiled to help determine intervention objectives. The most pressing issue was overexertion caused by overload (i.e., intensity of exertion). Cartloads in five out of seven observed projects ranged from 455 to 907 kg which substantially exceeded the safety limit of 227 kg. Another cluster of concerning measurements was prolonged exertion (i.e., duration of exertion), prolonged motion (i.e., duration of motion), and prolonged non-neutral posture (i.e., duration of posture). In six out of seven observed projects, cart handling activities were performed for four hours per day which exceeded the two-hour threshold. Long travel distance (i.e., intensity of motion) was also an ergonomic issue for three out of

seven projects, but it was primarily determined by physical sizes of construction sites and cannot be modified easily.

Table 7. The matrix of excessive exposures when operating four-wheel hand carts

	<b>Exertion</b>	<b>Motion</b>	<b>Posture</b>
<b>Intensity</b>	<b>Unacceptable:</b> Actual cartload substantially exceed the 227-kg safety threshold. Poor conditions of carts can escalate the injury risk.	<b>Unacceptable:</b> For three out of seven projects, travel distances exceed the 30-meter safety threshold	Acceptable: Body is moderately inclined in direction of exertion. Handhold allows a comfortable grip
<b>Duration</b>	<b>Unacceptable:</b> For six out of seven projects, pull with more than 20 lbs of force for more than four hours per day, exceeding the 2-hour threshold	<b>Unacceptable:</b> Pull/push objects for more than four hours per day, exceeding the 2-hour threshold	<b>Unacceptable:</b> Working with the back bent for more than four hours, exceeding 2-hour threshold
<b>Frequency</b>	Acceptable: Frequency (four min every pull/push) is less than 200 per 8-hour shift	Acceptable: Frequency is less than 200 per 8-hour shift	Acceptable: Frequency is less than 200 per 8-hour shift

Note that the screening tools only suggest general at-risk thresholds without considering specific working conditions. The actual situation could be even worse due to the following reasons: (1) most carts utilized in the field were in poor state of repair; (2) solid (polyurethane foam-filled rubber) tires were utilized which were heavier than conventional pneumatic (air-filled rubber) tires; and (3) required operating forces and times could increase when physical environment-related hazards present. Four sets of intervention controls were determined in order to reduce the prioritized exposure measures of cart handling: intensity and duration of exertion. They are cart preventative maintenance, tire selection, workplace layout, and task pre-planning (i.e., adapt load

restriction and job rotation based on working conditions). Then, literature review was conducted to examine if existing evidence is sufficient to define the relations between the problematic job elements, excessive ergonomic exposures, and health outcomes in a way that can support the design of these four controls. Below is a summary of evidence gap identified through the participatory process:

- **Preventative cart maintenance.** Although existing studies (Garg et al. 2014; M. J. Hoozemans et al. 1998; Argubi-Wollesen et al. 2017) have acknowledged the detrimental effect of cart deterioration on cart operation, only subjective and descriptive narratives were provided without any numerical evidence. Little is known about the degree to which a cart's ergonomics and productivity performance will deteriorate over time, giving practitioners limited evidence to determine whether preventive maintenance is a worthy decision and when is the best time to proceed with it.
- **Tire selection.** Solid tires have been recently introduced in the construction industry as a replacement for pneumatic tires because it will not become flat or deformed. However, solid tires are heavier and more expensive. To our knowledge, no study has been dedicated to empirically comparing these two tires when incident prevention and productivity enhancement are prioritized.
- **Workplace-layout planning.** The adverse effects of physical environment–related factors have been confirmed; however, the research efforts thus far have been focused on addressing single hazards, e.g., obstacles (Lawson, Potiki, and Watson 1993; Jäger, Luttmann, and Laurig 1984), ramps (Bennett et al. 2008; Nimbarte et al. 2013), or space constraints (Boyer, Lin, and Chang 2013; Marras,

Knapik, and Ferguson 2009). For example, Nimbarte et al. (2013) measured the effects of three ramp slopes (0, 5, and 10 degrees) on the musculoskeletal loads of cart operators. At workplaces, however, it is not uncommon to see physical environment–related factors at play simultaneously, such as moving a cart up a slope within a tight space. To competently maneuver in workplace layouts, practitioners should be aware of the effects of multiple hazards, rather than single hazards, which is missing from existing level one evidence. Another limitation of existing studies is that the effects of physical environment–related factors are primarily measured at low cart-load ranges: from 20 to 170 kg. It remains unknown whether the findings apply to higher cart-load ranges (Marras, Knapik, and Ferguson 2009), e.g., 243 to 469 kg, which are commonly seen on construction sites (Table 6).

- **Task pre-planning.** Several efforts have been made to provide numerical standards on load restrictions and job rotations (British Health and Safety Executive 2016; Chengalur 2004; Andersen, Haahr, and Frost 2007). However, none of them consider the impacts of the cart condition, tire type, and physical environment–related factors. Only fixed, unadaptable thresholds are recommended, limiting their applicability when imposing load restrictions under various working conditions.

To summarize, four research questions were identified that will be addressed in the next step: (1) How overexertion in pulling and push (OPP) risk and productivity deteriorates as carts age and develop structural problems; (2) How tire types (solid versus pneumatic tires) impact OPP risk and productivity; (3) What the main and interaction

effects of physical environment-related factors (i.e., obstacle height, ramp slope, and space constraint) are on the cart operation; and (4) how the above risk-injury relations change under different loads.

### **5.3 Assessment**

The objective of this step was to assess how cart condition, tire type, physical environment-related factors, and load interact to influence cart operations. Level one evidence were created to support the design of intervention controls in the following steps. To provide evidence for preventative cart maintenance and tire selection, Experiment 1 measured the forces and time required to operate carts of different conditions and equipped with different tires during dynamic cart pulling in straight-line and turning motions. In Experiment 2, the author focused on cart operations in relation to a combination of physical environment-related factors and loads to provide evidence for workplace layout and task-preplanning. This subsection provides a brief summary of study design and key research findings, while details have been published in a peer reviewed article (Zhang, Lin, and Lin 2021) (see Appendix B).

#### **5.3.1 Experiment 1**

##### **5.3.1.1 Experiment Design**

The objective of Experiment 1 was to uncover the effects of the cart condition and tire type on the ergonomics and productivity of cart operations under various loads. 18 roof four-wheel carts (Figure 5) with varying ages and tire types (Table 8) were tested. A digital force gauge was used to measure the required operating forces (ROFs) for cart maneuvering. An industrial-grade attitude/heading reference sensor was mounted on the

cart's front axle to gather acceleration and attitude data to characterize the cart movement and to measure the required operating time (ROT).

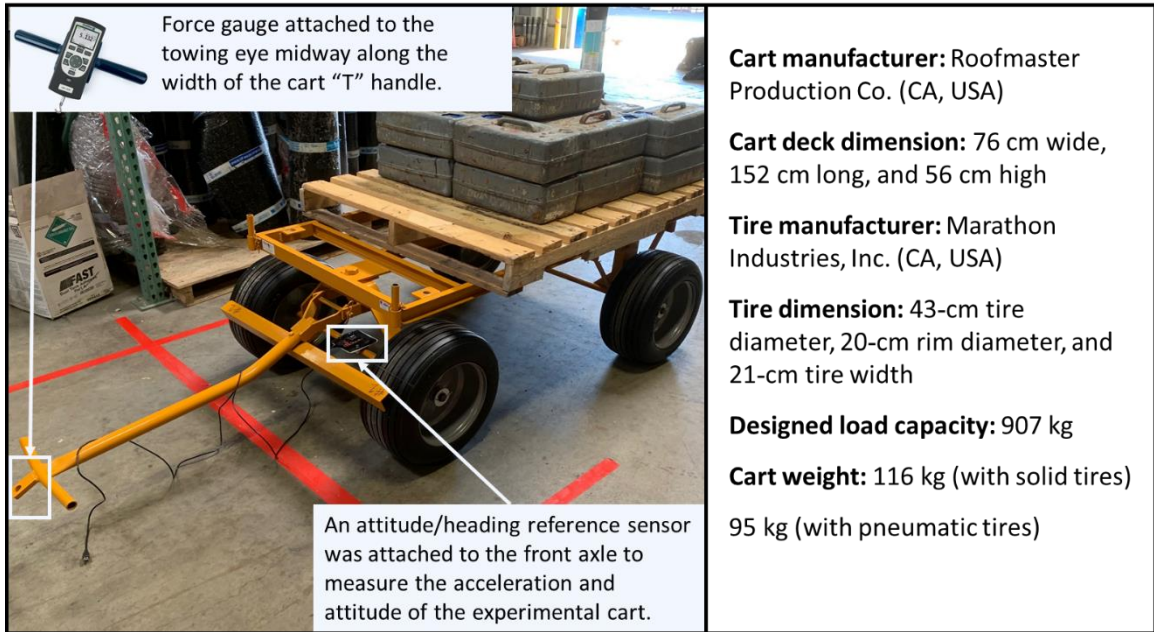


Figure 5. Instrumented cart

Table 8. Experimental carts

Cart Condition	Tire type	Number of carts tested
Brand-new	Pneumatic	2
Brand-new	Solid	2
One-year-old (no noticeable structural damage)	Pneumatic	5
One-year-old (no noticeable structural damage)	Solid	5
Five-year-old (contaminated tires, broken/deformed bearings, warped axles, and loose turntables)	Solid (three years old)	2
Five-year-old (curved axles and loose turntables)	Solid (brand-new)	2

A male graduate student, with a stature of 177 cm and a body mass of 88 kg, was recruited as the research subject. The anthropometric characteristics of the subject are representative of construction workers in the greater Seattle metropolitan area, based on a

regional worker-profile survey (Trivedi, Yellapragada, and Lin 2020). The subject visited five roofing jobsites to videotape and learn how workers operated carts and then received 30 minutes of training on pulling techniques from two experienced workers and was given observational feedback in practice trials.

An L-shaped track (Figure 6) was constructed to represent the common working conditions for cart operations. The subject was instructed to pull a cart forward for 762 cm and then make a 90 ° turn with a 244-cm diameter, followed by a 366-cm straight pull to the marked finish point. All of the trails were performed with three cart loads: 243, 356, and 469 kg. Each experimental setup was repeated at least three times until consistent ROF measurements were obtained. All 162 experimental trials (18 carts × 3 cart loads × 3 trials) were completed in five days.

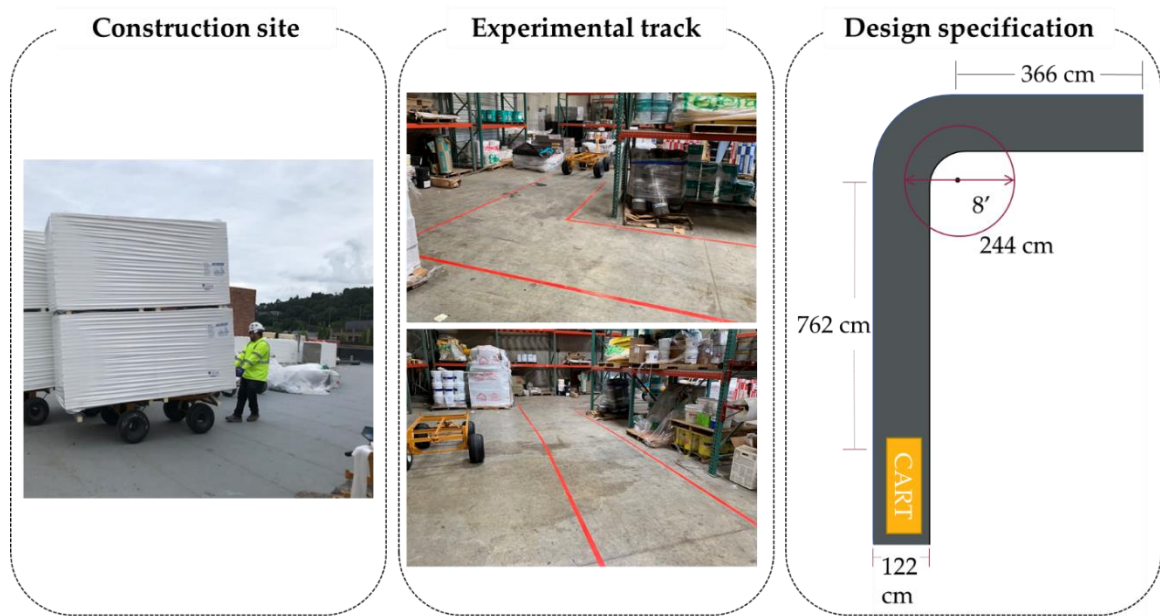


Figure 6. L-shaped track

The mean force over the sustained and turning phases (Figure 7), which constituted the majority of the cart movement, was obtained as the primary outcome

measure of the ROF for statistical analysis. The required operating time (ROT) to finish the course of motion on the track was recorded as a measure of productivity. To understand how the changing ROFs are associated with the OPP risk, the ROFs were converted into capability percentages (CPs) by referencing the Liberty Mutual Manual Materials Handling Table (Snook and Ciriello 1991) to denote the percentage of the male population who are psychophysically capable of performing the experimental pulling task.

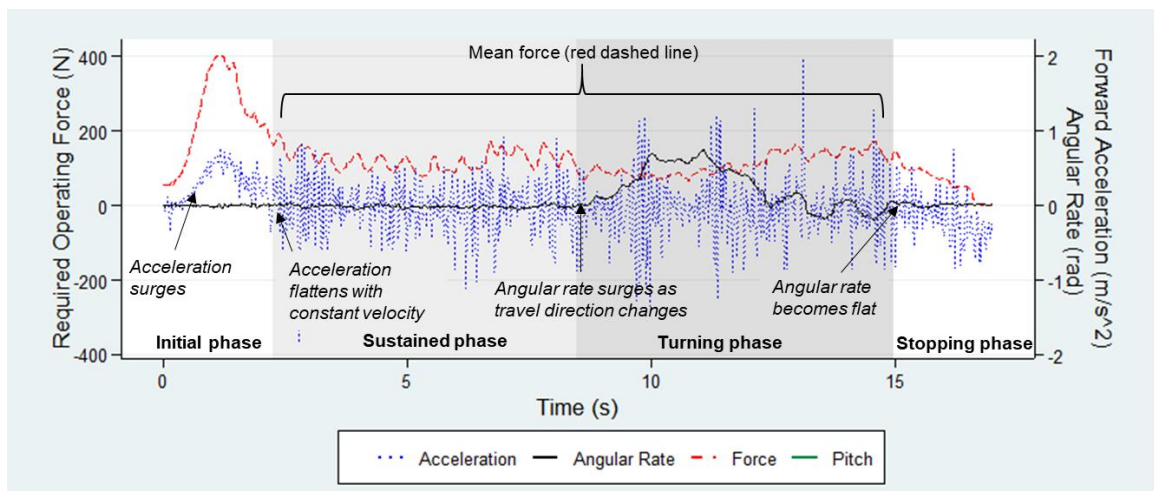


Figure 7. Sample trial with the L-shaped track

Experiment 1 employed two full-factorial designs. Experiment 1a included three dummy independent variables for the cart condition to compare a *one-year-old cart*, *five-year-old cart*, and *five-year-old cart after tire replacement* against a *brand-new cart* (the reference category) and a continuous independent-variable cart load. Three multiple linear regression models were created to investigate the effects of the cart condition on the ROF, CP, and ROT under different cart loads. Experiment 1b included a binary independent-variable tire type (pneumatic and solid tires) and a continuous independent-

variable cart load to estimate the association between the tire type and the ROF/ROT/CP under different loads.

### **5.3.1.2 Results**

Table 9 summarizes the regression analysis results for Experiment 1a which aimed at examining the effects of the cart conditions on the cart operation under different loads. The estimated ROF, CP, and ROT for carts of different conditions are shown in Figure 8. According to Table 9, operating a five-year-old cart was risky (placing an additional 30.5% of the male population at an elevated risk for overexertion) and non-productive (requiring 35.4% extra time to complete the experimental task). The malfunctions of old tires appear to explain 50% to 59% of the performance degradation, as a 17.2% increase in CP and 17.4% decrease in ROT after tire replacements for five-year-old carts were observed. Altogether, the findings suggested that tire replacement is a convenient administrative control worth considering; however, it is less effective than replacing the entire cart, when structural framing problems have developed causing excessive friction in axle shafts and vibration in the turntable.

Table 9. Statistical results of Experiment 1a: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and p-values from the final models, featuring independent variables: cart condition (brand-new as reference category) and cart load (243 kg as baseline) and dependent variables: ROF, CP, and ROT.

Effect	Required operating force, ROF (N)			Capability percentage, CP (%)			Percentage change in required operating time, ROT (%)		
	$\beta$	s.e.	P-value	$\beta$	s.e.	P-value	$\beta$	s.e.	P-value
Intercept	114	3.51	< .001	83.6	1.95	< .001	989	2.02	< .001
Cart condition									
<i>One-year-old vs. brand-new</i>	5.76	4.61	.215	-3.02	2.70	.266	17.1	2.04	< .001
<i>Five-year-old vs. brand-new</i>	65.5	4.61	< .001	-30.6	3.52	< .001	35.4	3.08	< .001
<i>Five-year-old after tire replacement vs. brand-new</i>	27.1	5.98	< .001	-13.4	2.21	< .001	18.0	3.08	< .001
Cart load (kg)	.487	.025	< .001	-.289	.013	< .001	.046	.008	< .001

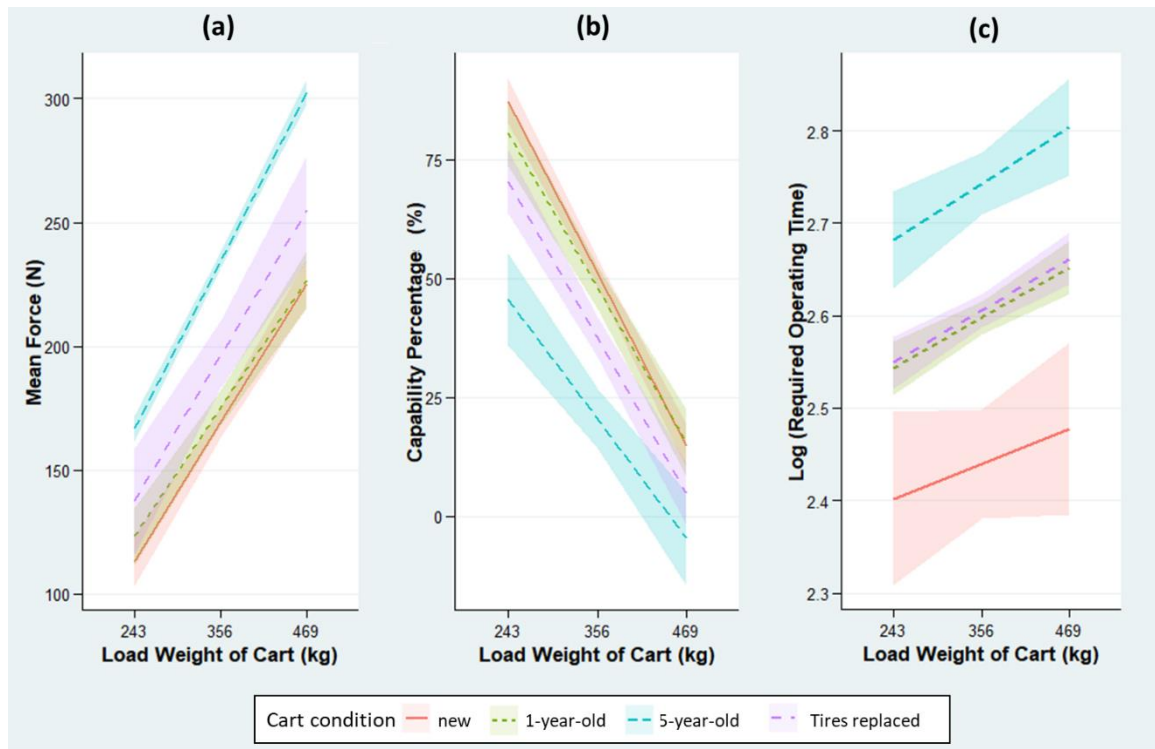


Figure 8. Estimated values: (a) ROF, (b) CP, and (c) ROT for carts of different conditions by fitting the actual measurements in Experiment 1a from the final linear regression models. The ribbons indicate 95% confidence intervals.

Experiment 1b aimed at comparing the difference between pneumatic and solid tires. The regression-analysis results are summarized in Table 10. The pneumatic tires outperformed the solid ones with a moderate margin in CP (-11.9%), which could be ascribed to the light weight of the pneumatic tires. Table 10 identified an interaction effect between the tire type and cart load on the ROF/CP, implying that the advantages of pneumatic tires become increasingly salient under a higher cart load (Figure 9). The results supported the use of pneumatic tires, especially when transporting heavier loads. However, it should be noted that the advantages of pneumatic tires are modest, and can be offset by the labor and administrative costs caused by flat-tire downtimes.

Table 10. Statistical results of Experiment 1b: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and p-values from the final models, featuring independent variables: cart condition (brand-new as baseline), tire type (pneumatic tire as baseline), and cart load (243 kg as baseline), an interaction term between the tire type and cart load, and dependent variables: ROF, CP, and ROT.

Effect	Required operating force, ROF (N)			Capability percentage, CP (%)			Percentage change in required operating time, ROT (%)		
	$\beta$	s.e.	P-value	$\beta$	s.e.	P-value	$\beta$	s.e.	p-value
Intercept	92.6	3.0	< .001	98.1	1.88	< .001	1029	2.01	< .001
Cart condition ( <i>One-year-old vs. brand-new</i> )	11.7	2.79	< .001	-7.30	1.82	< .001	15.6	1.82	< .001
Tire type ( <i>solid vs. pneumatic</i> )	22.0	3.55	< .001	-11.9	2.12	< .001	-0.75	1.64	.645
Cart load (kg)	.326	.023	< .001	-.201	.017	< .001	.036	.009	< .001
Tire type $\times$ cart load	.173	.031	< .001	-.115	.020	< .001	-	-	-

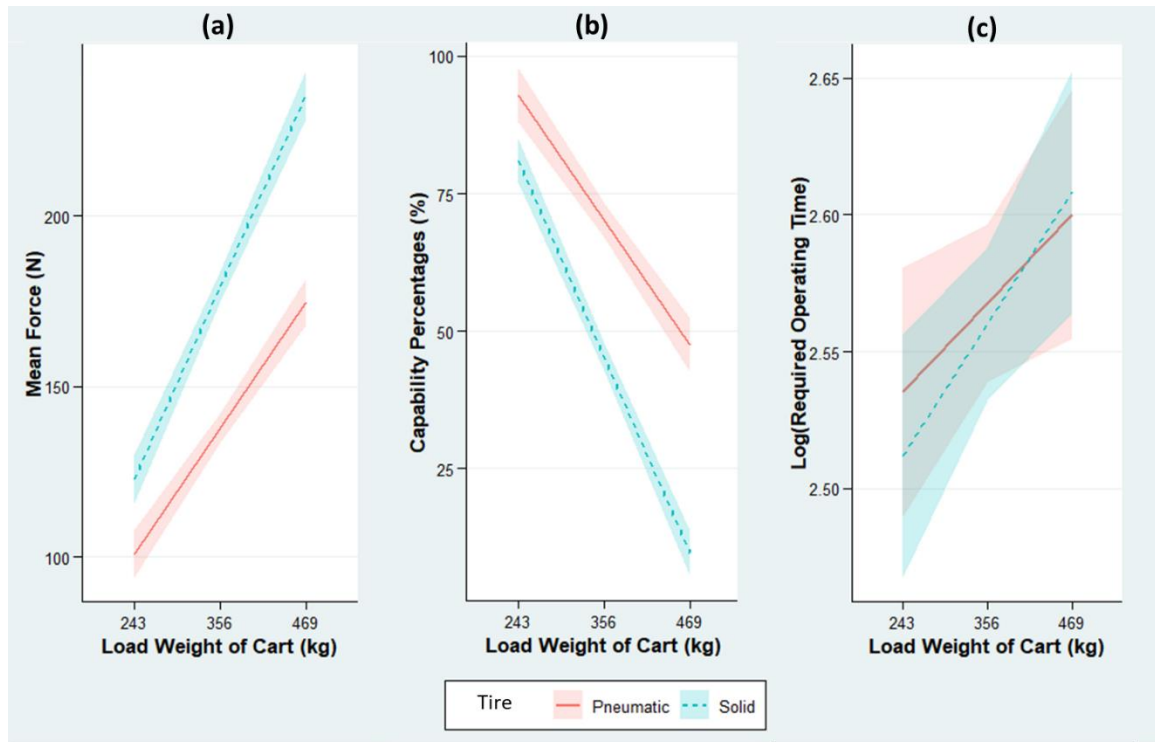


Figure 9. Estimated values: (a) ROF, (b) CP, and (c) ROT for two tire types by fitting the actual measurements in Experiment 1b from the final linear regression models. The ribbons indicate 95% confidence intervals.

## 5.3.2 Experiment 2

### 5.3.2.1 Experiment Design

The objective of Experiment 2 was to uncover the main and interaction effects of physical environment-related factors (obstacle height, ramp slope, and space constraint) on the cart operation under different loads. Four brand-new carts (two with pneumatic tires and two with solid tires) were tested in Experiment 2. The other deployed apparatuses and research subject were identical to those in Experiment 1.

Two laboratory tracks were created by the authors and two roofers to simulate the actual physical environments on construction sites: an obstacle track (Figure 10 (a)) with three heights: 1.9, 3.8, and 5.7 cm and a ramp track (Figure 10 (b)) with three slope

gradients: 4 °, 8 °, and 12 °. Three levels of space constraint were simulated by defining the travel distance (i.e., from the front axle of the cart to the closest edge of an obstacle/ramp): 335 cm (an open space), 61 cm (moderately constrained space), and 15 cm (extremely constrained space).

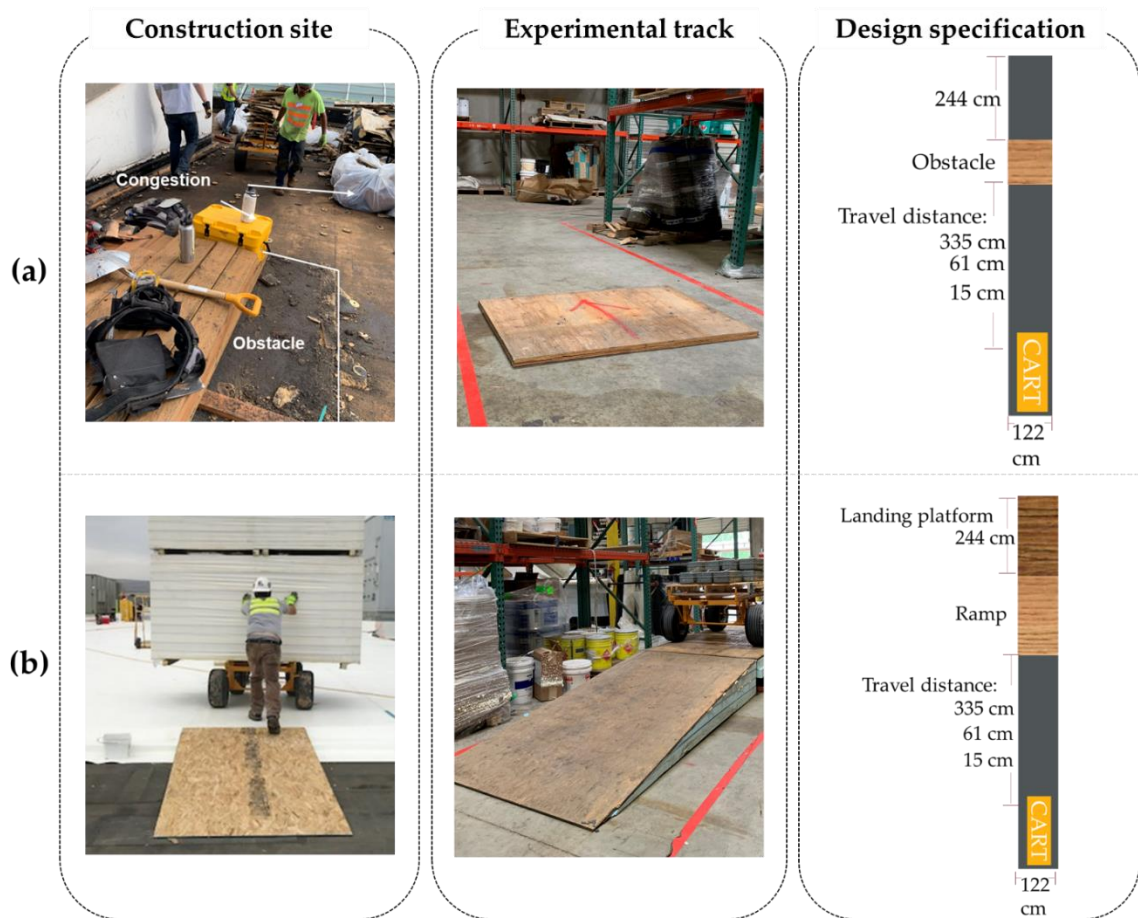


Figure 10. Laboratory tracks for Experiment 2: (a) obstacle track and (b) ramp track

In Experiment 2, a cart was first placed upon a level surface with an obstacle/ramp located at a pre-defined distance to simulate space constraints. The subject was requested to follow a set procedure: pull the cart over the pre-defined distance, then surmount the obstacle/ramp, followed by a 244-cm straight pull to a marked finish point. The entire experiment was conducted with five loads: 16, 129, 243, 356, and 469 kg. The

subject mimicked the roofers' pulling technique by jerking to overcome an obstacle/ramp when within a moderately or extremely constrained space. The other experimental details were identical to those in Experiment 1. All 963 experimental trials were completed in 25 days.

The cart movement on the obstacle track was divided into initial and surmounting phases (Figure 11 (a)). As surmounting an obstacle requires impulsive forces, the peak force during the initial and surmounting phases was recorded as the ROF. The duration of the initial and surmounting phases was collected as the ROT. The cart movement on the ramp track was divided into three phases: front wheels on ramp, all wheels on ramp, and rear wheels on ramp (Figure 11 (b)). The mean force and operating time over the three phases, which constituted the majority of the cart movement, were recorded as the primary outcome measures for ROF and ROT, respectively.

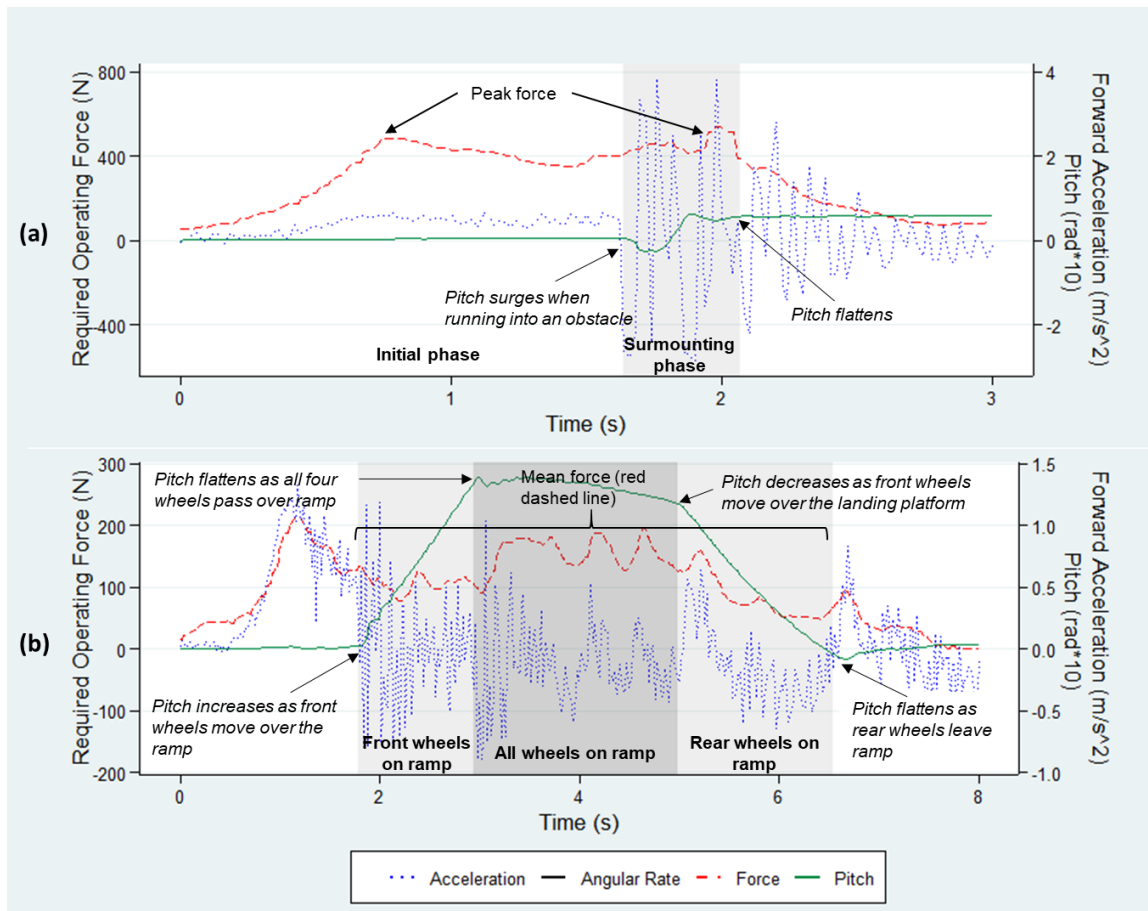


Figure 11. Sample trial data: (a) obstacle track within a moderately constrained space and (b) ramp track within a severely constrained space

Experiment 2 employed respective full-factorial designs for the obstacle and ramp tracks. As an investigation of the effects of the obstacle height and space constraint on the cart operations under different cart loads, Experiment 2a included a continuous independent-variable obstacle height, two dummy independent variables for space constraints to compare *moderate space constraints* and *extreme space constraints* against *open space* (the reference category), and a continuous independent-variable cart load. Experiment 2b was designed for the ramp track and included a continuous independent-variable ramp slope, two dummy independent variables for space constraint, and a

continuous independent variable cart load. The other technical details for data analysis replicated those of Experiment 1

### **5.3.2.2 Results**

Table 11 summarizes the regression analysis results for Experiment 2a (obstacle track). The space constraint was found the strongest risk factor when surmounting obstacles. This factor also considerably amplified the adverse effects of both obstacle height and cart load on the cart operation (Figure 12): in a constrained space, a much greater force is needed to overcome a bigger obstacle.

Table 11. Statistical results of Experiment 2a: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and p-values from the final models, featuring four independent variables: tire type (pneumatic tire as baseline), obstacle height (1.9 cm as baseline), space constraint (open space as baseline), and cart load (16 kg as baseline), interaction terms between the obstacle height and space constraint and between the cart load and space constraint, and finally dependent variables (ROF, CP, and ROT).

Effect	Required operating force, ROF (N)			Capability percentage, CP (%)			Percentage change in required operating time, ROT (%)		
	$\beta$	s.e.	p-value	$\beta$	s.e.	p-value	$\beta$	s.e.	p-value
Intercept	29.8	7.44	<b>.008</b>	110	1.73	<b>&lt; .001</b>	353	2.67	<b>&lt; .001</b>
Tire type (solid vs. pneumatic)	60.5	5.91	<b>&lt; .001</b>	-14.7	1.38	<b>&lt; .001</b>	2.38	1.87	<b>.003</b>
Obstacle height (cm)	25.0	2.23	<b>&lt; .001</b>	.996	.523	.057	-1.83	.612	.204
Space constraint									
<i>Moderate vs. open space</i>	46.8	10.4	<b>&lt; .001</b>	.744	2.56	.772	-75.5	2.21	<b>&lt; .001</b>
<i>Extreme vs. open space</i>	190	15.2	<b>&lt; .001</b>	-45.0	4.68	<b>&lt; .001</b>	-88.6	2.36	<b>&lt; .001</b>
Cart load (kg)	.546	.022	<b>&lt; .001</b>	-.210	.005	<b>&lt; .001</b>	.071	.006	<b>&lt; .001</b>
Obstacle height × space constraint									
<i>Obstacle height × Moderate vs. open space</i>	2.03	4.59	.569	-3.77	.486	<b>&lt; .001</b>	-	-	-
<i>Obstacle height × Extreme vs. open space</i>	76.8	5.99	<b>&lt; .001</b>	-14.2	1.21	<b>&lt; .001</b>	-	-	-
Cart load × space constraint									
<i>Cart load × Moderate vs. open space</i>	.386	.036	<b>&lt; .001</b>	-.028	.007	<b>&lt; .001</b>	-	-	-
<i>Cart load × Extreme vs. open space</i>	.845	.057	<b>&lt; .001</b>	.072	.012	<b>&lt; .001</b>	-	-	-

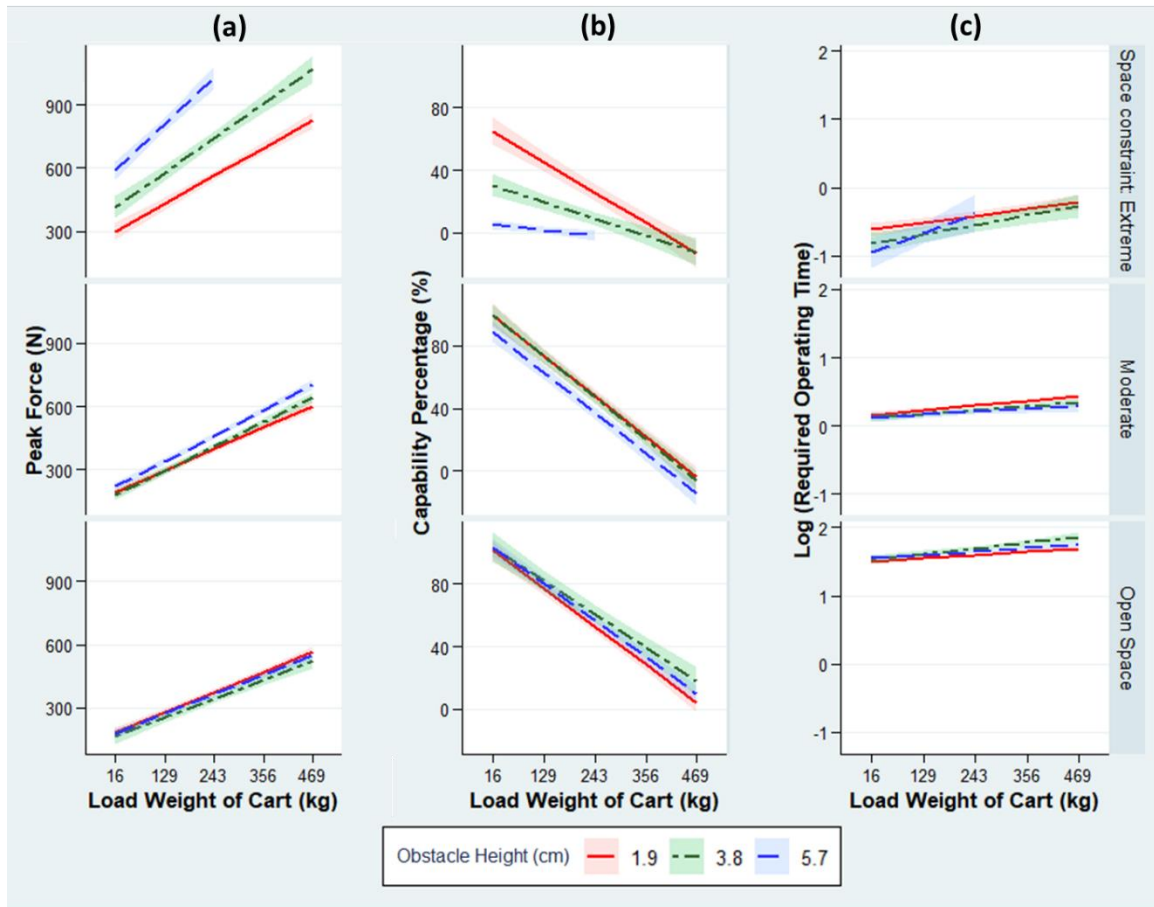


Figure 12. Estimated values: (a) ROF, (b) CP, and (c) ROT for three obstacle heights by fitting the actual measurements in Experiment 2a from the final linear regression models, stratified by the space constraint. The estimated values are adjusted for tire type. The ribbons indicate 95% confidence intervals.

The regression analysis results for Experiment 2b (ramp track) are summarized in Table 12. The ramp slope was found as the strongest predictor of ROF, CP, and ROT when overcoming a ramp, suggesting that practitioners should build gentler ramps for cart operations. Furthermore, the detrimental effect of the ramp slope was stronger for carts with heavier loads (Figure 13). This could be due to that heavier carts lose momentum more easily on steeper ramps and operators need to constantly apply a much larger force to initiate the cart movement.

Table 12. Statistical results of Experiment 2b: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and p-values from final regression models, featuring four independent variables: tire type (pneumatic tire as baseline), ramp slope (4 ° as baseline), space constraint (open space as baseline), and cart load (16 kg as baseline), an interaction term between the ramp slope and cart load, and dependent variables: ROF, CP, and ROT.

Effect	Required operating force, ROF (N)			Capability percentage, CP (%)			Percentage change in required operating time, ROT (%)		
	$\beta$	s.e.	P-value	$\beta$	s.e.	P-value	$\beta$	s.e.	P-value
Intercept	37.5	2.54	< .001	119	1.46	< .001	275	1.95	< .001
Tire type (solid vs. pneumatic)	31.5	1.91	< .001	-6.96	.848	< .001	4.24	1.29	.0013
Ramp slope (°)	10.3	.385	< .001	-2.29	.217	< .001	2.19	.335	< .001
Space constraint									
<i>Moderate vs. open space</i>	19.2	2.31	< .001	-3.92	.988	< .001	6.28	1.56	< .001
<i>Extreme vs. open space</i>	41.5	2.27	< .001	-8.76	1.05	< .001	11.9	1.56	< .001
Cart load (kg)	.756	.009	< .001	-.196	.004	< .001	.098	.006	< .001
Ramp slope $\times$ cart load	.123	.003	< .001	-.030	.001	< .001	.015	.002	< .001

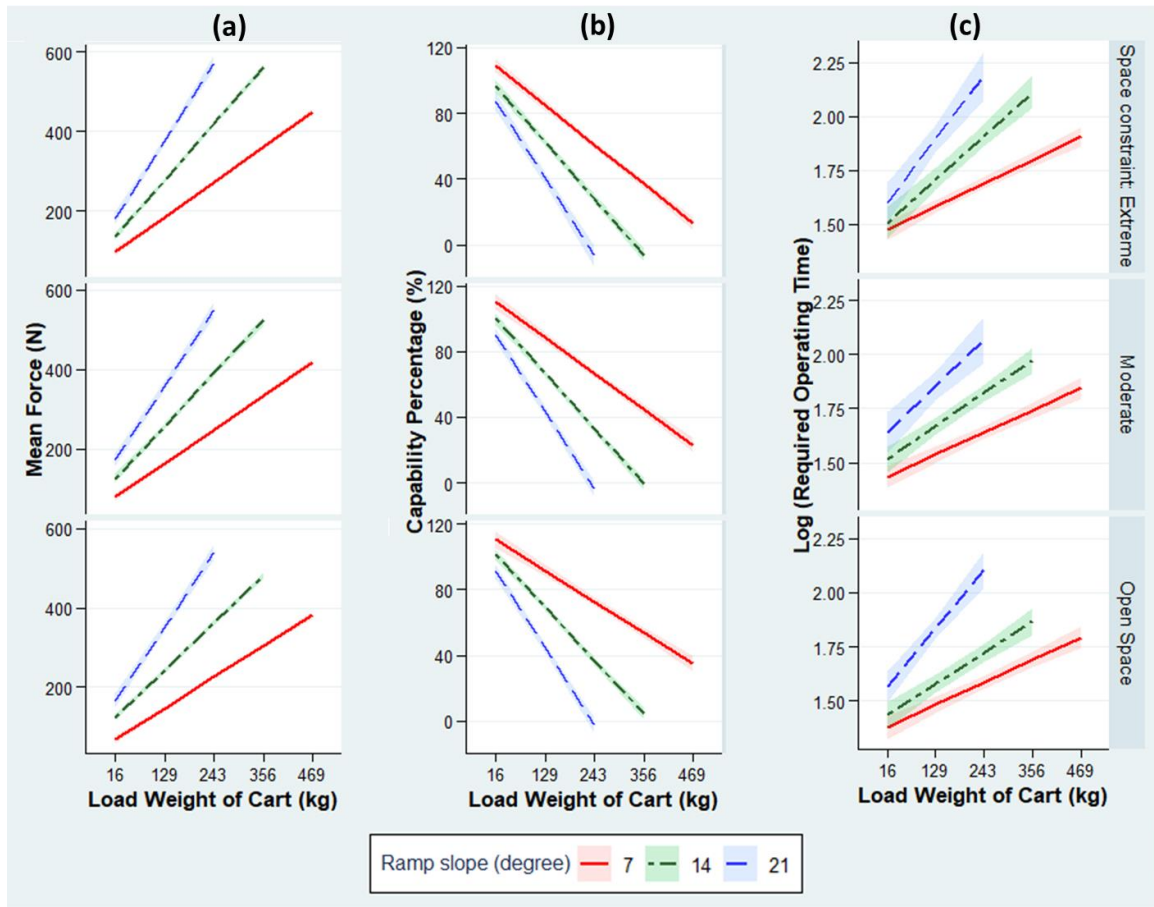


Figure 13. Estimated values: (a) ROF, (b) CP, and (c) ROT for three ramp slopes by fitting the actual measurements of Experiment 2b from the final linear regression models, stratified by the space constraint. Estimated values are adjusted for tire type. The ribbons indicate 95% confidence intervals.

Based on experiments 1 and 2, cart load has a greater effect on CP (L-shaped track: -0.289%, obstacle: -0.210%, and ramp: -0.196% for every 1-kg increase in cart load). Despite being statistically significant, the effect of cart load on ROT is rather minimal (L-shaped track: 0.046%, obstacle: 0.071%, and ramp: 0.98%). It is also found that the cart load can modify the effects of the tire type, ramp slope, obstacle height, and space constraint (Figure 9, 12, and 13).

## 5.4 Framing

Following principles of the fourth step in the 2SAFE model, this section situates the assessment results within operational contexts to formulate intervention measures and implementation plans.

### 5.4.1 Numerical Guideline

It was difficult for the raw results from the regression analysis to resonate with construction practitioners based on the participatory feedback. As a result, assessment outcomes did not immediately get the industry partner to buy in. Particularly, ROF and CP were found confusing and drew skepticism, serving as a barrier during health communication. Some relevant quotes are as follow:

*“I don’t understand what operating forces mean. Nobody in the field know how much force they put in to pull a cart. Horsepower should make more sense because we’re motorheads!” (Warehouse manager commented after observing experiments and reading preliminary results)*

*“Pulling a cart with 35 lbs force doesn’t sound strenuous, but this tool [Liberty Mutual Manual Materials Handling Table ] told us it is only acceptable to 60% of the male population! I lift much heavier weights than that in the gym, and our roofers are stronger and tougher. Their physical strengthen better than 60th percentile!” (The company CEO commented during top management team meeting)*

Although it is impossible to convert ROF into horsepower, the feedback from the warehouse manager reminded the author to select a health outcome that is tangible to practitioners. Furthermore, the CEO’s skeptical view pinpointed a fundamental problem of CP as a health outcome for risk communication with lay audience. CP specifies the

percent of population that is psychophysically capable of finishing a physical task under a given working condition. However, as indicated by the CEO's comment, human beings tend to have optimistic overconfidence that they have better than average "ability" on many desirable traits (Dunning, Heath, and Suls 2004; Kahneman 2011; Kim, Kwon, and Chiu 2017), such as physical capability. Not only did the CEO, but many roofers expressed such overconfidence. During a field observation, for example, the author recommended a foreman to carry one bucket at a time per NIOSH lifting equation (Waters, Putz-Anderson, and Garg 1994). He explained: "*Come on! I have done this many times before and never get hurt. These buckets are not heavy. Do you want to have a try?*" It should be noted that this foreman was still on light duty from knee hyperextension.

The participatory feedback compelled the author to interpret and translate CP into "ideal team size" when designing intervention solutions and communicating the efficacy of intervention. The measure of "ideal team size" is more tangible for practitioners to visualize the changes of injury risk. Managers generally embrace teamwork and are, therefore, less likely to doubt the credibility of underlying scientific evidence. More importantly, this measure is immediately transferrable and implementable to the roofing day-to-day operation where workers have a better control over team sizes than over cart loads during material handling. During jobsite observations, the author noted that workers oftentimes have low self-control on cartloads because they must comply with site logistic plan: oftentimes a crane loads bundled materials directly onto a cart which is then moved to storage locations.

As a critical interim output of this step, ideal team sizes under various working circumstances are summarized in Table 13. The recommended team sizes are equivalent to 60% CP for the male population in pulling carts on 8-hour shift. This threshold was determined by the authors and the industry partner to make a balance between safety precaution and productivity requirement. For each selective working circumstance, linear interpolation was applied to find the safety load level when CP reaches 60%. Considering the existence of combined effects, subgroup data that is corresponding to the selective working circumstance for interpolation was used. Ideal team sizes were then inferred for seven cartload levels, and each level represents the weight of a type of roofing materials that is commonly transported by four-wheel carts. For simplicity and ease of communication with practitioners, the team sizes are rounded off.

Table 13. Recommended team sizes for various working circumstances in roofing

Risk Factor		Cartloads (kg)						
		318	371	437	724	871	1,114	1,311
<b>Cart Condition</b>	Brand-new	1	1	1	2	2	3	3
	1-year-old	1	1	1	2	2	3	3
	5-year-old	2	2	2	3	3	4	5
	Tire replacement	1	1	2	3	3	4	4
<b>Tire type</b>	Pneumatic tire	1	1	1	1	2	2	3
	Solid tire	1	1	1	2	2	3	3
	<b>Obstacle × Space Constraint</b>							
	Any height × open space (549 cm)	1	1	1	2	2	3	3
	1.9 cm × moderate (61 cm)	1	1	1	2	2	3	4
	1.9 cm × extreme (15 cm)	2	2	2	3	4	4	5
	3.8 cm × moderate (61 cm)	1	1	2	2	3	4	4
	3.8 cm × extreme (15 cm)	2	3	3	4	5	5	6
	5.7 cm × moderate (61 cm)	1	2	2	3	3	4	4
	5.7 cm × extreme (15 cm)	3	3	4	5	6	7	8
<b>Ramp</b>	4-degree	1	1	1	2	2	3	3
	8-degree	2	2	2	3	4	5	6
	12-degree	2	3	3	5	5	7	8

Table 13 assists in the design and communication of four intervention measures: preventative cart maintenance, tire selection, workplace layout, and task preplanning.

### ***Preventative cart maintenance***

The table first compares ideal team sizes between carts of different conditions, using solid tires and the L-shaped track as the reference working environment. The results make it clear that operating aged carts is risky: a 5-year-old cart consistently requires one to two additional operators than a new or 1-year-old cart does under all cartloads. Replacing old tires for 5-year-old is helpful and can reduce ideal team sizes but only under three out of seven cartloads: 318, 371 and 1,311 kg. Altogether, the findings

lead to our guideline for preventative replacement: Material carts should be properly maintained, and old carts with warped axles, loose turntable, worn tires, and broken/deformed bearings should be replaced immediately.

### ***Tire selection***

Table 13 also recommends ideal team sizes for both solid and pneumatic tires, with brand-new carts on the L-shaped track as the reference working circumstance. Pneumatic tires are advantageous over solid ones under two out of six cartloads: 724 and 1,114 kg. Our results supported the use of pneumatic tires, especially when transporting heavier loads. However, it should be noted that the advantages of pneumatic tires are modest and can be offset by the labor and administrative costs caused by flat-tire downtimes.

### ***Workplace layout***

Table 13 recommends team sizes required to overcome obstacles and ramps, using brand-new carts equipped with solid tires as the reference working environment. In an open space, an obstacle of any height commonly seen on a commercial roofing jobsite barely presents additional risk than a flat surface does. But in a moderately or severely constrained space, two to four additional operators are needed to safely overcome the same obstacles. The results highlight the first guideline for workplace layout: Keep an open and clean workstation to ensure the travel distance from a cart to any physical hazard is larger than 61 cm. Furthermore, the findings suggest 1.9 cm as the upper tolerance limit, because an obstacle of this height introduces negligible additional risk compared to a flat floor, even under moderately constrained space. This leads to the second workplace layout guideline: Eliminate any obstacle larger than 1.9 cm. Ramp is

another important physical hazard to OPP: the extra forces required to overcome 8- and 12- degree ramps are equivalent to needing one to three and one to five extra operators, respectively. Hence, the third guideline for workplace layout is up to 4-degree slope for ramp. Note that space constraint is excluded when developing ramp guidelines because of its minimal effect on OPP (Table 13).

### ***Task pre-planning***

Some construction sites may not allow for a gentle slope, open space, or minor obstacle. In these cases, preplanning cart operation is necessary to make the task safe. Table 13 was visualized into an infographic (Figure 14) to provide easy-to-follow guideline for the assignment of team pulling/pushing and job rotation under different working conditions on construction sites. More specifically, job rotation was designed for materials heavier than 724 kg (Red zone in Figure 14) because this is when ideal team sizes rise sharply and become hard to follow. For red zone materials, workers should be assigned to handle carts no more than two hours within an 8-hour work shift.

Alternatively, cart handling should be conducted at a lower frequency: no more than one pull every 30 minutes, without other physically demanding activities in between. The team sizes for read zone materials in Figure 14 were recommended by adapting the frequency of pulling from 5 minutes to 30 minutes within the Liberty Mutual Manual Materials Handling Table .

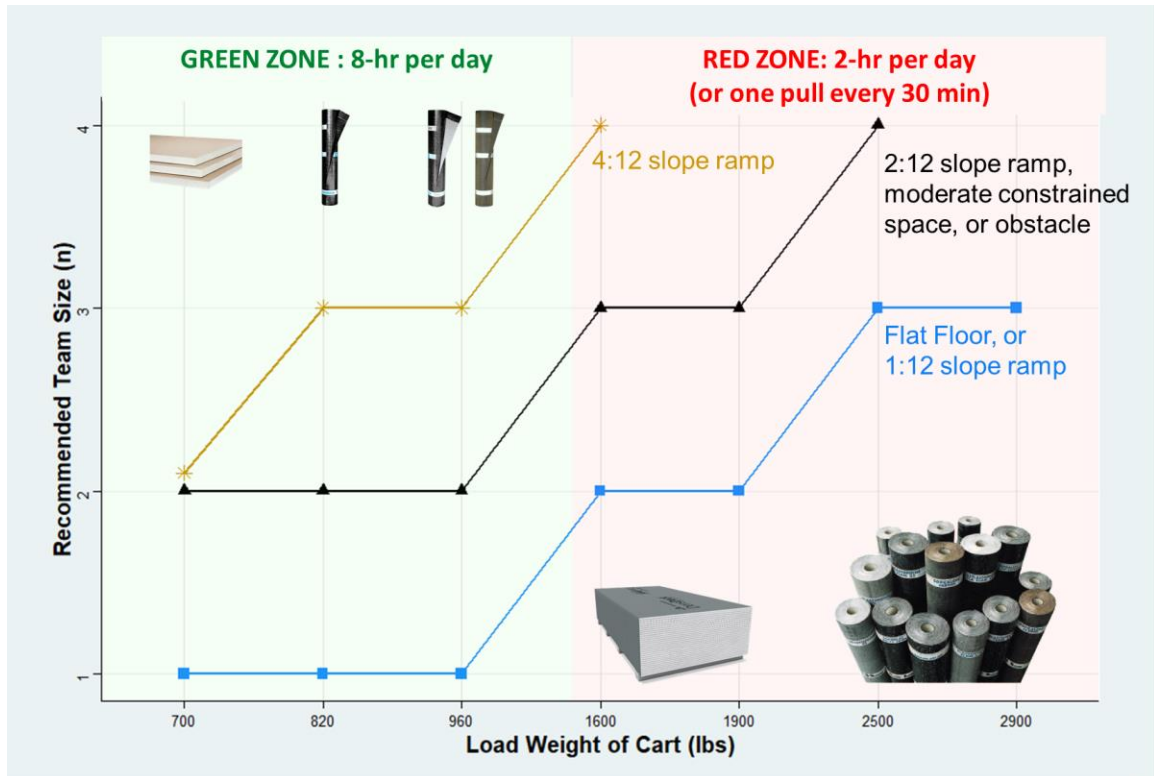


Figure 14. Recommended team sizes and operating hours for cart handling under different working conditions

#### 5.4.2 Program Products

Three types of program products were created as the main outputs of this step: safety animations, a training handout, and a planning tool. Level two evidence was then gathered from both industry partner and external experts to validate and refine the program products.

#### *Safety Animations*

Two safety animations were created based on the numeric guideline. Animation #1 (link: <https://youtu.be/OyPGBUggwyw>) recreates the real-life story of a roofer who ruptured his Achilles tendon while maneuvering a heavily loaded cart. Three solutions are recommended with embedded scientific evidence showing that even a simple solution

like team pulling could have prevented this injury. The moral of the Tortoise and the Hare is embedded in the animation to remind audiences to avoid taking shortcuts and pay attention to the danger of ergonomic hazards.

Animation #2 (link: <https://youtu.be/2v6p52GRJIE>) is based on the real-life story of a roofing apprentice who left the industry after getting injured while overcoming a poorly-setup ramp with a material cart. Three evidence-based solutions are provided to inform supervisors how a similar incident can be prevented through ergonomic workplace layout and task pre-planning. The moral of the Tortoise and the Hare is embedded in the animation to encourage supervisors to become thoughtful leaders, creating a safer and caring environment for their crews.

During the PE program, the two animations were presented to three focus group, nine safety orientations, and one foremen's meeting at the industry partner company. A total of 71 workers and 20 foremen participated to test the one of the animations and provide feedback. The demographics of the participants was shown in Table 14.

Table 14. Survey participants in the test of the animations

	Animation #1		Animation #2	
	Focus groups (19 workers)	Safety orientations (45 new hires)	Focus group (7 workers)	Foremen's meeting (20 foremen)
<b>Gender</b>				
<i>Male</i>	19 (100%)	39 (86.7%)	7 (100%)	20 (100%)
<i>Female</i>	0 (0%)	6 (13.3%)	0 (0%)	0 (0%)
<b>Ethnicity</b>				
<i>Asian</i>	0 (0%)	1 (2.2%)	1 (14.3%)	0 (0%)
<i>Black/African American</i>	3 (15.8%)	6 (13.3%)	1 (14.3%)	1 (5%)
<i>Hispanic/Latino</i>	7 (36.8%)	20 (44.4%)	2 (28.6%)	5 (25%)
<i>Native Hawaiian</i>	0 (0%)	0 (0%)	0 (0%)	0 (0%)
<i>White/Caucasian</i>	6 (31.6%)	15 (33.3%)	2 (28.6%)	13 (65%)
<i>Pacific Islander</i>	1 (5.2%)	0 (0%)	0 (0%)	0 (0%)
<i>Mixed Race</i>	2 (10.5%)	2 (4.4%)	1 (14.3%)	1 (5%)
<b>Work experience</b>				
<i>None</i>	3 (15.8%)	20 (44.4%)	2 (28.6%)	0 (0%)
<i>1 – 9</i>	13 (68.4%)	19 (42.2%)	4 (57.2%)	0 (0%)
<i>10 – 19</i>	1 (5.2%)	1 (2.2%)	1 (14.3%)	5 (25%)
<i>Over 20</i>	2 (10.5%)	3 (6.7%)	0 (0%)	18 (70%)
<i>Prefer not to answer</i>	0 (0%)	2 (4.4%)	0 (0%)	0 (0%)
<b>Musculoskeletal injury history</b>				
<i>Yes</i>	8 (42%)	8 (17.8%)	1 (14.3%)	N/A
<i>No</i>	11 (58%)	36 (82.2%)	6 (85.7%)	N/A
<i>Prefer not to answer</i>	0 (0%)	1 (2.2%)	0 (0%)	N/A

Overall, 96% of participants agreed or strongly agreed that they would show the animations to employees if they were a safety manager. One worker commented in the focus group: “*Why they didn’t show this in orientation?*” Another worker suggested how the animations could potentially change safety culture of a company: “*We all know that having someone help you pull the cart but getting someone to actually do it [is hard]. But when they've seen the same video, one can reference the video and say we saw the same thing!*” Furthermore, 92% of participants agreed or strongly agreed that the animations improved their ergonomic knowledge and skills. One worker shared his thought after

watching the animation #1: *“I think I might use the cart all wrong!”* A foreman clearly pointed out what he learned from the animation #2: *“Numbers like pitch and height [of obstacle] are useful for folks and help you set up or do a task!”*

### ***Training Handout***

The second program product is a 5-page training handout (Appendix C). The design of the training handout incorporated health belief information collected in the previous steps. Each page discusses an ergonomic hazard that was associated with cart handling. Field photos and animated pictures were combined with the scientific evidence to show that the prevalence and severity of the cart handling hazards. Based on the numerical guidance, general measures were suggested with clear instruction to improve workers’ knowledge and self-efficacy in addressing the hazards. Lastly, the handout also introduced the secondary benefits that can be expected from adopting the suggested measures.

The training handout was presented to 12 safety trainers from the United Union of Roofers, Waterproofers & Applied Workers through individual interviews. Interviewees came from different regions of the US and have many years of work experience in safety training and curriculum development (Table 15). The expert inputs not only helped test if the training handout was an effective, concise training resource that can be broadly applied in the roofing trade, but they were also combined with participatory feedback from the EHS team for refinement.

Table 15. Interview subjects in the test of the training handout

	<b>Individual interview 12 safety trainers</b>
<b>Gender</b>	
<i>Male</i>	12 (100%)
<i>Female</i>	0 (0%)
<b>Geographical region</b>	
<i>Northeast</i>	1 (8.3%)
<i>Southeast</i>	0 (0%)
<i>Midwest</i>	7 (58.3%)
<i>Southwest</i>	1 (8.3%)
<i>West</i>	3 (24.9%)
<b>Job title</b>	
<i>Apprenticeship coordinator</i>	6 (50%)
<i>Business manager</i>	1 (8.3%)
<i>Director of curriculum development</i>	1 (8.3%)
<i>Training coordinator/director</i>	4 (33.3%)
<b>Work experience in the industry</b>	
<i>1 – 9</i>	1 (8.3%)
<i>10 – 19</i>	1 (8.3%)
<i>Over 20</i>	10 (83.4%)

Overall, the interviewees consistently perceived that the training handout provides detailed instructions on how to recognize and address risk factors associated with cart handling under different circumstances in the roofing trade. For example, one foreman concluded the interview by saying: *“It’s a pleasure working with you guys. I’m really impressed with how in depth you could take a simple topic like carts.”* More importantly, some safety topics the training handout brought up, such as ramp setup, seemed to be overlooked by practitioners. For example, one trainer commented that *“This [properly set up ramps] is something that I had not really been proud about my years as a foreman. When we would set up a ramp, we would generally try to set it up the quickest and easiest way possible. Not taking much consideration about how much slower it’s going to be to use that ramp and how much harder it’s going to be on the people to use it. This was a little bit more enlightening to me.”*

The handout was also considered readable and relatable to any journeyman and foremen. In particular, the interviewees thought that the scientific data was visualized in a meaningful way: *“I understood it pretty easily. You know the steeper the ramp the harder to pull. I think it does a good job of breaking it down on the subtle notice that a little bit of difference means a lot over the course of an eight-hour workday. So I like that.”*

Lastly, 11 out of 12 interviewees clearly stated that they will use the training sheets in in their training programs, while one interviewee indicated he would share the handout by posting it in the union hall.

The positive feedback was shared with the EHS director to enhance her confidence in using the material. The suggestions were then discussed, and changes were made collectively to finalize the training handout.

### ***Planning Tool***

The third program product is a planning tool (Appendix D) for safety personnel to plan for cart handling activities. The tool was adapted from Best Built Plan (CPWR 2018b), a generic planning tool for manual material handling in the construction industry. The author tailored the Best Build Plan to the roofing trade and focused specifically on material handling activities using manual carts. This tool provides a workflow to help safety personnel tap into their company’s existing safety procedures and incorporate best practices for cart handling activities. The tool was first designed to fit into the industry partner company’s safety procedures. Then, the safety trainers (Table 15) were invited to test if the planning tool is useful and has a potential for broad application.

Feedback received from the safety trainer interviews were positive and encouraging. The interviewees perceived that the workflow behind the planning tool

cover almost every aspect of safety management during the lifecycle of a construction project and has a great potential of preventing OPP injuries. For example, the planning tool suggests safety personnel share material handling plan with general contractors, and one foreman perceived it to be a valuable suggestion: *“The conflict in material delivering is definitely a great goal, because that that is always an ergonomic hazard. But it's always a point of confusion on job sites. General contractors don't follow the delivery process very often. I think If this was implemented, it could be more effective not only for the ergonomics but a better run job site.”*

Similarly, another foreman highlights the importance of post-job evaluation that was recommended in the planning tool: “I think this is a good idea, but it very rarely happens. Unfortunately, all my years of doing it nobody asked me after the job was over: ‘Was there something that we could have fixed with your mechanical equipment that would have made it better?’ But I think it's a good thing to put in there, because it would make someone aware [of the problems and solutions].”

Lastly but not the least, the interviewed safety trainers offered suggestions for how to effectively implement the planning tool in a roofing company, such as explicit incentives for participation (e.g., T-shirt, safety points) and clear definition of implementation participants’ roles and responsibilities. Those inputs were incorporated later in this step when the EHS and research team brainstormed the implementation plan.

### **5.4.3 Implementation Plan**

To build the industry partner’s self-efficacy in using the program products in daily business operation, four-component implementation plan were designed: awareness campaign, skill training, policy intervention, and redesign of working environment. This

implementation plan created an opportunity for a new PE program which was funded by State of Washington, Department of Labor and Industries. This new program will be adopted immediately after the completion of the current one.

### ***Awareness campaign***

The program will begin with awareness campaign at the industry partner's All-Hands meeting in December 2021. All workers and managers will be shown safety animations, followed by a researcher-led presentation to introduce the severity and prevalence of overexertion hazards caused by cart handling and general measures they can adopt to prevent such injuries. Participants will also learn about the goals and processes of the intervention program. The awareness campaign aims to set the stage by increasing employees' ergonomics awareness and motivation to participate in the program.

### ***Skill training***

The author and the EHS director will provide six training sessions to foremen and introduce them detailed instructions for the prevention tips and application examples, using the 5-page training handout (Appendix C). Each session will be about 10 minutes and take place in conjunction with the monthly foremen's meetings beginning in December 2021. After each session, foremen will lead toolbox talks to convey key training messages to the field workers. Such training will help both foremen and workers acquire the skills/knowledge to address ergonomic hazards associated with cart handling.

### ***Policy intervention***

To gear up the industry partner for the intervention as an organization, the company's safety management documents will be revised as recommended by the planning tool (Appendix D). At the company level, Safety Policy Book will be revised to add a new subsection for ergonomic cart handling. The book will be introduced to Snyder's managers at its corporate meeting in early August 2021. At the project level, the Project Startup Form (used by safety personnel to gather project information when preparing safety plans), Job Hazard Analysis, Site-specific Safety Plan, and Inspection Checklist will be revised. The revisions will ensure incorporation of the evidence-based measures and the revised documents will be pre-tested in September by the project team members. Enacting the revised policies to provide an encouraging organizational environment for the intended changes.

### ***Redesign of working environment***

The warehouse manager and workers of the industry partner will be recruited to remodel material carts as illustrated in Figure 15 (a). The design of the handle (e.g. handle height, orientation) will follow ergonomic principles recommended in existing studies (M. J. M. Hoozemans et al. 2007; M. J. M. Hoozemans et al. 2004; Lett and McGill 2006; Marras, Knapik, and Ferguson 2009; Jansen et al. 2002; Seo, Armstrong, and Young 2010). The remodeling is scheduled to be completed by November 2021. Warning signages (Signage A and B), as shown in Figure 15 (b) and (c), will be produced and attached to carts and bundled materials to provide cues for team pulling/pushing and job rotation. The warning signages creation is scheduled to be completed by November 2021.

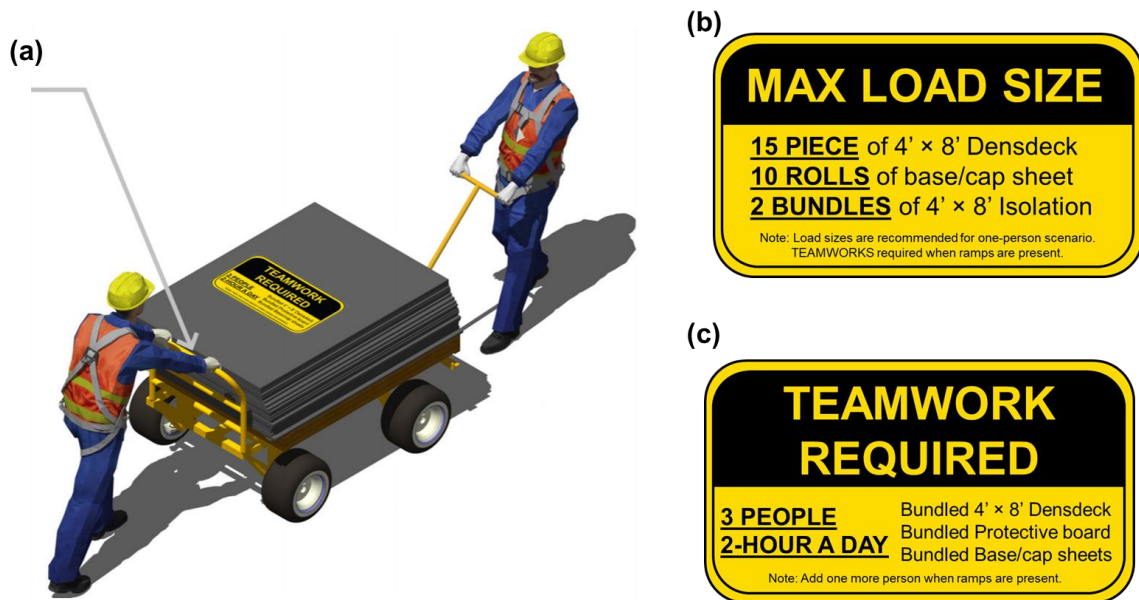


Figure 15. Redesign of working environment: (a) remodeling carts to allow teammates to more easily push by installing a rear handle; (b) a warning signage attached to material bundles to provide reminder on team pulling/pushing; (c) a warning signage attached to the additional handle to offer reminder on job rotation.

The timeline of the intervention activities is illustrated in Figure 16. To summarize, the whole intervention program will go through three phases, including preparation (five months), implementation (six months), and sustainment (10 months). During the program preparation, the industry partner and research team will build an intervention team and collectively prepare intervention materials. In the next phase, the intervention team will lead the program for six months. Subsequently, the program will become self-managed by the industry partner, and the intervention team will meet up regularly for check-in and consultation. Furthermore, as indicated by Figure 16, evaluation data will be collected throughout the program to allow a pre-intra-post comparison for the program effectiveness (details will be discussed in the next step).

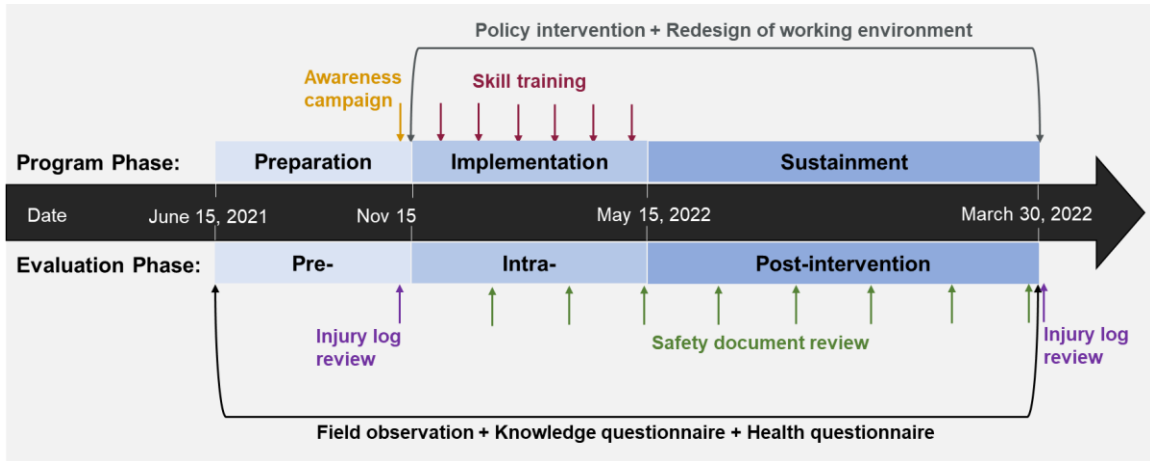


Figure 16. Overall approach to the proposed implementation: the design of the ergonomic program and evaluation protocol

## 5.5 Evaluation

The step 5 in the roadmap is evaluation – gathering level three evidence to evaluate the efficacy of the four-component intervention. As shown in Figure 16, the evaluation process in this case example will take two additional years beyond the current PE program. This exceeds the typical timeline of a doctoral dissertation. Therefore, this case study only presents an evaluation protocol to demonstrate the last step of the 2SAFE planning model. Specifically, evaluation data will be collected periodically during all three phases of the intervention, namely, preparation, implementation, and sustainment, to examine the hypothetical real-world effect of the intervention. The outcome variables will include increased knowledge by workers and foremen, changed practices by workers and foremen, changed practices by safety professionals, improved health status of workers, reduced overexertion injury, and sustained program implementation.

### *Increased knowledge by workers and foremen*

Project team members will visit jobsites to deliver attitude and know-how questionnaire to evaluate workers' and foremen's ergonomics knowledge on cart handling. Based on the industry partner's business records, there would be an average 13 roofing projects across the 18-month period and each roofing project lasts in average two months. Given that the plan is to visit every project twice every month, there will be a total of 52 field visits and generate 156 time-series data points that track the changes of knowledge (16 workers and eight foremen in pre-intervention, 32 workers and 16 foremen in intra-intervention, 56 workers and 28 foremen in post-intervention). It is hypothesized that the knowledge scores will be improved gradually during the intervention phase as the awareness campaign and skill trainings are launched. It is expected that the scores will maintain at a high level in the post-intervention phase.

#### ***Changed practices by workers and foremen***

During jobsite visit, project team members will also observe and document field workers' practices of cart handling. A designated inspection checklist will be used to determine if ergonomic hazards are addressed properly. The program will have a total of 52 field visits and generate 52 time-series data points that track the changes of working practices (eight in pre-intervention, 16 in intra-intervention, 28 in post-intervention). It is expected that the work practice will improve gradually over both intra- and post-intervention phases. The rate of change is expected to be slower than that of knowledge enhancement because of a time lag between knowledge acquisition and application.

#### ***Changed practices by safety professionals***

Safety document will be reviewed by project team every two months in both implementation and sustainment phases. A designated checklist will be used to measure

the extent to which ergonomic guidelines are incorporated into safety management, including job hazard analysis, site-specific safety planning, and safety inspection. It is hypothesized that the changes will occur immediately after the intervention begins when the researchers provide full support and guidance on implementation. The program also hypothesized that the changes become permanent after the intervention is completed.

### ***Improved health status of workers***

A standardized health questionnaire will be delivered to workers along with the attitude and know-how questionnaire during the field observation. The survey results will help track the changes of workers' health status. A lag period is expected before the intervention program has a noticeable impact on workers' health. Therefore, it is hypothesized that the health scores will begin to improve several months after the start of the intervention and then maintain an increasing trend.

### ***Reduced overexertion injury***

During the program preparation, the industry partner's injury log in the past five years (2016 - 2020) will be reviewed. Claim numbers, total lost days, and economic cost that are associated with cart handling will be extracted as the baseline. Injury log will be reviewed again when the sustainment phase is completed, and the results will be compared to the baseline data to determine if the program accomplished its long-term goal of reducing overexertion injuries. It is hypothesized that the changes will occur immediately after the intervention begins when the researchers provide full support and guidance on implementation. The program also hypothesizes that the changes become permanent after the intervention is completed.

### ***Sustained program implementation***

The program will document how the intervention is carried out and if it is sustained by gathering process data after every intervention activity (e.g., toolbox talk, safety inspection) takes place. A combination of qualitative and quantitative data will be collected to evaluate the program sustainability from multiple aspects: reach (e.g., number of employees being trained or inspected), duration, frequency, engagement (e.g., the number of feedbacks gathered from toolbox talks), and unexpected events that could influence the program implementation or account for the outcomes of interest. A composite index will be constructed to reflect the extent to which the program is implemented. The program will have an intra-post comparison of the index to understand whether the withdrawal of the researcher's support leads to a reversal of implementation. It is expected that the index will drop slightly but still maintain at a high level in the post-intervention phase.

Interrupted time series (ITS) analysis will be employed to analyze the collected time series data to determine if the intervention effects are statistically significant. Following the ITS methodologies recommended by Bernal, Cummins, and Gasparrini (2017) and Taljaard et al. (2014), a segmented regression model will be created for each outcome to test the proposed hypothesis. The segmented regression analysis can help detect "break-points" where linear relations between an outcome and time would change (e.g. the time when workers' work practices begin to change). Then, the slope of change can be calculated to measure the magnitude of intervention effect. The package "Segmented" in R project will be used to create such statistical model (Muggeo and Muggeo 2017).

## **5.6 Summary**

This chapter described the use of 2SAFE model in a PE program at a construction contractor. The goals of the program came into focus through the surveillance of historical incidences and screening of ergonomic hazards that were jointly performed by researchers and practitioners. In order to identify solutions, a combination of experiment and field data was collected to assess how the identified ergonomic hazards can affect overexertion injuries. Individuals from all levels of the industry partner company were involved in the collection and analysis of assessment data. Subsequently, assessment findings were converted into various end products which were well received and immediately implemented by the industry partner company. Positive feedback was also obtained from external subject matter experts, suggesting the products' great potential of wide distribution in the industry. Lastly, an evaluation plan was designed to measure the effectiveness of the implementation of the end products. The next chapter will focus on the program's achievement in facilitating R2P and P2R process to understand the usefulness of the 2SAFE model.

## **CHAPTER 6 MODEL IMPLEMENTATION OUTCOMES**

The 2SAFE model is designed to achieve the dual purposes of a participatory ergonomics (PE) program: to encourage practitioner involvement to adopt research evidence for problem solving and to enhance the scientific enterprise of embedded research projects using participatory inputs. To understand whether the model helped the case PE program fulfill its P2R2P purpose, this chapter reports the program's performance in practitioner involvement and research enterprise. Specifically, the program's P2R performance was analyzed post hoc using research diary data to reflect on how research enterprise of the PE program has been strengthened by involving practitioners. The program's R2P performance was discussed using qualitative data obtained from participant observation, documentation, and interview recording each participant's motives for participation, level of involvement, and influence on program success.

### **6.1 Enhancement of Research Enterprise**

The PE program described in this case study has an embedded research project providing level one evidence to support the design of intervention solutions. By following the 2SAFE model, practitioners were involved in all research activities which shaped the way how this project was conducted and helped strengthen almost all aspects of the scientific enterprise that were outlined in Table 4. Specifically, the participatory process made the research goals and study design relevant to practice, strengthened the rigor of data collection and analysis, and improved the reach of research results, which demonstrate the values of the 2SAFE model in driving P2R process in the case example.

### 6.1.1 Relevance of Research Goals (P2R-1)

At the beginning of the embedded research project, participatory input assisted in defining study aims and formulating research questions.

#### *Definition of Study Aims*

Despite the PE program's focus on assisting the industry partner company, the study aims jointly established in the research project reflected practitioners' shared needs for evidence-based administrative controls to prevent cart handling injuries. The industry relevance has been repeatedly verified when the program products were tested by subject matter experts external to the program – safety trainers from the roofers unions. One relevant quote is: *“I think it [training sheets] explains a lot of what a foreman and a lot of workers don't understand. How many people you need to apply to move this amount of material? They could give them at least a base to go up, where before they were probably guessing one guy can move that. This gives them something to reference, so they have an idea.”* Another relevant comment on one of the animations: *“I think it'll make everybody more aware of the proper ramps up. It's something that we've, at least I failed when teaching the apprentices about ramps. We do a lot of ramps to dump stuff off the edge of the roof, and we teach safety in that, but we never really stressed the angles [of ramps] like we should. Thanks for tackling this issue, which I think it's very worthwhile.”*

Originally, the author's interest was in the ergonomic design of manual carts because this has long been a hot ergonomics research topic (Argubi-Wollesen et al. 2017; M. J. Hoozemans et al. 1998; Jung, Haight, and Freivalds 2005). Although this line of research could inform the industry partner's purchasing decisions, the surveillance and screening results suggested that more pressing issues was how to properly maintain and

operate carts in daily operations. When incorporating this practitioner perspective into literature review, the author surprisingly found that administrative controls have not been an explicit subject of ergonomics research, with little empirical evidence being offered to support the design of numerical ergonomic standards for cart handling. Eventually, a consensus resting on both practitioners' needs and researchers' interests was reached.

In addition, closeness to real-life contexts enabled the program to capture nuances of the causations of WMSDs at both individual and organization levels. As a result, this research was attentive to structural determinants of safety issues and sought to serve the needs of young workers who were more vulnerable to WMSD injuries. For example, surveillance results indicated that 86% of cart handling injuries happened to individuals who were employed for less than 1 year. Field observation suggested that it was an organizational determinant caused this susceptibility. Physically demanding tasks were primarily assigned to newcomers, who not only were given little autonomy in determining how to complete their works but also had difficulties voicing their grievances to management. This perspective transformed the way the author defined research goals with special attention being paid to address the power inequality.

### ***Formulation of Research Questions***

The research questions co-formulated in the participatory process acknowledged the practical complexity of the real world and accurately pinpointed risk-injury relations that should be investigated in order to generate applicable evidence. For instance, after observing that physical environment-related hazards were usually at play simultaneously, the author developed a research question to measure the interaction effects of multiple hazards. The answer to this question was proven to be relevant for both researchers and

practitioners because it not only unveiled complex interaction effects between physical environment-related hazards but also yielded useful results to reliably inform cart operation in a complex working environment.

To summarize, the author adhered to the 2SAFE model and involved site supervisors, workers, and EHS team in the surveillance and screening of WMSD issues. This helped the research project formulate meaningful study aims and research questions that balanced practitioners' pressing needs and researchers' interest (Figure 17).

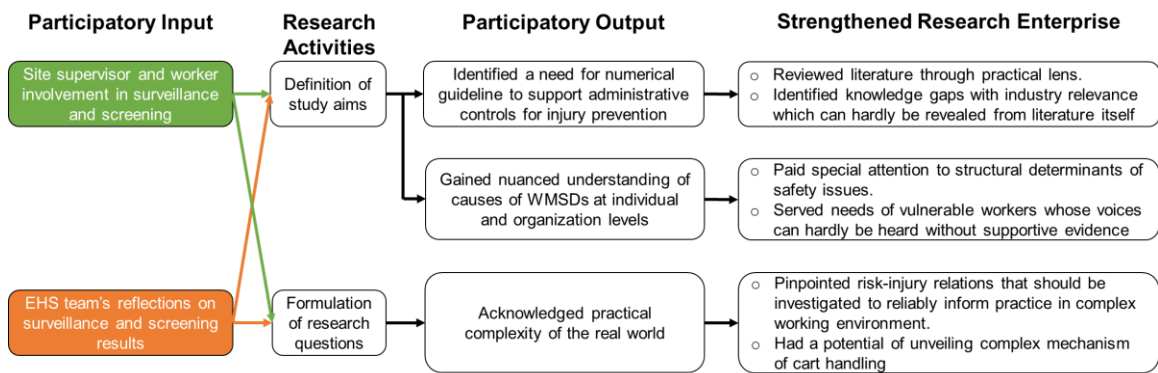


Figure 17. Participatory feedback ensured the relevance of research goals in the research project embedded in the PE program

### 6.1.2 Relevance of Study Design (P2R-2)

Practitioners were engaged in selecting experiment variables and defining the range of each variable which ensured the practical relevance of study design.

#### *Selection of Experiment Variable*

Involving the EHS team in the study design helped the program select experiment variables that are manipulable in practice, thereby making research findings more applicable. For example, the author was originally uncertain about how to deal with individual variables in the experiment. For one, the causal mechanisms of individual factors on cart handling were unclear, refraining the author from deliberately selecting

subjects to consider individual factors. On the other hand, obtaining a large subject pool for the full randomization of individual factors was constrained by the cost and difficulty of recruiting field workers. As inspired by the EHS director, individual variables were eventually controlled by selecting a representative subject. This is because characterizing and assessing individual differences was not meaningful in terms of the design of administrative controls. It is either unethical or unrealistic for supervisory personnel to assign cart handling tasks based on body weight, fitness, or age. Because of this methodological choice, the experiments can focus on examining the factors of interest that can lead to attainable administrative controls.

### ***Definition of Variable Range***

Because the experiments were designed collaboratively by incorporating field supervisors' and workers' inputs, ranges of experiment variables were determined in a way that can best simulate actual physical environments to ensure the practical implications of research findings. For example, the effect of cart loads on OPP in relation to other factors was assessed at a range commonly seen on construction sites. In doing so, this embedded research project was not restricted to identify the causal relationships between OPP injury and its risk factors; rather, it captured the variations of the risk-injury relations under complex working environments. This methodological choice made research results readily usable. Practitioners can refer to the results (Figure 8, 9, 12, and 13) to directly search for the safe load under a certain circumstance or to find the at-risk threshold of a physical environment–related factor, given a fixed cart load.

Figure 18 summarizes the contributions of site supervisors, workers, and EHS team in ensuring the practical relevance of study design.

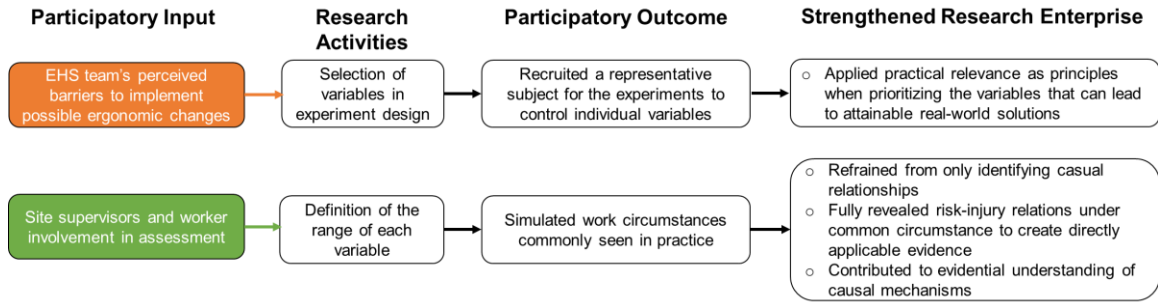


Figure 18. Participatory feedback ensured the relevance of study design in the research project embedded in the PE program

### 6.1.3 Rigor of Study Design (P2R-3)

No evidence was found to prove participatory inputs in this case example contributed to the rigor of study design, which was primarily ensured through inputs from the research team.

### 6.1.4 Rigor of Data Collection (P2R-4)

In this case study, practitioners contributed to the rigor of data collection, as they were involved in designing field data collection protocol, field data collection instrument, and experiment instruments.

#### *Design of Field Data Collection Protocol*

A compatible study protocol was developed for field data collection to ensure the subject recruitment and retention and quality of research data. Accurate field data on the use of carts were important because the data was synthesized with experiment data to estimate overexertion risk of cart handling. The original plan was to perform bi-weekly phone survey, but the author and EHS director conceived an idea of incorporating the

survey questions into the company's timecard. In doing so, the survey data became more precise as it captured variations of cart operation over the lifecycle of a project.

### ***Design of Field Data Collection Instrument***

Owing to warehouse personnel's technical competency and field experience, rigorous research instruments were designed to improve the field data quality. For example, the author worked closely with the warehouse personnel to develop an instrument for cart inspection and maintenance. An exhaustive list of structural problems was created, along with the scales of measurement, to evaluate cart conditions at a more granular level. Although the scale variables were not included in the final statistical models due to a lack of enough sample size of aged carts, the co-developed research instrument has a potential to help gain more insightful into which structural problems are more detrimental to cart performance and to what extent.

### ***Design of Experiment Instruments***

The warehouse personnel helped the author design and modify research instruments to collect accurate and reliable experiment data. The force gauge did not function properly on the first day of the experiment. The author found that, due to a poor design, the accessory handle partially obscured the force gauge's USB port. Without the accessory handle, the subject cannot mimic actual cart handling postures in the experiment. The problem was quickly solved by the warehouse manager who ground down the obstructing edges to make the handle fit to the force gauge (Figure 19 (a)). Moreover, the warehouse manager and mechanic jointly developed an aluminum mounting bracket for the attitude/heading reference sensor (Figure 19 (b)). Coming with two tailored mounting straps, the bracket (together with the sensor) can be firmly

mounted onto the axle of an experiment cart enabling the sensor to reliably characterize cart movement in the experiment.

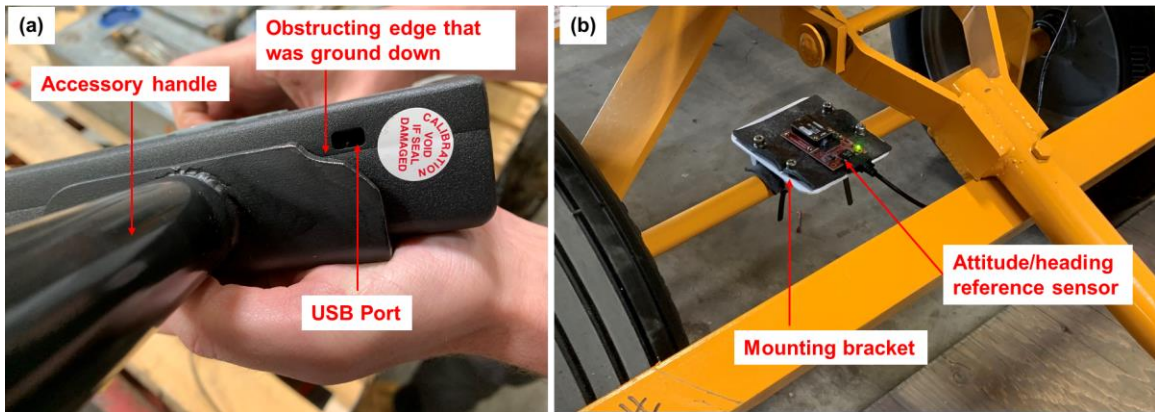


Figure 19. Two examples of how participatory input contributed to the design and alteration of research instruments in experiments

Because of using 2SAFE model, the EHS team and warehouse personnel were fully motivated and played a proactive role in data collection of the embedded research project. Their inputs ensured accuracy and reliability of both field and experiment data (Figure 20).

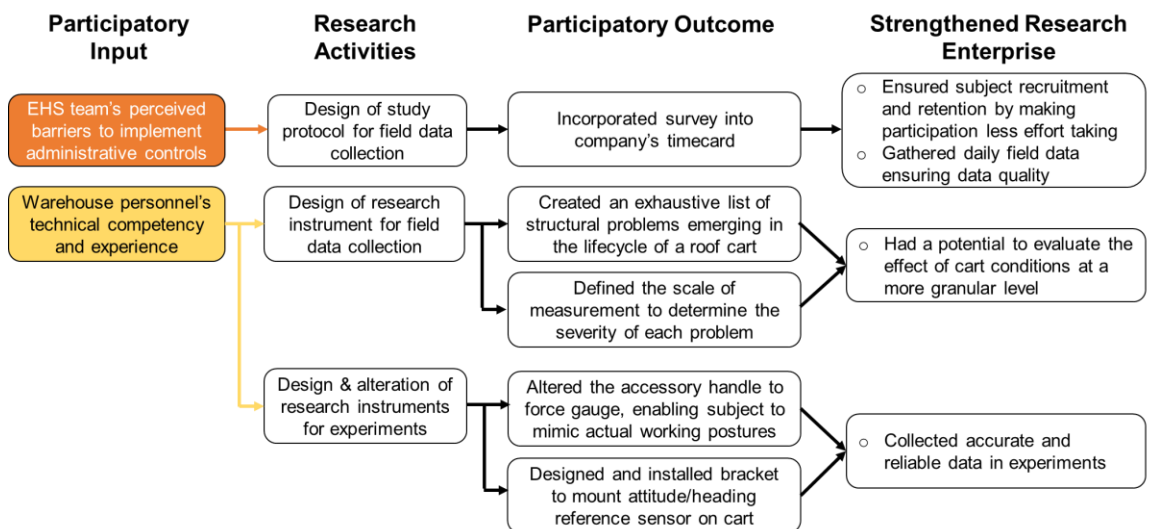


Figure 20. Participatory input ensured the rigor of data collection in the research project embedded in the PE program

### 6.1.5 Rigor of Data Analysis (P2R-5)

Practitioner participation in data analysis helped “audit” research findings and gain insights for a deeper interpretation (Figure 21). For example, one finding drew from the experiment was that pneumatic tires start to deteriorate earlier than solid ones, but this finding was obtained from a relatively small sample size. To confirm the credibility of this finding, the warehouse personnel further inspected experimental carts and helped the research team exclude other cart-related factors that could interfere with the statistical results. The mechanic also offered practical insights to explain the pattern for why two types of tires could deteriorate differently.

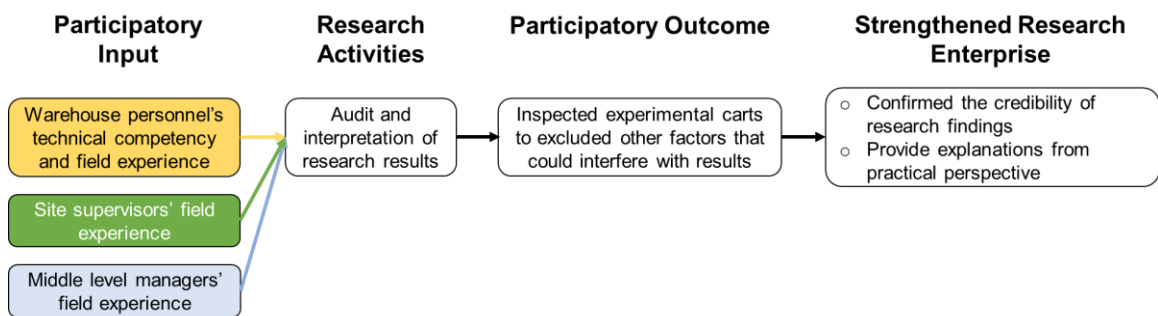


Figure 21. Participatory input ensured the rigor of data analysis in the research project embedded in the PE program

### 6.1.6 Reach of Research Results (P2R-6)

The program engaged practitioners in the following research activities to ensure the reach of research results: framing evidence into easy-to-understand information, creating contextually appropriate research products, and leveraging the industry partner’s network for research dissemination.

#### *Framing of Research Results*

The embedded research project generated accessible information that industry practitioners can understand. This was partially achieved by soliciting practical insights to reasonably simplify the results of statistical analysis. For example, the experiment originally selected four types of hand forces (i.e., initial force, sustained force, turning force, and stop force) as dependent variables in the statistical models. However, participatory feedback from the EHS team indicated that this methodological choice would overcomplicate research findings and make results hard to understand. The collective discussion led to the final decision of selecting the sustained force that constituted the majority of the cart movement as the primary outcome measure. By slightly compromising the scientific merit, the research results were framed into simplified information to be disseminated to practitioners.

The accessibility was also strengthened through deliberating the way statistical results were presented. This research project went beyond the traditional way of reporting statistics, that is, illuminating the relation between one risk factor and health outcome while holding or averaging out all other factors (e.g., every 1-kg load added to a cart, the ROF is predicted to increase by 0.756 N for a 4 ° ramp). Such result is technically sound for communication in the academic community but could hardly make its own way into the industry because it is neither understandable nor readily usable for practitioners. As commented by a senior manager after reading preliminary statistical results: *“Now I understood how these measurement instruments work. Your charts also look cool, but could you tell me how they can help us in safety?”* The reality is that practitioners have neither time or interest in interpreting statistical results themselves, and they would easily walk away if no demonstrable benefits were explicitly present. In view of this, the author

made one step further by interpreting risk-injury relations while introducing variations to other factors to simulate the actual working conditions and make results immediately usable. An example can be seen in Table 13 which recommends team sizes for ramps of different slopes under various cart loads.

Furthermore, participatory feedback from the EHS team, site supervisors, and workers helped translate statistical reports into plain language that practitioners use in daily work. For example, the author originally used 14 as the factor of the ratios for ramp slope, but the EHS director expressed concerns that: *“All roofers work with 1:12 or 4:12 or some other ?:12 to measure slope. If the numbers could be translated to a factor of 12 instead of ?:14 or degrees would make more sense to them. You could put the accurate degree in brackets following the estimation, for example: 4 degrees (approximately 1:12).”* Her suggestion not only covered the accuracy of the message but also gave a good visual to roofers. This framing choice can arguably increase the reach of the research findings, as it is evident in the literature that easy-to-visualize recommendations are more memorable (Paivio, Walsh, and Bons 1994; Riis and Ratner 2015) and more likely to be implemented (Woolfolk, Parrish, and Murphy 1985). Because of using the everyday language in the industry, the author found that practitioners easily captured the meanings of the research results and gave positive feedback. A relevant quote from a journeyman roofer is as follow: *“Just got this [the booklet and handout] and I want to say that the information is put together perfectly. I believe this is a readable document that anyone can read and understand. Great work!”*

### ***Development of Research Products***

The research findings were converted into a training handout, two animated stories, and a planning tool. Originally, the research team was only going to develop a booklet. However, the author noted that the EHS team regularly receive documents of this kind, but the key messages were rarely passed down to workers. One main reason is that safety professionals themselves have limited time to convert such “lengthy” documents into suitable materials for workers to use. This researcher-in-residence experience enabled the author to identify a need to develop materials that were contextually appropriate to be used in various training venues (e.g., safety orientation, all-hands meeting, and toolbox talk). Research products were crafted and iterated with the full support of practitioners at all levels of the company. The strong, positive feedback from around 100 workers and 12 safety trainers has proven the value of the final products. In particular, some trainers’ desire to incorporate them into their training curricula demonstrated the wide reach of this research project embedded in the PE program.

### ***Dissemination of Research Findings***

Because of the industry partner’s participation, the research dissemination in this PE program went beyond the traditional academic venues and reached to practitioners through various communication channels. For example, the EHS director voluntarily shared the research outputs with external trainers who came to the company for safety training. The company’s networks with industry associations, safety consultants, and insurance companies were also leveraged which enabled the research products to be disseminated to key players in the roofing industry. Company management also attended various workshops and conferences to co-present research findings with local contractors,

subcontractors, and consultants. In less than half year since launched, the program products have been used by two roofing contractors and two roofing contractors associations and featured in the trade magazine of Chicago Roofing Contractors Association Today.

In a nutshell, the reach of research results in this embedded research project was ensured by involving individuals at almost every level of the organization to provide insights into creating easy-to-understand scientific information and developing contextually appropriate research products. Company management was also motivated to co-disseminate products using their network (Figure 22).

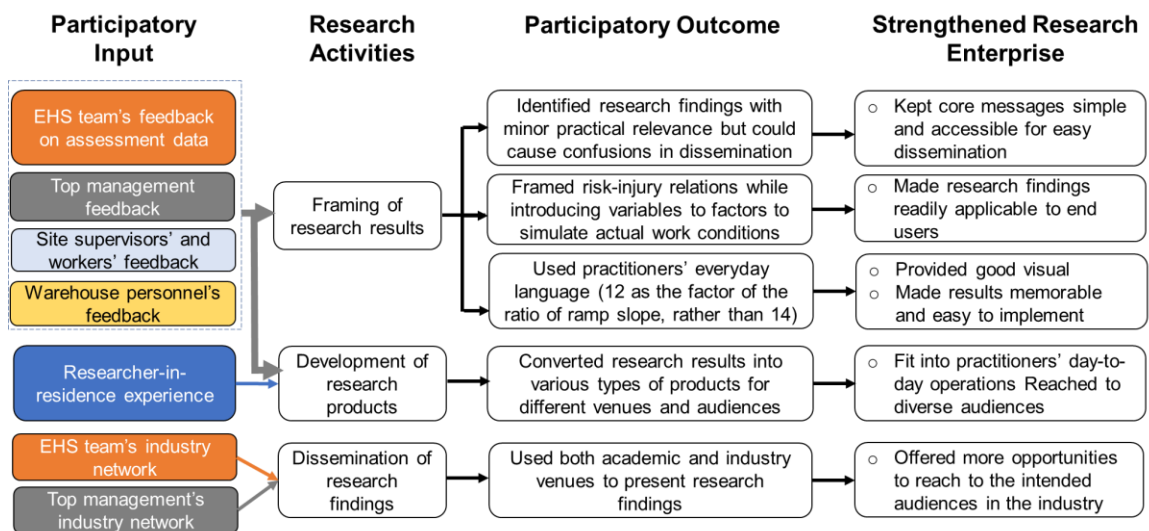


Figure 22. Participatory input ensured the reach of research results in the research project embedded in the PE program

## 6.2 Practitioner Involvement

The PE program had participation from all areas of the organization, including top-level management, middle-level management, site supervisors, and field workers. Most of participation were voluntary and self-motivated. The results below illustrate how

participants of each organizational area improved ergonomic awareness and knowledge against the outcome measures outlined in Table 3 and what actions they carried out to facilitate the problem-solving process in the PE program.

### **6.2.1 Top-Level Management**

Both the company CEO and the president were deeply involved in the PE program. Top management support was demonstrated to employees by word and deed on various occasions throughout the program, which can be largely ascribed to changes in their perceived severity, perceived benefit, and self-efficacy.

#### ***Perceived Severity (R2P-TM2)***

At the beginning of the program, information on severity created by the program allowed the top-level managers to pinpoint ergonomic problems that were previously unknown and recognize the need for change. For example, the severity of operating aged equipment demonstrated in the 2018 All-Hands meeting presentation led to the CEO's immediate action of purchasing new manual equipment (Figure 23 (a) and (b)). A relevant quote from the CEO: *“Originally, I thought that a cart is a cart. I don't see any difference. But your research data changed my mind. Old carts could double the force required to pull and make the task unsafe!”* This action, along with the replacement of four-wheel carts (Figure 23 (c) and (d)) using the research funding, made the PE program well-known and accepted among employees, paving the way for a participative intervention process.



Figure 23. Preventative replacement performed during the PE program: (a) Insulation Cart; (b) Dolly; and (c) Four-wheel cart frame and (d) wheels.

***Perceived Benefit (R2P-TM3)***

As the program progressed, top management received positive employee feedback which strengthened their commitment to the program. For example, the president stated in an internal staff email when the PE program was awarded research fundings: “*I want*

*to start by saying what a positive impact you [Zhenyu] have had at Snyder since you've been a part of the team. Your contributions to our safety culture, morale and operations have been phenomenal. You should be very proud of your accomplishments, and we are happy to be riding the coattails of the research project. I will make sure you get the buy-in and support for a successful study."* A similar quote is from the CEO: *"Knowing we [top level managers] could support a project that ultimately makes our people able to operate a little safer in their jobs was reason enough to support you [the author]."* In fact, top-level managers' supportive messages were clearly and consistently communicated to employees at all levels of the company, which helped the program get company-wide buy-in.

Company management also perceived the program's benefit in building brand image. For example, after attending a construction safety conference in which the EHS director and the author showcased the PE program, the president reflected: *"I just wanted to take a brief moment to acknowledge Lu [EHS director] and Zhenyu for another great presentation on the roof cart study at the SafeBuild Alliance Meeting yesterday afternoon. It was well thought out and I believe it left a great impression on our peers from Mortensen, Skanska, Hoffman, UW [University of Washington], WSU [Washington State University], Sound Transit, Fred Hutch and many others."*

#### ***Self-Efficacy (R2P-TM4)***

Top management commitment was also driven by senior managers' self-efficacy in what changes the program could bring to the company. In particular, the CEO were impressed by how scientific evidence was framed into easy to understand and engaging information: *"One thing makes you [the author] so successful here is that you understand*

*how to communicate to our workers. The way you used weights and the animation effect [in your All-Hands meeting presentation] to show the pressure on spinal discs is easy to understand and vivid to our workers.”* The president once commented on safety animations: *“I like numbers [embedded in the animations]. I like how you broke it down like 57% is the equivalent of five men. It is good visual, and I thought that was powerful.”*

As top-level management saw the benefits from the PE program, adequate in-house resources were supplied which ensured the smooth implementation of the program. The program had full accessibility to materials, equipment, and miscellaneous items while conducting experiments in the company’s warehouse. Throughout the PE program, various types of research activities were taken place during the company’s work time, such as foremen’s meeting (Figure 24). The involved personnel resources were always made available by company management. For the next phase of the PE program that will aim at gauging real-world impact of the evidence-based interventions, financial commitment was also made by top management to reward active participants.



Figure 24. Top management made resources available for the program activities: Program products were shown and tested in a foremen’s meeting at the company

Top management commitment was also demonstrated by senior managers’ regular check on status update of the program. For example, the PE program had some difficulties of gathering daily cart operation data because integrating survey questions into timecard added additional confusions while the company was in transition from paper-based timecard to an electronic one. To address the problem, the president told foremen: *“Just a quick note thanking you guys for filling out the cart forms for Zhenyu’s [the author] ergonomics study. I know we haven’t ironed out the kinks on the electronic version of the form and most of you are probably still using the paper copies, but please keep the paperwork coming.”* At the end of this email correspondence, the president

acknowledged the importance of this program to the company: “I know you all have a lot on your plates on a daily basis, but please keep up the consistency of turning in the forms as this is of the utmost importance for Zhenyu. Ultimately the study will help us keep our crews safe out there and we need accurate information to do that. Thanks in advance and have a good one out there today.”

As summarized in Figure 25, top-level managers notably changed their health beliefs after receiving health belief information and participating in program activities that were mapped out by the 2SAFE model. As a result, they made a series of informed decisions and provided financial and managerial commitment to the PE program

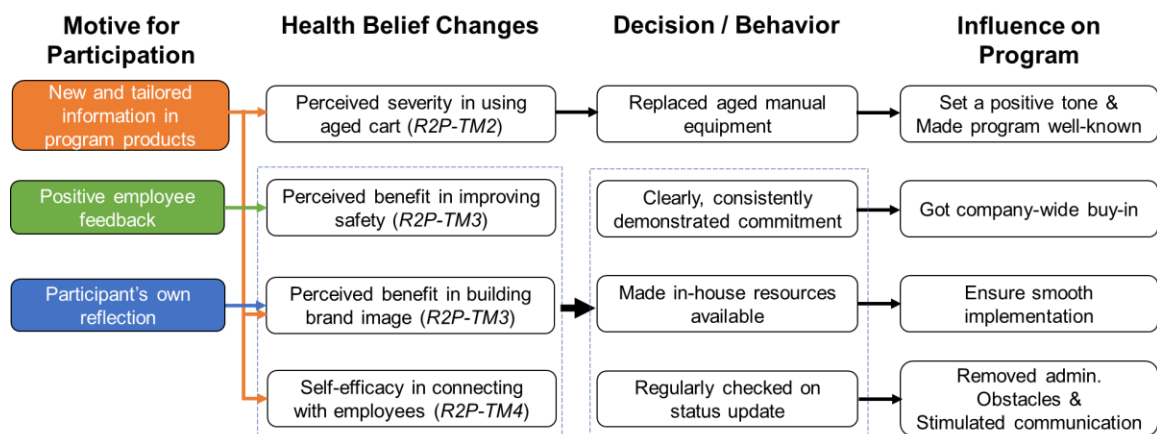


Figure 25. The participation of top-level management in the PE program

### 6.2.2 Middle Level Management: the EHS Team

The EHS director and the EHS manager were two main implementers in the PE program. Their roles were coordinating between the research team and the industry partner. They also served as subject matter experts ensuring that the program products can meet the needs of the company. Economic incentives were offered to compensate their time contributed to the program. Nevertheless, the qualitative data suggests that the

EHS team was highly engaged because they perceived health and reputational benefits and felt confident in promoting changes through implementing the PE program.

***Perceived Benefit (R2P-ET3)***

First, workers' growing ergonomic awareness was one primary source of incentives. For example, the EHS director witnessed that the 2018 ergonomics presentation received positive employee feedback. A relevant quote from a worker is as follows: "*I am applying ergonomic techniques you [Zhenyu] taught us. They are very helpful. I injured my back before, and I can still feel the pain. I don't want it to happen again. Everyone [he yelled his co-workers] watch your back! Injuries are no joke!*". Such positive responses motivated the EHS director to continue research-practice collaboration and extend this "small" training program into a long-term PE program.

Second, the EHS team's motivation was strengthened because of workers' increased understanding of ergonomic hazards associated with cart handling. A relevant quote from the EHS manager: "*My observation is that people certainly do more teamwork when moving materials. When I worked on the site [as a roofer], I always pulled carts myself and no one was aware of teamwork. They [field workers] also load less materials on carts and try to build ramps as gentle as possible. I know what they are doing are still not perfect. But compared to how things got done before, we've made a big improvement.*" It should be noted that the EHS manager had more than ten years' experience as a journey level roofer with the industry partner. He became the EHS manager around the time of the program's inception and was responsible for field safety inspection. This unique experience allowed him to closely observe worker practice and reflect on whether and why the changes happened: "*I believe it was the research you did*

*with us that makes a difference! We were used to how to get stuff [manual material handling activities] done. Just load as much materials as we can [on a cart] and pull. We didn't give any thought to it [while doing it]. What you suggested [teamwork, job rotation, pre-plan workspace setup] are simple but ironically they are sort of eye opening to us.”*

Third, the EHS team's motivation was sustained as they continually received positive feedback to reinforce their perceived benefit. For example, the EHS manager shared an anecdote which verified his account of how the PE program brought changes to the company: *“Last week, two new hires came to find me after the safety orientation. They told me that ‘We really liked the animation. It was well put together. We had never thought of those methods [to prevent cart handling injury] before watching it. We were asked to do this and that to be safe out there on the site. But nobody told us how to protect ourselves from strains when handling material carts!’”*

Fourth, improving reputation at work was another factor in the EHS team's acceptance of the PE program. For example, the EHS director enjoyed prestige for being able to develop a company-wide ergonomic program by bringing in university researchers and getting government funding. Here is one quote from a safety orientation when she introduced the author and the PE program to new hires: *“Zhenyu [the author] is a PhD student and began with Snyder as an Intern. He applied for a SHIP Grant and was awarded \$180k by State of Washington to partner with Snyder in a program for safe ergonomic use of four-wheel carts. He got Snyder 14 new four-wheel carts and developed best practices that can help Snyder improve material handlings. The video you just watched is made by him.”* Subsequently, she emphasized that this research-practice

collaboration was ongoing as we continued to help the company: “*Zhenyu has just been awarded a second grant to continue his research with Snyder as a partner for another two years.*” This perceived benefit in professional reputation, as well as public commitment to the program, gave the EHS team impetus to ensure the program will achieve continued success.

Fifth, a sense of fulfilment acted as another incentive for participation. For example, the EHS director’s enthusiasm about the program grew substantially after noting that the program products could be disseminated through the trade union to impact the roofing industry at the national level. In addition to providing administrative and management support to the program as she usually did, she began to think more from a researcher’s perspective and offered insights to contribute to the research enterprise (e.g., what logistical arrangements can facilitate workers’ active participation in a focus group?).

#### ***Self-Efficacy (R2P-TM4)***

Increased self-efficacy in capability to tackle ergonomic issues encouraged the EHS team’s enthusiasm in participation. For example, the EHS manager was proud of his newly acquired knowledge on weights of various roofing materials, as well as the skill of quickly recognizing risk level of a material handling activity. Prior to the program’s inception, the EHS team did not have a clear understanding of WMSD risk factors, and the ergonomic trainings used to be limited to simple prevention tips, such as “watch your back” and “remember to warm up”. Furthermore, the EHS team appreciated the access to useful information to better communicate ergonomic problems at different levels of the organization. For example, one message repeatedly used by the EHS director was “*Aged*

*carts can easily double the force required to pull!*” At the early stage of the PE, this message quickly drew company management’s attention and made the program well known within the organization. An immediate affect was the commitment made by top-level managers to invest in new equipment. This message was subsequently incorporated into the company’s templates for job hazard analysis.

In addition, seeing that intervention solutions succeeded fueled the EHS team’s self-efficacy that the PE program can continue to succeed. For example, the EHS director found that incorporating animations in the company’s safety orientation provided immediate benefit in raising ergonomic awareness. She shared an anecdote that, when she tried to reach personal protection equipment on the top of a closet during a safety orientation, she was reminded by new hires: *“Did you forgot to ask for help? We just learned it from the animation. We should always work as a team!”* Having such direct and positive experience, the EHS director was motivated to play a proactive role in conducting focus groups to refine the animations (Figure 26).



Figure 26. The EHS director and the EHS manager helped with organizing and facilitating the focus groups to refine the safety animations

### ***Perceived Barrier (R2P-TM5)***

There is low perceived barrier among the EHS team to implement interventions during the program. First, the program was well-received in the company and presented little organizational challenges. Second, intervention activities were structured to be synergistic with the company’s safety management system and barely created additional workload. Third, the EHS team was open about the barriers that existed to inhibit the PE program but retained a positive outlook on overcoming them. For example, the EHS director reflected that: *“We need to improve accountability. Otherwise, we can’t enforce these ideas [like job rotation]. Asking foremen to change may take many years as they*

*have got used to how things get done. But I would say the first step is awareness change and this is happening now. This is what I am expecting from this project.”*

The EHS team’s health belief changes and contributions to the program are summarized in Figure 27. It is evident that the EHS team greatly improved their perceived benefits and self-efficacy in addressing ergonomic issues during the PE program. As a result, their contributions have extended past the author’s original expectations, as they not only provided basic administrative and management support to ensure a smooth implementation of the program, but also spent extra time and efforts in refining program products and creating opportunities for continued collaboration.

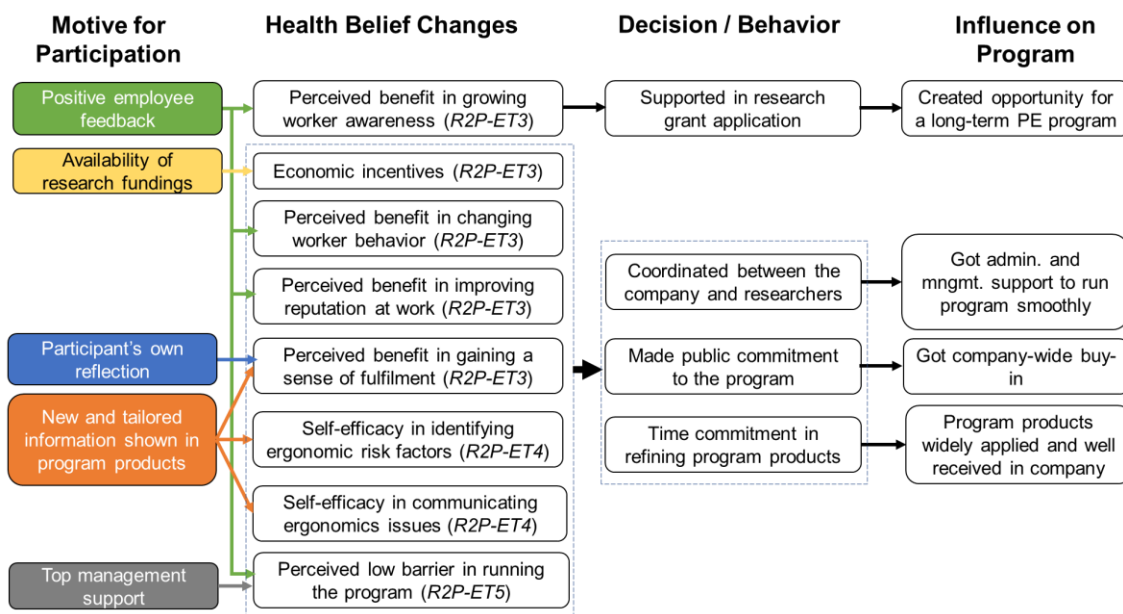


Figure 27. The participation of the EHS director and the EHS Manager in the PE program

### 6.2.3 Other Middle Level Management

Middle level managers, including senior estimators, project managers, and warehouse manager, are not key implementers in the PE program but were involved to

address logistical and administrative issues. The program observed changes in their perceived susceptibility, severity, and benefit.

***Perceived Susceptibility (R2P-MM1) and Perceived Severity (R2P-MM2)***

Some middle level managers made voluntary contributions because of shared concerns about prevalence and severity of cart handling injuries. For example, a senior estimator expressed that the evidence shown in program products aligned with his industry experience: *“What you are doing here is extremely important. I was a roofer for many years before doing estimating. I used to pull this [four-wheel] cart everyday. Sometimes, I had to do it throughout the day. It almost killed me. I’m glad that finally there is someone one interested in helping us prevent cart injuries!”* This senior estimator’s support to the PE program was in word and in deed. He voluntarily helped the program incorporate the cart usage survey into the electronic template of field crew timesheet.

***Perceived Benefit (R2P-MM3)***

The warehouse manager was motivated to participate as a reciprocal gesture towards economic benefit and management support he obtained in the program. The warehouse manager received seven \$25 gift cards to help oversee the purchase and assembly of experimental carts, coordinate and track the status of carts, and assist in cart inspection. Nevertheless, the warehouse manager also made voluntary contributions beyond the scope of his responsibility. For example, he shared insights on how to frame research results into meaningful information that workers can understand. He also assisted in designing and assembling research instruments. His enthusiasm stemmed from his appreciation of the external funding and internal management support for preventative

replacement brought in by the PE program which saved his significant administrative workloads in repairing aged manual carts.

Some middle managers' support on the program depended on the availability of top management commitment. For instance, the program had difficulties of gathering field data when starting to roll out the cart usage survey. Project managers did not originally put adequate emphasis on the survey, leading to poor communication between the office and field. This problem was soon resolved after the company president brought up this problem in senior managers' meetings.

In summary, there was a generally good commitment to the program among middle level managers due to multiple reasons: shared concerns about WMSDs issues, economic incentive, and top management commitment (Figure 28). Their participation provided logistical and administrative assistance needed for the success of the PE program.

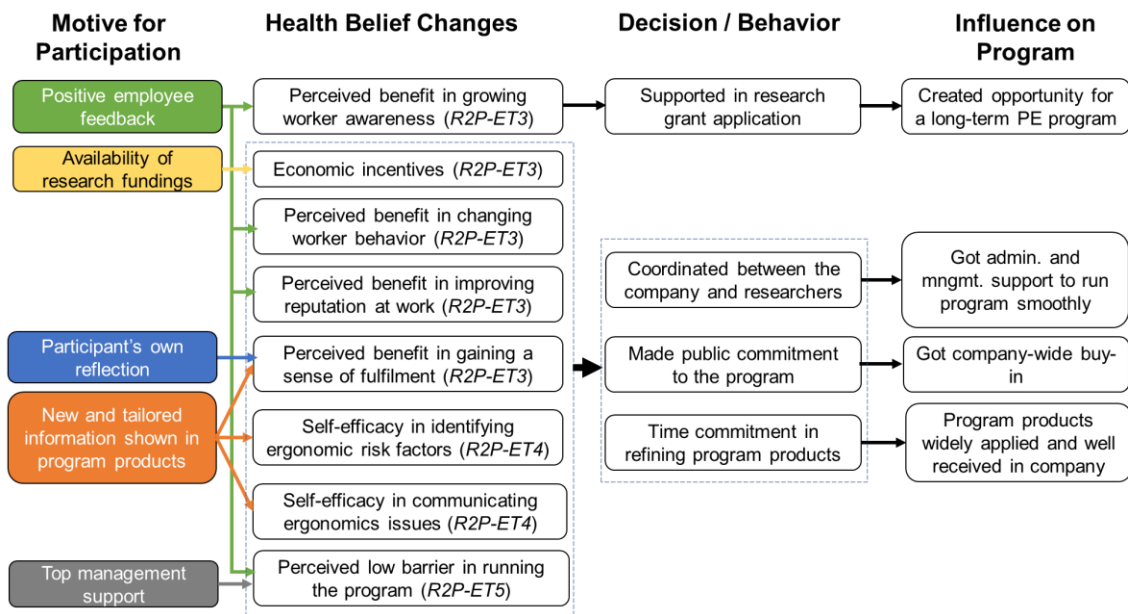


Figure 28. The participation of middle level managers in the PE program, including senior estimators, warehouse manager, and project managers

#### **6.2.4 Site Supervisors**

When it came to site supervisors, including superintendents and foremen, the program witnessed mixed outcomes in participation. Most foremen were cooperative and actively engaged because of perceived benefit in participating in the program, while the program did not get buy-in from two superintendents and one foreman.

##### ***Perceived Benefit (R2P-SS3)***

Foremen had an economic incentive to participate in the program. A \$25 gift card was paid every month for those foremen who filled out the cart usage survey. However, most of foremen were pleased to put in extra effort to support the program. For example, almost every time when the author visited a jobsite, foremen paused tasks at hand, showed the author around the sites, and explained how carts were being used. Sometimes, cart handling activities were completed when the author visited jobsites. When this happened, foremen usually asked crews to simulate the activities. This allowed the author to fully understand work scenarios wherein cart handling activities were performed, translate evidence into real world solutions, and identify field restrictions to implementation. Cases for change (see Figure 29 for examples) were also crafted to strengthen company management's self-efficacy in the program's capability to fulfill desirable changes.

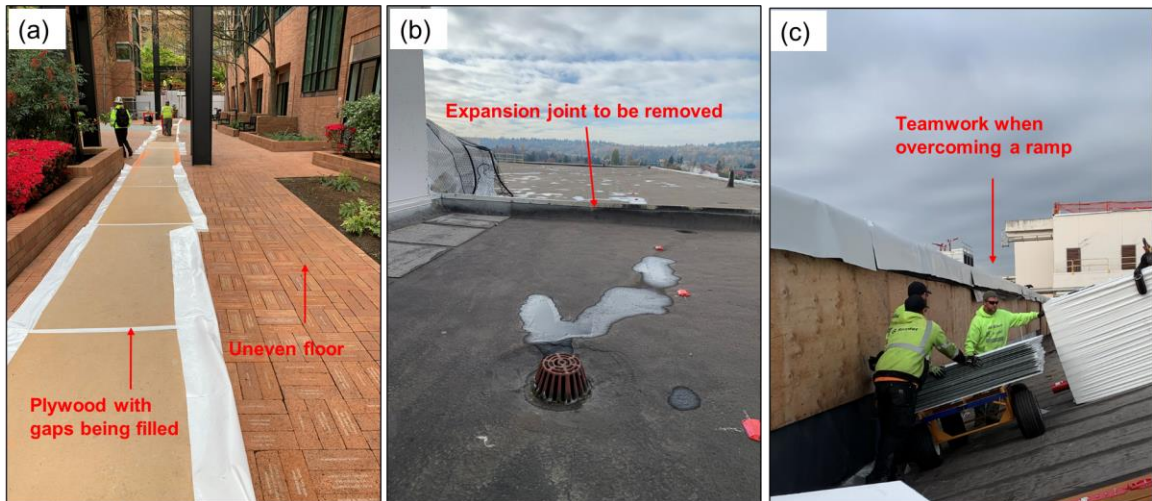


Figure 29. Cases for change. (a) an obstacle impeded cart movement, and the situation was further escalated by the space congestion caused by poor housekeeping. Given that the obstacle was unremovable, workers were requested to relocate debris bag and lunchbox to keep a clean and wide passages. (b) a ramp was poorly set up with loose insulation boards. Workers were asked to use heavy sheets to bridge gaps and make a smooth surface. (c) a ramp was built too steep and with an uneven bottom landing. Foreman was asked to rebuild the bottom landing to make it stable. Because there was no room for extended ramp lengths to reduce the slope, workers were asked to perform team pulling.

Foremen’s strong commitment was also demonstrated by their straightforward and insightful suggestions. For example, a foreman commented when the author rehearsed the All-Hands meeting presentation: *“I am not sure what you [the author] are trying to say with your fancy charts. I feel like you are showing off your mathematical skills. I bet most people in the All-Hands meeting won’t be able to read your charts. Could you find a simple way to show your information?”* This comment led to the decision of using the analogy between lifting weights and spinal cord compression to illustrate the risk levels of material handling activities (Figure 30). The foremen’s advice

was proven helpful since managers and workers still recall this “weight” analogy when looking back the presentation.

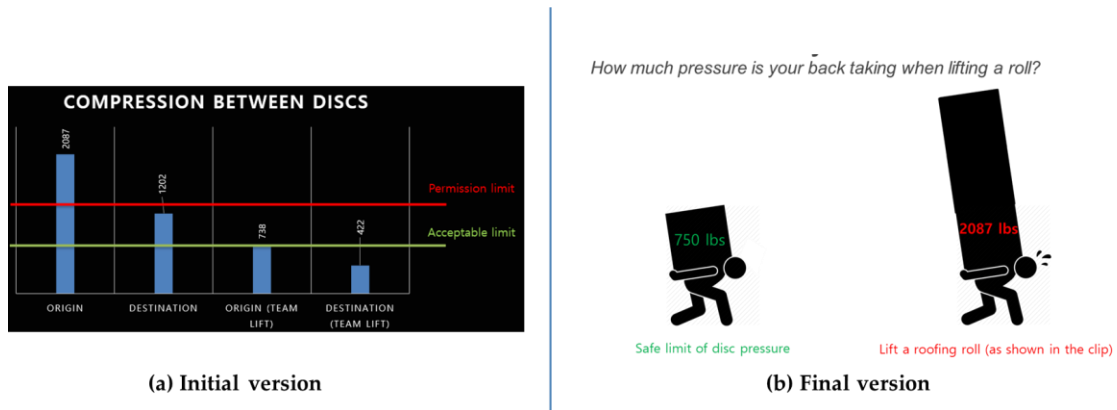


Figure 30. An example of the training presentation being iteratively designed based on foremen’s feedback.

The qualitative data suggests that there were multiple factors in the foremen’s overall acceptance of the PE program. In addition to gift cards, some foremen were enthusiastic about the opportunities of making contributions because they appreciated new manual equipment that was brought by the PE program. There is also adequate evidence that foremen found the program beneficial in improving workspace safety. One relevant quote from a foreman: *“I like your presentation yesterday. I learned a lot from it. I have asked the shop to send us 4-foot by 4-foot Densdeck, instead of 4-foot by 8-foot. Smaller size sheets have no impact on the quality on this particular job, but I know this will make our guys lives easier when moving materials.”* Lastly, the EHS director’s good work relationship with foremen was a also driven force behind foremen’s participation.

***Failure in changing health belief***

On the negative side, strong resistance to the program emerged among the two superintendents and one foreman at the industry partner company. First, this foreman was

involved in the program in a reactive way. He filled out the cart usage survey but rarely provided any feedback. It should be noted that this foreman was well known in the company for prioritizing productivity over safety and having low safety attitude. Field observation indicated that he did not change health belief and repeatedly failed to take ergonomic precautions recommended by the PE program (Figure 31).



Figure 31. (a) A ramp was poorly set up and come with two gaps that could cause both ergonomic injuries and trip/slip incidents. (b) A ramp was built too steep and with an uneven bottom landing; (c) Although the cart was extremely overloaded, teamwork was not conducted. The situation was further escalated by space congestions caused by improper material storage that impeded cart movement.

Two superintendents expressed strong resistance and were not involved in the PE program. One superintendent commented on the PE program: *“I don’t understand this. In the old days, we [roofers] can carry a heavy roll [each one weighs around 100-lb] while climbing a ladder. Nobody complained. Nobody got injured. Now, we are told that carrying a roll alone is not safe, but we are seeing more sprains. Ergonomics only means more rules to us.”* It appears that the superintendents’ health belief did not improve as the program processed, although they were present at various program events. When having casual conversations with the author, one superintendent appeared to intentionally and

repeatedly bring up how productive and hard-working roofers used to be. This gave an impression that he was proud of the hard-working tradition in the roofing industry and was intrinsically resistant to any ergonomic change that could give excuses to squash productivity.

As summarized in Figure 32, by participating in the program, most site supervisors perceived benefit in replacing aged equipment and in improving safety knowledge. This change in health belief, along with good personal relationships with the EHS team, ensured that they provided field data and additional insights for the development and evaluation of program products.

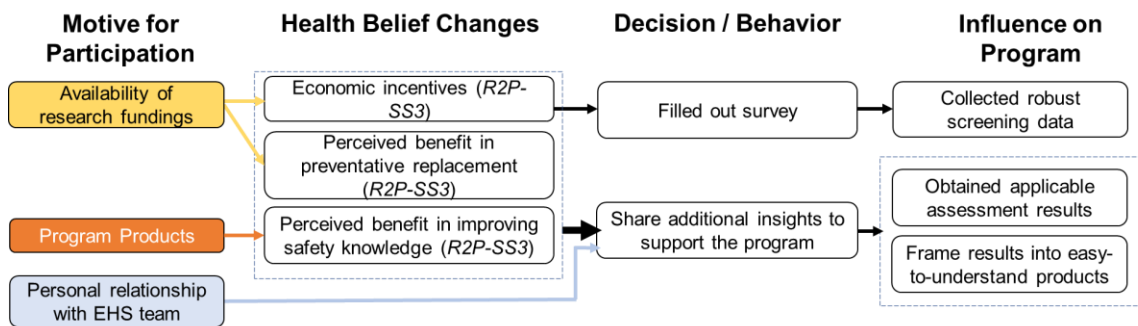


Figure 32. The participation of site supervisors in the PE program

### 6.2.5 Field Workers

Worker involvement primarily emerged in two forms: voluntary participation and paid research studies. The former occurred at the early phase of the program when worker inputs were solicited to identify needs for change.

#### 6.1.5.1 Voluntary Participation

The participation observation from the author and the key informants suggests that the voluntary participation could be driven and reinforced by multiple reasons:

### ***Perceived Benefit (R2P-FW3)***

Workers found the program intrinsically beneficial because it offered an opportunity with them to speak up about ergonomic concerns.

### ***Self-Efficacy (R2P-FW4)***

First, given the strong management commitment to the program, workers perceived the program was worthy of being spoken to because voiced concerns had a better chance of being heard and addressed.

Second, workers also felt comfortable confiding in the author who managed to build trustworthiness through frequent interactions with them. As the EHS director put it, *“Zhenyu approached people with a humble confidence that put them at ease. This allowed him to collaborate with and gain support from each person in our company, from the entry level workers to the President and CEO.”* As a result, “inside” information became increasingly accessible as the PE program progressed which helped precisely identify needs for change.

Third, the author was well known within the company as a PhD student specialized in construction ergonomics; an availability of the ergonomics expert conveyed a sense of technical competency and boosted workers’ self-efficacy in what the PE program can accomplish eventually. It is worth mentioning that, prior to this PE program, the industry partner had a successful experience of being involved in research studies in which workers received evidence-based, individualized advice. Workers could therefore build confidence in the power of scientific evidence and have a positive outlook on the PE program.

Fourth, workers' self-efficacy in the program was further reinforced as the author visibly accumulated field experience to understand the real-world contexts of ergonomic problems. Through workers' eyes, field experience was equally, if not more, important than technical competency when it comes to resolve problems on construction site. During a job visit, a worker jokingly asked the author to lift a roofing roll: "*If you don't do it yourself, how can you help us on this?*" The author's credibility as a problem-solver did not develop instantly; rather, it grew with the work the author put into it. For instance, frequent jobsite visits increased the author's visibility and gave workers the sense that the author was dedicated to understanding ergonomic needs in the field. During jobsite visits, workers were actively engaged in micro communication which showed the author's eagerness to learn the practical aspects of ergonomic problems. The program products, such as training presentation slides, demonstrated to workers that the author not only personally understood their concerns but also had capability of acting upon that understanding to provide appropriate solutions.

#### ***Low Perceived Barrier (R2P-FW5)***

Workers experienced low stigma of losing jobs or being replaced to speak up because the company had good culture of seeking feedback, along with the trusting relationship established between the EHS team and workers.

#### **6.1.5.2 Paid Research Activities**

On the other hand, workers participated in focus groups to help refine animated videos at the end of the program. The observation from the author and the key informants suggests that worker involvement in this paid research activity could be driven by multiple reasons:

### ***Perceived Benefit (R2P-FW3)***

Economic incentives for participation included a \$25 gift card and foods. Having foods together prior to a focus group helped create a warm and friendly environment for discussion. Moreover, workers were actively engaged in the focus groups partially because they perceived the program beneficial in improving workplace safety. In other words, they chose to return the program's contributions with active participation in the focus groups. For example, one participant shared his reflection during a focus group: *"I'm being on a position in any trade for long time... Until I watched that video over here, and then we got sent out to the field and work over there and see, everybody would be worried about yourself and your safety. They changed my mind completely. So that helps a Lot."* This worker tended to be one of the most active participants in the focus groups who provided constructive comments.

### ***Low Perceived Barrier (R2P-FW5)***

There is low physical barrier to worker involvement. Workers can participate easily because the focus groups were scheduled to occur during or immediately after the company's routine safety trainings. Workers also perceived low information barrier to participation, as the EHS director reached out to them individually to brief about the research opportunity and invite participation. Because of low physical and information barriers, the focus groups had a high turnout rate of 60%.

In a nutshell, the two forms of field worker involvement have different driving factors which are depicted in Figure 33. For voluntary participation, workers were open and transparent about their safety concerns because of perceived benefits in speaking up and self-efficacy in getting concerns resolved. This allowed the program to gather

meaningful information with ease. On the other hand, many workers were motivated in the paid research studies to help refine program products because they perceived the usefulness of those products.

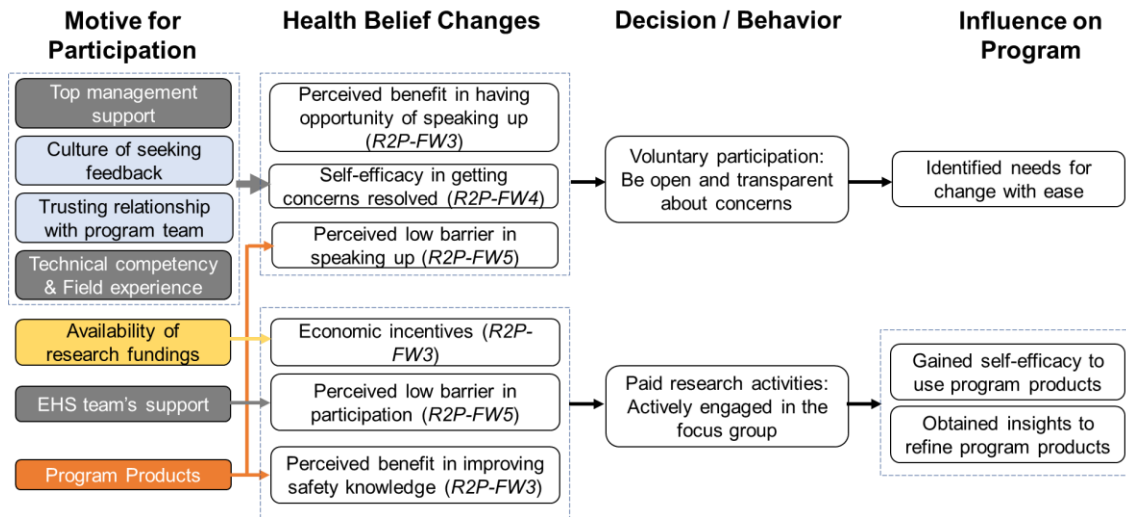


Figure 33. The participation of field workers in the PE program

### 6.3 Summary

The use of the 2SAFE model was proven successful in driving both R2P and P2R process in this PE program. As summarized in Table 16, owing to the ergonomic information that was collected, framed, and communicated within the company, almost all the program stakeholders improved health beliefs, made informed decisions, and played important roles in translating research outcomes into practice for problem-solving. A strong researcher-practitioner relationship was built and sustained during the PE program, opening up an opportunity of extending the current PE program for another two years. On the other hand, scientific level one evidence was created from the embedded research project in the PE program. The evidence not only reveals the risk-injury relations in material cart handling but also has practical relevance for immediate

implementation in the roofing industry. Practical inputs were collected from various stakeholders in every step of the 2SAFE model which collectively strengthened the relevance, rigor, and reach of the research enterprise of the PE program.

Table 16. Summary of the PE program’s achievements in promoting P2R2P transition

<b>Program stakeholders</b>	<b>Changes in health belief</b>	<b>Roles in R2P</b>	<b>Contributions to P2R</b>
Top level managers	<ul style="list-style-type: none"> <li>○ Perceived severity (<b>R2P-TM2</b>)</li> <li>○ Perceived benefit (<b>R2P-TM3</b>)</li> <li>○ Self-efficacy (<b>R2P-TM4</b>)</li> </ul>	<ul style="list-style-type: none"> <li>○ Public commitment</li> <li>○ Resource commitment</li> </ul>	<ul style="list-style-type: none"> <li>○ Reach of research results (<b>P2R-6</b>)</li> </ul>
EHS team	<ul style="list-style-type: none"> <li>○ Perceived severity (<b>R2P-ET2</b>)</li> <li>○ Perceived benefit (<b>R2P-ET3</b>)</li> <li>○ Self-efficacy (<b>R2P-ET4</b>)</li> <li>○ Perceived barrier (<b>R2P-ET5</b>)</li> </ul>	<ul style="list-style-type: none"> <li>○ Administrative and management support</li> </ul>	<ul style="list-style-type: none"> <li>○ Relevance of research goals (<b>P2R-1</b>)</li> <li>○ Relevance of study design (<b>P2R-2</b>)</li> <li>○ Rigor of data collection (<b>P2R-4</b>)</li> <li>○ Reach of research results (<b>P2R-6</b>)</li> </ul>
Middle level managers except EHS team	<ul style="list-style-type: none"> <li>○ Perceived susceptibility (<b>R2P-MT1</b>)</li> <li>○ Perceived severity (<b>R2P-MT2</b>)</li> <li>○ Perceived benefit (<b>R2P-MT3</b>)</li> </ul>	<ul style="list-style-type: none"> <li>○ Logistical and administrative assistance</li> </ul>	<ul style="list-style-type: none"> <li>○ Rigor of data collection (<b>P2R-4</b>)</li> <li>○ Rigor of data analysis (<b>P2R-5</b>)</li> <li>○ Reach of research results (<b>P2R-6</b>)</li> </ul>
Site supervisors	<ul style="list-style-type: none"> <li>○ Perceived benefit (<b>R2P-SS3</b>)</li> </ul>	<ul style="list-style-type: none"> <li>○ Sharing field data</li> <li>○ Giving feedback</li> </ul>	<ul style="list-style-type: none"> <li>○ Relevance of research goals (<b>P2R-1</b>)</li> <li>○ Relevance of study design (<b>P2R-2</b>)</li> <li>○ Rigor of data analysis (<b>P2R-5</b>)</li> <li>○ Reach of research results (<b>P2R-6</b>)</li> </ul>
Field workers	<ul style="list-style-type: none"> <li>○ Perceived benefit (<b>R2P-FW3</b>)</li> <li>○ Self-efficacy (<b>R2P-FW4</b>)</li> <li>○ Perceived barrier (<b>R2P-FW5</b>)</li> </ul>	<ul style="list-style-type: none"> <li>○ Sharing field data</li> <li>○ Giving feedback</li> </ul>	<ul style="list-style-type: none"> <li>○ Relevance of research goals (<b>P2R-1</b>)</li> <li>○ Relevance of study design (<b>P2R-2</b>)</li> <li>○ Reach of research results (<b>P2R-6</b>)</li> </ul>

## CHAPTER 7 DISCUSSIONS

The research for this dissertation applied theoretical synthesis to develop the 2SAFE planning model to guide research-practice collaboration in participatory ergonomics (PE) programs. The model was tested empirically via a case study and was proven helpful in driving the case PE program to achieve the P2R2P transition. In this chapter, the theoretical contributions and the practical usefulness of this model are discussed first, followed by a description of areas requiring improvement that were revealed when the model was implemented in the case study. The chapter concludes by sharing implications for practice, examining the limitations of this study, and making suggestions for future research.

### 7.1 Theoretical Value of the 2SAFE Model

An interdisciplinary model can facilitate the transfer of knowledge between ergonomics and other disciplines, and can increase the likelihood that an intervention will be successful (Wijk and Mathiassen 2011). The 2SAFE model integrates theories from three disciplines: the health belief model (HBM) from behavior change, the typology of evidence from the health sciences, and the layered structure of WMSD exposure from ergonomics.

First, by linking ergonomic concepts and methods to those from behavior change, the 2SAFE model combines the process of an ergonomic intervention with individual decision making as the basic unit of analysis. It provides theoretical insights into the behavior-related factors that researchers should consider when communicating with their industry partners in a PE program. The core premise behind this theoretical integration is that presenting scientific information alone cannot persuade practitioners to adopt a PE

program; researchers need to tap into practitioners' health beliefs to reframe the information in such a way as to capture their attention and promote changes in ergonomics. Although existing PE guidelines have standardized the procedure for collecting information about ergonomics (Wells et al. 2003; van der Beek et al. 2017; Punnett et al. 2009), there is still a need to understand how to convert the information into meaningful messages that promote changes in behavior. One of the main purposes of the model was to map a route for this.

In this sense, the 2SAFE model is a novel theoretical lens through which one can better understand how research-practice collaboration can be improved. The model supports Rost and Alvero's (2020) observation that health behavior interventions and PE have shared strategic goals, and can therefore be integrated. In the 2SAFE model, any information can be viewed from the perspectives of both ergonomics and health beliefs, and PE is characterized as a process of gathering and sharing information to promote the desired behavioral decisions.

Ergonomics researchers have traditionally applied health behavior theories as instrumental strategies to measure readiness for change (van der Molen, Sluiter, and Frings-Dresen 2005; Haslam 2002; Whysall, Haslam, and Haslam 2007), to design intervention activities (McCann and Sulzer-Azaroff 1996; Gravina, Lindstrom-Hazel, and Austin 2007; Sasson and Austin 2004; Oakman, Rothmore, and Tappin 2016; Whysall, Haslam, and Haslam 2006), and to evaluate the effectiveness of a program (Greene, DeJoy, and Olejnik 2005; Nieuwenhuijsen 2004; Robertson et al. 2009; Aliakbari et al. 2020). By contrast, the strategy proposed in this dissertation views health behavior theories as a frame of reference to rethink and transform research-practice collaboration

when implementing PE programs. The 2SAFE model provides a coherent strategy to ensure that intervention stakeholders can stay prepared with sufficient health beliefs to proceed with a PE program. In this sense, a fuller theoretical integration was achieved via the model in order to inform both the development of the intervention and stakeholder engagement.

Second, by linking ergonomic concepts and the typology of evidence from the health sciences, the 2SAFE model combines the process of an ergonomic intervention with the progression of a research project. It highlights three types of scientific evidence that researchers can potentially create during a PE program, namely the risk-injury relations, the efficacy of the intervention, and the efficacy of the implementation. The main premise underlying this theoretical synthesis is that practical insights can contribute to every aspect of a research study (that is, relevance, rigor, and reach); hence, researchers should engage practitioners in all the phases of a PE program. Although some PE programs described in the existing literature have reportedly involved practitioners in their embedded research projects (Nobrega et al. 2017; Hess et al. 2004), such participation was limited to certain phases, such as obtaining feedback about the research results. In this regard, the 2SAFE model is a novel theoretical lens through which researchers can improve their understanding of how they can benefit from research-practice collaboration.

Moreover, integrating the typology of evidence into the 2SAFE model addresses an important yet overlooked topic in ergonomic intervention studies, which is the efficacy of the implementation. According to the literature review (Rasmussen et al. 2018), most existing intervention studies do not explicitly describe and evaluate the

components of the implementation; as a result, the reasons that these programs succeeded or failed remain elusive. Implementation strategies have not received scholarly attention thus far, with only a few studies aiming at empirical comparisons of different implementation strategies (Visser et al. 2018; van der Molen, Sluiter, Hulshof, Vink, van Duivenbooden, Holman, et al. 2005; Brandt et al. 2018). In this regard, an important theoretical integration was achieved within the 2SAFE model to place program implementation and evaluation under the spotlight in academia, which will eventually help to reveal the causal mechanisms of ergonomic interventions.

## **7.2 Practical Usefulness of the 2SAFE Model**

The usefulness of the 2SAFE model was confirmed by the research for this dissertation via a PE program at a commercial roofing and waterproofing company. First, the 2SAFE model was found to be of assistance in navigating the complex nature of WMSDs, thus allowing the program to create explicit problem statements and research focuses. Specifically, the program allowed for a thorough search of problematic job elements that could increase the intensity of exertion during cart handling. Beginning with an explicit problem statement, the author dug deeply into the topic of cart handling, and eventually developed comprehensive evidence to assist practitioners to identify the various types of ergonomic hazards they may encounter in their daily workplaces. The surveillance and screening data that were generated by following the model also allowed the author to review the literature through a practical lens, and to identify knowledge gaps that could not have been revealed without these practical insights.

Second, the 2SAFE model provided information regarding how to prioritize behavioral determinants during R2P collaboration. It provided an effective workflow

within the case study to delve into ergonomically related data to highlight information about health beliefs that could promote better decisions on the part of the program's stakeholders. For example, the effect of cart conditions on the risk of overexertion was framed as information to describe the danger of using old carts, which led to top-level managers' decisions to implement preventative replacement. The evidence concerning how physical-environmental factors and cart loads interacted to influence the risk of overexertion was framed as information to describe the preventative health benefits of an appropriate proper workplace setup, which motivated the EHS director to upgrade the company's safety standards. Due to the informed decisions made by the key stakeholders, the program obtained the strong resource commitment and managerial support that are necessary for a program to be successful.

Third, by calling for an assessment of implementation barriers by understanding the target audience and the intervention context, the 2SAFE model was used to guide the case study to package information about health beliefs as actionable, contextually appropriate, and understandable resources for implementation. For example, through intensive field observations, the PE program identified that no solution is universally applicable. Hence, a comprehensive list of administrative controls was developed to provide a variety of actionable options for different circumstances to reduce cart handling injuries. Various intervention products that were appropriate for use on different occasions were then created in order to train employees to implement the administrative controls. Significant efforts were also dedicated to the iteration process, which ensured that the products were user-friendly and that the intended audience could understand and relate to them. As a result, the intervention products greatly increased the author's and the

EHS team's self-efficacy when communicating the research findings to the target audience during the program.

Fourth, a number of positive changes took place for the industry partner during the PE program at both the organizational level (e.g., an enhanced safety culture and a decreased number of overexertion injuries) and at the individual level (e.g., increased knowledge to address ergonomic issues and the increased use of ergonomic measures). This could have been partially due to the company's well-established safety management system and safety culture. However, none of the changes would have been possible without the use of the program to share the evidence-based control measures and information about health beliefs that promoted the informed decisions. More importantly, the program's participants attributed these notable changes to the implementation of the PE program. Despite the subjective nature thereof, the stakeholders' beliefs indicated that the 2SAFE model succeeded in achieving one of the objectives, which was to bring about practitioners' positive attitudes toward a PE program.

Finally, the 2SAFE model assisted the researcher to improve the scientific enterprise of the research project embedded in the case PE program. This research project did not simply replicate past works performed in the contexts of healthcare, waste collection, aviation, and manufacturing (Jäger, Luttmann, and Laurig 1984; Lawson, Potiki, and Watson 1993; Bennett et al. 2008; Nimbarte et al. 2013). Instead, it considered the levels of the variables and their interaction effects to simulate actual working conditions in the roofing trade. This was achieved by following the 2SAFE model to engage practitioners in the experimental design and in the interpretation of the results. As a result, the research not only generated reliable evidence for applications in

the PE program, but also provided new insights into the mechanics of cart operation by revealing the complex interaction effects among various risk factors.

For example, the detrimental effect of the ramp slope was found to escalate the more heavily a cart was loaded. This challenged the previous observations (Jung, Haight, and Freivalds 2005) that the ramp slope had a simple linear association with the ROF. This means that prior research (Lawson, Potiki, and Watson 1993; Jäger, Luttmann, and Laurig 1984) that were obtained using lighter cart loads (20–100 kg) could have underestimated the risk of injury when navigating a ramp when the cart load is heavier. In addition, this embedded research project confirmed that the cart load could modify the effects of the tire type, the ramp slope, the obstacle height, and the space constraints, thus contradicting previous observations that the cart load was linearly proportional to the operating forces (Al-Eisawi et al. 1999) and physiological demands (Jung, Haight, and Freivalds 2005).

### **7.3 Areas for Improvement in the 2SAFE Model**

Various improvisations were allowed during the case study to ensure the usefulness of the 2SAFE model in practice, which revealed several areas for improvement.

First, although the five steps were presented in a linear order, the results of the case study suggested that an ideal process would actually be iterative. Some steps could be developed concurrently because the results from a later step, or even a preliminary finding, may indicate how an early step can be implemented more successfully. For example, during the surveillance (step 1) in the case example, familiarity with the literature obtained via the screening (step 2) helped to identify real-world problems that

required new scientific evidence for the development of a solution. As a result, the program reflects not only the practitioners' needs, but also the researcher's interests. Moreover, beginning the assessment (step 3) with a sound understanding of the barriers to implementation obtained in the framing (step 4) helped to determine the experimental variables and their ranges, thus leading to applicable inferences concerning the operational context of interest. Therefore, there is no need for strict adherence to the linear workflow outlined by the 2SAFE model. A holistic approach is suggested in order to consider the integral contributions of each step to the overall success of a PE program and then embed steps earlier in the workflow if necessary.

Second, it is necessary to replicate the five-step workflow during a PE program. In the case study, the workflow was repeated twice: first in the preliminary phase, and then in the detailed phase. Retrospectively, the author found that this method of implementing the 2SAFE model was necessary for the reasons listed below:

- The overall process was incremental as a deeper understanding of ergonomic issues was established. For example, during the preliminary phase, the program focused on only one problematic job element in the assessment (step 3), which was the condition of the carts. However, three types of factors related to the physical environment were added in the detailed phase, which resulted in a more comprehensive set of administrative controls.
- Furthermore, the data collected during the preliminary phase contributed greatly to writing the proposals for the research grants and helped to secure external funding, which ensured the success of the entire program.

- The preliminary phase achieved rapid initial success by starting “small” with a data-driven training presentation. This allowed practitioners at different levels of the company to improve their health beliefs and to envision the benefits that could be reaped from implementing a full-scale intervention. The shared vision, together with the team rapport that was created in the process, created the opportunity for a participatory, multiple-year PE program.
- The program began broadly with a wide range of manual material handling activities in the preliminary phase. The investigation results were also presented at the All-Hands meetings to satisfy the industry partner’s desire to touch on broader WMSD issues during company-wide trainings, which was conducive to building a reciprocal client relationship.
- A detailed use of the 2SAFE model requires sustained and strong commitment from the industry partners. As shown by this case example, it took more than three years for the program to generate a comprehensive set of actionable solutions for real-world challenges. However, the external funding, strong health beliefs, collective visions, team rapport, and reciprocal relationships that were achieved in the preliminary phase paved the way for the intensive application of the 2SAFE model in the detailed phase.

Third, the results of the case study suggest an expansion of the workflow to consider the program stakeholders’ self-transcendent and social motivations. The original model mainly emphasized information about health outcomes, such as the perceived preventative benefits of reducing ergonomic exposure. However, secondary effects, such

as self-transcendent and social motivations, which were previously unanticipated, played a crucial role in achieving high-level stakeholder engagement during the case study. For example, the self-transcendent motivation to share knowledge with the entire industry greatly increased the EHS director's passion for refining the program products.

Improving the brand image was another factor in the company management's increasing enthusiasm during the PE program. Other identified motivations included improving one's reputation at work, practicing reciprocity, and maintaining interpersonal relationships. The 2SAFE model can be enriched by outlining program activities that can increase self-transcendent and social motivations (e.g., inviting senior managers to co-present program results), and by highlighting post-activity feedback to reinforce the practitioners' participation.

Finally, the model needs to place more emphasis on "micro" communication by expanding the workflow to involve the development of short, powerful messages. Due to the focus on well-planned and structured communication opportunities (e.g., 20-minute presentation at an All-Hands meeting), the original model only mapped out the program outputs that were in written form and had an extensive level of detail. However, the case example indicated that information transfer also took place spontaneously on less formal occasions, when concise messages were needed to ensure rapid yet powerful communication with minimal interruption of the practitioners' daily operations. For example, the EHS director condensed the research evidence into the simple message "aged carts can easily double the force required to pull" to remind the warehouse manager and the foremen about the inspection and maintenance of carts during job hazard analysis. The usefulness of the 2SAFE model could be enhanced by facilitating

the translation of evidence into short, impactful messages to increase practitioners' self-efficacy when communicating about ergonomic issues.

#### **7.4 Implications for Practice**

This dissertation described a successful PE program, and several insights regarding how to use PE as a methodology to resolve real-world problems and conduct research activities emerged. One important implication is that communication is at the core of an effective PE program, and a dedicated effort to crafting appropriate materials for communication is worthwhile. The format, content, and level of detail may vary depending on the intended contexts of use (e.g., researcher-practitioner communication during ergonomics committee meetings, and cross-departmental communication during practitioners' daily operations). However, behavior change theory can provide fundamental principles for determining the key messages that need to be conveyed in any communication materials. An iterative design approach is also necessary to ensure that the practitioners remain central throughout the development of the communication materials (E. R. Haines et al. 2021).

Despite this research being focused explicitly on the communication aspect of a PE program, another lesson that the author learned was that initiating a PE program is rarely an exclusive process of information exchange. Social exchange almost always takes place concurrently and plays an irreplaceable role in a program's success; thus, researchers need to invest in social relationships while communicating with practitioners. For example, frequent field visits and in-person interactions will visibly demonstrate that researchers care about workers, which will result in increased intimacy that allows workers to feel more comfortable about expressing their safety concerns. Researchers can

build reciprocal relationships with a company's management by providing support regarding additional problems that are beyond the scope of a PE program. It is also advisable to identify and leverage a company's existing social capital when developing a PE program, such as recruiting a site champion to drive the intervention process (Burgess-Limerick et al. 2007).

Moreover, this dissertation suggests that an ideal PE program should be oriented toward process excellence rather than focusing solely on the result. The reasons are listed below:

- Process performance indicators, such as changes in health beliefs, can be used to assess practitioners' readiness to change (van der Molen, Sluiter, Hulshof, Vink, van Duivenbooden, and Frings-Dresen 2005). The results of assessments can help to determine communication priorities and to adjust intervention activities to ensure the program is on the correct path to achieve success.
- Process achievement that is recognized along the way can also be incorporated into communication materials to continuously motivate practitioners and to encourage them to remain committed to the program.
- Changes in health beliefs (e.g., self-efficacy) can be a reliable indicator that can be used together with health outcomes to evaluate the overall performance of a program (e.g., the sustainability of the program) (Punnett et al. 2009). Such process data can be particularly helpful when it is difficult to definitively link associate changes in health outcomes with intervention activities (Hess et al. 2004).
- Finally, the program stakeholders' behavioral changes are the intermediary

between intervention activities and health outcomes. Measuring and analyzing data pertaining to health beliefs will allow for a nuanced understanding of why and how a program is or is not effective (Dale et al. 2016).

Furthermore, the successful implementation described in this dissertation implies that participatory research can extend beyond problem solving for individual organizations, as it can also be applied as a methodology to guide scientific inquiry.

One advantage of using PE as a research methodology is that the practitioners' input can add value at every stage of a research project. Traditionally, there has been a tendency for researchers to rely solely on their own interpretations of the type of research that is meaningful to practitioners and how the results should be adopted in practice (Minkler, Salvatore, and Chang 2012). Given a deeper understanding of the real-world contexts in which the research results will be implemented, practitioners will tend to have distinctive interpretations (E. R. Haines et al. 2021). Considering these distinctions from the start of a research pipeline constitutes a prerequisite for creating new knowledge that has practical relevance and actionability. Furthermore, the adoption of the new knowledge can be significantly expedited via the practitioners' sense of ownership, intellectual support, resources, and industry networks.

Another reason for using PE as a research methodology is that an embedded research project can help to overcome barriers to the implementation of ergonomic changes. For example, practitioners tend to be resistant to change (Dasgupta et al. 2017; Hess et al. 2004), but objective measurements derived from a rigorous research project have been proven to be more powerful in convincing practitioners to take action (Cuny-Guerrier, Savescu, and Tappin 2019). An insufficient budget is another major challenge

(Yazdani and Wells 2018). Research grants can serve as “seed” funding to finance the initial steps of a program, and the initial success will encourage the industry partners’ financial commitment to the program (Burgess-Limerick 2018). Economic incentives can also be provided to maintain the practitioners’ time commitment, which is another commonly reported barrier to the success of PE programs (Yazdani and Wells 2018; Driessen et al. 2010). By overcoming these barriers, significant ergonomic changes can be facilitated, which will in turn create a supportive environment for an embedded research project to bring a PE program in a virtuous circle to achieve P2R2P transition.

It must be admitted that, having local interests as the point of departure, PE has an inherent disadvantage as a research methodology. The knowledge it produces may be context dependent and may not be able to be generalized to a wider population. However, it can be argued that one could generalize based on a single case via the intense collection and analysis of the greatest possible amount of data (Flyvbjerg 2001). At the very least, this study demonstrated that transferrable evidence can be created from an intensive PE program to be of immediate benefit to those who are in a similar context. Accordingly, PE can be considered to be an appropriate methodology for applied ergonomics research, which is complementary to the traditional research trajectory that is primarily driven by the theoretical importance to academia.

## **7.5 Limitations and Future Research**

Although the 2SAFE model is relatively new, the author considers it to be a useful theoretical lens through which one will be able to view and improve research-practice collaboration in ergonomic interventions and expects to see its continued

enrichment. Nonetheless, there are some limitations and knowledge gaps concerning this model that have yet to be resolved.

First, like other ethnographic studies, the results of applying the model observed in this study may be influenced by the Hawthorne effect, i.e. a change in the subjects' normal behavior is attributed to the knowledge that their behavior is being studied (Oswald, Sherratt, and Smith 2014). This study adopted several approaches that have been proven effective in limiting the Hawthorne effect, including data triangulation (Holden 2001), secondary observational evidence (Fetterman 2019), complete participant observation (Bernard 2017), and development of trusting relationship with subjects (Oswald, Sherratt, and Smith 2014). Nevertheless, future studies should also consider using a combination of qualitative and quantitative methods to measure health beliefs to provide more robust evidence for the effectiveness of the model.

Second, there is a need to test the reliability of the model in different contexts. Thus far, the model has only been tested at a company that ranks highly for safety that has a sound safety culture and is open to innovation. The model was being implemented effectively, in part because it was linked to the company's well-established safety program. In addition, the application of the model started as the author, a university graduate student, interned with the company. The personal relationships the author developed with the company staff during the internship may constitute a prerequisite for the effective use of the model. Despite the encouraging results, future studies must continue to examine whether the model can perform consistently well in different contexts and if personal relationships are irreplaceable prerequisite when using the model. For example, what are the needed adaptations in order to use the model at a

company with a culture of safety resistance or in a low resource setting? What are the needed adaptations when the users of the model have no prior personal relationships with a company? Moreover, the research described in this dissertation only revealed how the model helped strengthen the process of creating level one evidence (risk-injury relations). Future studies should aim to determine whether the use of the model can increase the rigor, relevance, and reach of level two (the efficacy of an intervention) and level three evidence (the efficacy of the implementation).

Third, the model's operability needs to be refined. The model synthesizes theories from multiple disciplines, and potential users' unfamiliarity with any of the theories could prevent the use of the model. This barrier could be reduced if a more concrete guideline can be provided. For example, how can behavior change methods be used to customize communication materials according to the needs of target stakeholders or individual circumstances? Moreover, future studies could draw on implementation science to enhance the operability of the 2SAFE model in creating evidence for the efficacy of its implementation. It is anticipated that, with further real-world applications, the model can be nurtured and ultimately extended to produce an instruction manual to facilitate ergonomics research in practice.

Fourth, although the HBM was selected as the theoretical foundation for the model, there are a number of other health behavior theories. The HBM is one of the most widely adopted theories with regard to individual health behaviors (Glanz, Rimer, and Viswanath 2015), and is aligned with the premise underpinning this research; that is, that individual behaviors are the basic unit of a PE program. However, this means that the model does not consider the interpersonal and organizational factors that can affect

behavioral decision making. For example, how can vulnerable employees create social pressure to persuade managers to invest in ergonomics, instead of relying solely on epidemiological evidence? Future studies will be able to apply interpersonal and ecological theories to improve the 2SAFE model.

Fifth, there is also a need to incorporate sociological theory to enrich the 2SAFE model, as social exchange is usually concurrent with information exchange during a PE program. For example, future research could draw on the theory of reciprocity (Molm, Collett, and Schaefer 2007) to examine the causal mechanism of reciprocity during a PE program in order for the model to be improved and to shed light on how desirable social capital, such as a shared vision and solidarity, can be achieved to create positive team norms.

Finally, the model is a reactive microergonomics PE model that is intended to solve particular WMSD-related problems as they occur. Future studies could extend this to create a proactive macroergonomics model to address organizational and psychosocial issues.

## CHAPTER 8 CONCLUSIONS

This dissertation aimed to answer two research questions regarding how to achieve P2R2P transition during a participatory ergonomics (PE) program. The first question was how to use practitioners' insights to inform the research, while the second was how to encourage practitioner participation, at the individual level, to facilitate the translation of the research findings into practice. To address these questions, the author developed the 2SAFE model that combines an understanding of the nature of work-related musculoskeletal disorders (WMSDs), the principles of the health belief model (HBM), and the typology of evidence. This practical usefulness of the theoretical model was demonstrated via the adoption of an empirical case study, as it was implemented in a PE program at a construction company for 39 months.

Based on a qualitative analysis of practitioner involvement in the PE program, it can be concluded that the 2SAFE model allowed the program to isolate the information needed to identify ergonomic problems and to develop solutions, and to then facilitate decision making for desired changes on the part of the intervention stakeholders, including top managers, the EHS team and other middle level managers, site supervisors, and field workers. The results indicate that any ergonomic information can be viewed from the perspective of behavioral change, and that health behavior theories can be applied to rethink and transform the research-practice collaboration during a PE program. By incorporating the HBM, the 2SAFE model provided a workflow for collecting and translating ergonomic data into intervention resources that improved the intervention stakeholders' perceived susceptibility to risk of injury, the perceived severity of an injury, the perceived benefits of ergonomic changes, and self-efficacy with regard to ergonomic

issues. The improved health beliefs stimulated the intervention stakeholders' motivations for ergonomic change and encouraged them to play an active role in ensuring that the program was implemented smoothly and effectively.

This dissertation also tracked and analyzed the practitioners' roles in the trajectory of the research activities in the PE program. The results of the case study show that the 2SAFE model enabled the program to provide a deeper understanding of the types of research studies that are meaningful to practitioners, and to democratize the knowledge production process by fully involving the practitioners in the definition of the research goals, the study design, the data collection and analysis, and the application and dissemination of the research results. Due to the integration of the typology of evidence, the 2SAFE model informed the case study's PE program regarding three types of evidence that can be developed to contribute to the literature, namely the risk-injury relation, the efficacy of an intervention, and the efficacy of the implementation. By following the 2SAFE model, the embedded research project improved the evidential understanding of how the condition of a cart, the tire type, factors related to the physical environment, and the load could interact to influence the risk of overexertion and decreased productivity during cart handling. The evidence was then translated into a series of practitioner-focused intervention resources that were proven to be actionable, contextually appropriate, and understandable. A rigorous plan was also designed to evaluate the efficacy of the intervention implementation, and the evaluation results have the potential to contribute to the evidential understanding of the implementation strategies that are suitable to be applied in the construction industry.

By reflecting on the various improvisations that were allowed when using the 2SAFE model in the case study, the author suggests that the model should be implemented iteratively. Because the framing (step 4) and the evaluation (step 5) concerned the implementation, the activities in these two steps could be embedded earlier into a PE program to ensure that the contextual factors and the practitioners' requirements can be considered immediately when a PE program begins. The entire five-step workflow could also be repeated in the course of a program, and the initial application can be fast tracked to achieve a small success that will help to create shared visions and team rapport for the remainder of the program. In addition, the case study indicated that the 2SAFE model should be expanded by paying more attention to gathering and communicating data pertaining to self-transcendent and social motivations, and to creating quick, powerful messages for "micro" communication in order to encourage practitioner involvement.

The use of this model will inspire more researchers to use PE as a means of scientific inquiry to create knowledge that can be transferred immediately to the industry. The model will also encourage further PE initiatives and will strengthen academia-industry collaboration to collectively apply research findings in practice. This will lead to a meaningful impact in the long term by decreasing the number of WMSDs and the associated economic burden on society. This overarching model also bridges the disciplines of ergonomics, behavior change, and health science; thus, it has the potential to spearhead more interdisciplinary studies.

In the future, more real-world applications are needed to validate and evolve the 2SAFE model. The model can be enriched by drawing on insights from health

communication, sociology, and implementation science in order to provide more actionable guidelines for enhancing the exchange of information and social interactions during a PE program. In addition, future researchers should attempt to synthesize interpersonal and ecological models of behavior change to construct a more comprehensive PE model.

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## APPENDIX A – DATA COLLECTION AND ANALYSIS IN CASE STUDY

The purpose of the case study was to understand how the 2SAFE model works in a realistic setting and identify areas requiring improvement. Therefore, when collecting data during the case study, special attention was paid to reflecting on the role of the 2SAFE model in the case PE program’s successes and failures. Given the dual objective of the case program, various forms of qualitative data were collected to discuss the achievements of the program according to the following two perspectives: the R2P translation and strengthening of P2R.

### R2P TRANSLATION

#### Data collection

The first function of the 2SAFE model was to provide researchers with insights into how to encourage practitioner participation at the behavioral level to facilitate the translation of research into practice. Ideally, by following the 2SAFE model, the case program should provide meaningful program outputs to change intervention stakeholders’ health beliefs motivating them to make informed decisions and exert a positive influence on the program. This study proposition (illustrated in Figure 1) informed the data collection and analysis process. Specifically, to understand whether the 2SAFE model helped the case program achieve the R2P goal and how, research data were collected to provide a narrative account of the program activities, the stakeholders’ decisions and influence on the program, and the underlying changes in health beliefs.

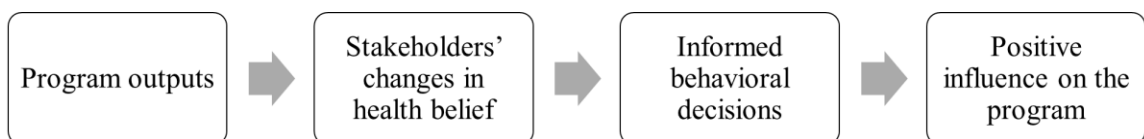


Figure 1. The study proposition related to the R2P goal of the case PE program

Here, the behavior is a broad concept that involves various intervention stakeholders at different levels of the organization, including top managers, the EHS team and other middle-level managers, site supervisors, and field workers. Given that the participants' behavior could be driven by changes in any health belief such as perceived susceptibility to risk of injury, perceived severity of the injury, perceived benefits of implementing the program, self-efficacy with regard to ergonomic changes, and perceived barriers to implementation, a total of five outcome objectives were defined based on the HBM (DiClemente, Salazar, and Crosby 2018; Glanz, Rimer, and Viswanath 2015) for each type of intervention stakeholder in the PE program, as shown in Table 1.

Table 1. Objectives for R2P translation

<b>Intervention stakeholders</b>	<b>Outcome objectives</b>
Top Managers (the company's CEO and the president)	<b>R2P-TM1:</b> perceived susceptibility <b>R2P-TM2:</b> perceived severity <b>R2P-TM3:</b> perceived benefit <b>R2P-TM4:</b> self-efficacy <b>R2P-TM5:</b> perceived barrier
EHS Team (the EHS director and the manager)	<b>R2P-ET1:</b> perceived susceptibility <b>R2P-ET2:</b> perceived severity <b>R2P-ET3:</b> perceived benefit <b>R2P-ET4:</b> self-efficacy <b>R2P-ET5:</b> perceived barrier
Middle-level Managers (the estimator, the warehouse manager, and project managers)	<b>R2P-MM1:</b> perceived susceptibility <b>R2P-MM2:</b> perceived severity <b>R2P-MM3:</b> perceived benefit <b>R2P-MM4:</b> self-efficacy <b>R2P-MM5:</b> perceived barrier
Site Supervisors (the superintendents and foremen)	<b>R2P-SS1:</b> perceived susceptibility <b>R2P-SS2:</b> perceived severity <b>R2P-SS3:</b> perceived benefit <b>R2P-SS4:</b> self-efficacy <b>R2P-SS5:</b> perceived barrier
Field Workers	<b>R2P-FW1:</b> perceived susceptibility <b>R2P-FW2:</b> perceived severity <b>R2P-FW3:</b> perceived benefit <b>R2P-FW4:</b> self-efficacy <b>R2P-FW5:</b> perceived barrier

To determine the success of the PE program in achieving the R2P outcomes defined in Table 1, qualitative data were gathered using an ethnographic method with participant observations as the primary source of data. One advantage of using participant observations was that intervention stakeholders' spontaneous responses to program outputs, including both verbal and non-verbal expressions, can be captured and analyzed. A contextual understanding of the participatory process can also be generated through the participation observations to add the richness to the research data and help results interpretation. In addition, repeated observations enabled observers to develop rapport with intervention stakeholders being observed which encouraged them to be transparent

in expressing opinions (Tong, Sainsbury, and Craig 2007). Taken together, the observational evidence allowed the case study to provide a narrative account of how changes in health beliefs resulted in informed behaviors and advanced the program.

As an intern at the industry partner (June 2018 – April 2019) and as the lead researcher in the PE program (May 2019 – September 2021), the author was able to observe the PE implementation process closely. Field notes and photographs were taken to record conversations and discussions among practitioners and between practitioners and myself. The participation observation data were collected while the author performed the following program activities:

- Visited jobsites in the preliminary phase between June 2018 and September 2018 and in the detailed phase between April 2019 and September 2020.
- Attended company meetings, including All-Hands meetings (August 2018, November 2018, and August 2021), safety committee meetings (four between June and September 2018, one in June 2020, and one in November 2021), and foremen’s meetings (four between June and September 2018 and one in August 2021)
- Conducted experiments in the warehouse (one in July 2018, and another one between June and August 2019).

The secondary observation by the EHS director was used for the weekly senior managers’ meetings, routine safety training, and safety inspections throughout the program period between June 2018 and September 2021. This source of observational data made complementary contributions to the case study because the EHS director has

close and frequent opportunities of observing the program activities as an “insider”. Hence, this particular source of qualitative data represented a company insider’s perspective and embodied unique insights into how the PE program promoted behavior changes and facilitated the problem-solving process. The secondary observational data was shared verbally with the author which was then converted into transcripts. Due to the spontaneous nature of participation observations, audio recording was not conducted.

Observational evidence was triangulated using archival data and formal interviews. Comparing qualitative data collected using different methods, namely methodological triangulation, is widely accepted as an appropriate approach to ensure the trustworthiness of the results of case study (Farmer et al. 2006; Bekhet and Zauszniewski 2012; Guion, Diehl, and McDonald 2011). In this study, the goal of using methodological triangulation was to confirm the findings from the participation observations, and findings were included in final content analysis only if they were supported by one or more than one data source without dissonance. The use of the methodological triangulation also provided a richer perspective to understand the implementation process of the PE program. As demonstrated by Farmer et al. (2006), different types of datasets typically provide distinctive perspectives on the same phenomenon, and the methodological triangulations can, therefore, ensure the completeness in perspective during results interpretation.

Textual analyses of corporate policy documents (including the safety policy book, various safety documents, safety inspection results, field photos, and injury data), emails, and meeting notes (including safety orientations, All-Hands meetings, foremen’s meetings, and safety committee meetings) were performed. The documents reflected the

intervention stakeholders' views, discussions, and decisions about the PE program. The author selected these documents to examine how the intervention stakeholders' decisions revealed during the participant observations were translated into written documents.

Key intervention stakeholders, including the EHS director and the company's president, and two foremen were interviewed following the completion of the PE program. The participants were purposefully selected because they were most extensively involved in the program from beginning to end and thus were most likely to have insightful discussions on the program. Each interview was semi-structured and lasted for approximately 20 minutes. The interviewees discussed their personal experiences within the program, with an emphasis on how their health beliefs had changed during the program and how this had shaped the decisions that they made. The interviews with the EHS director and the president occurred in the office, while the ones with foremen took place during site visits. The participants' views were recorded in field notes.

### **Data analysis**

The qualitative data were first sorted by the author into different categories based on the involved intervention stakeholders: top managers, EHS Team, middle-level managers site supervisors, and field workers. Then, the data was coded using a scheme that was generated both inductively and deductively. Specifically, the coding scheme for program outputs, intervention stakeholders' informed behaviors and positive influence on the program was derived through an inductive approach, with codes and themes emerging from the data itself. Changes in health belief were coded inductively and then categorized deductively into theoretical themes based on the behavior determinants depicted by the HBM.

The emphasis of the qualitative data analysis was on examining the study preposition described in Figure 1, that is mapping the program outputs against intervention stakeholders' changes in health beliefs, the actions they carried out to facilitate the problem-solving process, and the downstream program achievements. In other words, the relationships between themes (on program outputs, changes in health belief, actions, and influence on program) were explored, coded, and represented in mapping flow charts to depict a contextual understanding of how the program achieved its R2P objective and what the roles of the 2SAFE model are in the process.

To ensure the trustworthiness of results interpretation, the preliminary results were periodically discussed within the research team and consensuses were reached regarding the program performance in R2P and contributions of the 2SAFE model. Second, the EHS director performed a member check when the data analysis was completed. Before reviewing the report, she was asked to think aloud and come up with a list of behavioral motivators driving intervention stakeholders' participations in the program. This list was then compared with the results of data analysis, and this process offered the EHS director an opportunity to provide further inputs. There were only two instances of dissonance in the types of motivators, and consensuses regarding how to address the dissonances were reached after discussions. Lastly, the EHS director reviewed the mapping flow charts that reveal the causal mechanisms underlying the PE program to confirm the interpretations on how behavioral motivators helped each stakeholder make right decisions to advance the program. There was a full agreement, while the EHS director provided comments to further clarify the results interpretation.

## STRENGTHENING OF P2R

### Data collection

The second function of the 2SAFE model was to provide researchers with insights regarding how to use practitioners' input to enhance the scientific inquiry during a PE program. Ideally, by following the 2SAFE model, the case program should engage the various intervention stakeholders in each stage of the research process to effectively shape the research trajectory towards creating applicable results that can reliably inform practice. This study proposition (illustrated in Figure 2) informed the data collection and analysis process. Specifically, to understand whether the 2SAFE model helped the case program achieve the P2R objective, a research diary was kept by the author documenting the original research plan, participatory feedback received, and revisions to the research process. Research diary is a common method for researchers to record decisions and actions carried out during the research process (Engin 2011). In fact, research diary is not simply used as a reminder of past research ideas and activities. A narrative account of thinking process also allows researchers to practice reflexivity (Nadin and Cassell 2006). Hence, research diary is considered by the author as an appropriate source of data to reflect on how practical input shaped the research project embedded in the case study and what the roles of the 2SAFE model were in encouraging practical inputs.

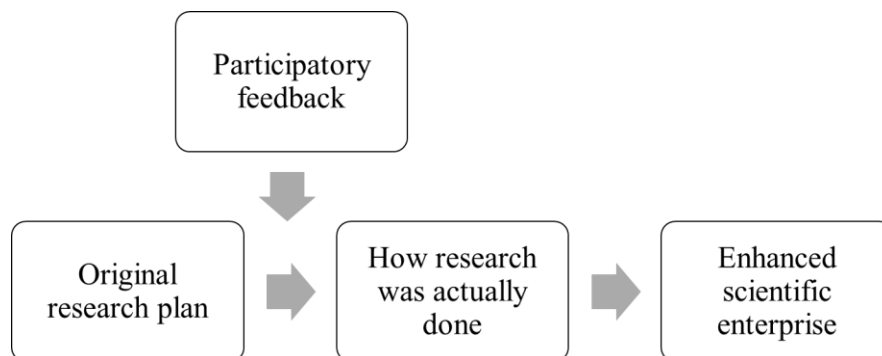


Figure 2. The study proposition related to the P2R objective of the case PE program

The research diary was kept both digitally in Microsoft OneNote and manually in a notebook throughout the research process. First, the author's personal thoughts and reflections were documented alongside the sketches of research ideas and plans, which indicates the changes of research trajectories and contains data about the underlying rationale for those changes. Second, after each time a research activity was done, its event, date, and location were logged, together with field photos and/or videos, while participatory feedback and personal reflections were documented on an as-needed basis. The focus was to track important feedback that shaped the trajectory of the research project and record the thinking process of how the feedback was considered and eventually incorporated by the author.

The evolution of the research project and enhancement of its scientific enterprise were tracked by comparing the planned and the actual ways in which the research was conducted. Here, the objective of enhanced scientific enterprise were defined by referring to the framework created by C. L. Balazs and Morello-Frosch (2013), which is one of the few that summarize the benefits of participatory research in strengthening research enterprises. This framework was deemed appropriate for this case study because it is sufficiently broad to include every aspect of the research process. Moreover, although the framework was derived from the examination of case studies in environmental science, it is general and can also be applied in a PE program.

Table. 2 Program objectives for strengthening P2R

<b>Category</b>	<b>Objectives</b>
Relevance	<b>P2R-1:</b> Relevance of the research goals <b>P2R-2:</b> Relevance of the study design
Rigor	<b>P2R-3:</b> Rigor of the study design <b>P2R-4:</b> Rigor of the data collection <b>P2R-5:</b> Rigor of the data analysis
Reach	<b>P2R-6:</b> Reach of the results

### **Data analysis**

The qualitative data from the research diary were first sorted by the author into different groups based on the stage of the research project the data emerged, which was defined by referring to the framework created by C. L. Balazs and Morello-Frosch (2013). There are five stages which are the definition of research goals, study design, data collection, data analysis, and dissemination of research results. Then, the data was coded using a scheme that was generated inductively and deductively. Specifically, the coding scheme for original research plan, participatory feedback, and the research process on the program was derived through an inductive approach, with codes and themes emerging from the data itself. The enhancement of scientific enterprise were coded inductively and then categorized deductively into theoretical themes based on Table 2.

The emphasis of the qualitative data analysis was on examining the study preposition described in Figure 2, that is mapping the participatory feedback against the ways of how research activities was done and the downstream P2R outcomes. In other words, the relationships between themes on original research plan, participatory feedback, research activities, and enhanced scientific enterprise were explored and coded. The final results were represented in mapping flow charts. To ensure the trustworthiness of the results, a researcher who fully participated in the embedded research project

performed a member check when the data analysis was completed. The manuscript was reviewed, and there was a full agreement regarding the roles of the 2SAFE model in engaging practitioners and the contributions of participatory feedback on the research enterprise.

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## APPENDIX B – PEER-REVIEWED ARTICLE



International Journal of  
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and Public Health



Article

# Factors Affecting Material-Cart Handling in the Roofing Industry: Evidence for Administrative Controls

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**Abstract:** Material-cart handling can be strenuous and lead to overexertion injuries. The aim of this study is to produce a thorough understanding of how the cart condition, tire type, physical environment-related factors, and load interact to influence the ergonomics and productivity of cart handling. Eighteen roofing carts with different conditions, tires, and loads were tested by one subject on three laboratory tracks: one L-shaped, one with ramps within constrained spaces, and one with obstacles within constrained spaces. A multiple linear regression analysis was performed to quantify the main and interaction effects of the factors of interest on the cart operations. The research findings confirm that using aged carts increases the injury risk by as much as 30.5% and decreases productivity by 35.4%. Our study also highlights the necessity of keeping an open space for cart operation; the travel distance from a cart to a ramp/obstacle should be greater than 61 cm. Finally, the results suggest the at-risk thresholds for different ramp slopes and obstacle heights, and the safe load capacities for the various working circumstances that are common on construction sites. The evidence created in this study can be translated into administrative controls for cart handling to reduce overexertion injuries and enhance performance.

**Keywords:** overexertion in pulling and pushing; material cart handling; roof construction; ergonomic risk factors; administrative control

## 1. Introduction

Manual carts are some of the most common material-handling equipment in various industrial settings. Cart maneuvering can be strenuous and may result in overexertion in pulling and pushing (OPP), a leading cause of work-related musculoskeletal disorders (WMSDs). OPP caused approximately 385,000 injuries from 2011 to 2017, constituting 15% of the WMSDs in the United States [1]. Similarly, in the U.S. construction industry, OPP accounted for 11.2% of the total lost days caused by WMSDs [2].

Extensive scholarly attention has been given to the ergonomic design of manual carts. The studied design parameters include the handle position [3,4], handle height [5,6], handle orientation and friction [7], inter-handle distance [8], and wheel diameter [5,9,10]. Although these engineering controls can prevent cart operators from encountering hazardous working conditions, it is widely accepted that administrative controls, namely, management initiatives that modify work procedures and processes [11], are needed as complementary measures to develop comprehensive and successful workplace interventions [12–15].

Despite their acknowledged importance, administrative controls have not been an explicit subject of ergonomics research, with little empirical evidence being offered to support the design of these critical measures. For example, cart maintenance and replacement are warranted to avoid overexertion and productivity loss caused by cart deterioration [16–18]. Although these studies acknowledged the detrimental effect of cart deterioration, only

subjective and descriptive narratives were provided without any numerical evidence. Little is known about the degree to which a cart's ergonomics and productivity performance will deteriorate over time, giving practitioners limited evidence to determine whether preventive maintenance is a worthy decision and when is the best time to proceed with it.

The tire type affects the cart operation. Solid (polyurethane foam-filled rubber) tires have been recently introduced in the construction industry as a replacement for pneumatic (air-filled rubber) tires. A solid tire will not become flat or deformed; however, it is heavier and more expensive. To our knowledge, no study has been dedicated to empirically comparing these two tires when incident prevention and productivity enhancement are prioritized.

Workplace-layout planning is an administrative control to reduce physical environment-related hazards for cart handling. The adverse effects of physical environment-related factors have been confirmed; however, the research efforts thus far have been focused on addressing single hazards, e.g., obstacles [19,20], ramps [21,22], or space constraints [6,23]. For example, Nimbarte et al. [22] measured the effects of three ramp slopes (0, 5, and 10 degrees) on the musculoskeletal loads of cart operators. At workplaces, however, it is not uncommon to see physical environment-related factors at play simultaneously, such as moving a cart up a slope within a tight space. To competently maneuver in workplace layouts, practitioners should be aware of the effects of multiple hazards, rather than single hazards.

This is particularly critical for the construction industry, where work stations are constantly evolving as projects progress, adding substantial variability to the physical environment-related factors [24–26]. Another limitation of existing studies is that the effects of physical environment-related factors are primarily measured at low cart-load ranges: from 20 to 170 kg. It remains unknown whether the findings apply to higher cart-load ranges [6], e.g., 243 to 469 kg, which are commonly seen on construction sites.

Finally, the cart load is the foremost risk factor for OPP [10,27], and workers should refrain from overloading a cart by following load restrictions. Several efforts have been made to provide such numerical standards [28–30]. However, none of them consider the impacts of the cart condition, tire type, and physical environment-related factors; only fixed thresholds are recommended which are not adaptable and thereby limit their applicability when imposing load restrictions under various working conditions.

The objective of this study is to measure how cart condition, tire type, physical environment-related factors, and load interact to influence cart operations to support the design of administrative controls for cart handling. In Experiment 1, we measured the forces and time required to operate carts of different conditions and equipped with different tires during dynamic cart pulling in straight-line and turning motions. Overexertion risks were estimated to offer empirical advice for cart maintenance, replacement, and tire selection. In Experiment 2, we focused on cart operations in relation to a combination of physical environment-related factors and loads to provide advice for workplace layout and load restrictions.

Our study rests on the premise that, to create transferrable evidence that practitioners can immediately adopt, laboratory experiments should acknowledge practical complexity and uncover the effects of risk factors in detail, by closely simulating actual working situations [31]. Owing to the authors' participation in an ergonomics program with a large roofing contractor in the U.S., our experiments managed to properly determine the levels and interactions of the risk factors of interest. Hence, our research findings apply strongly to applications in the roofing industry, or other industrial settings where similar scenarios exist, to reduce overexertion and enhance cart-handling performance.

## 2. Experiment 1

The objective of Experiment 1 was to uncover the effects of the cart condition and tire type on the ergonomics and productivity of cart operations under various loads.

2.1. Materials and Methods

2.1.1. Experiment Design

Apparatus

A typical cart in the roofing industry is composed of a deck (for loading materials), a turntable (in front of the deck), and a height-adjustable “T”-shaped handle (connected to the turntable for pulling) (Figure 1). In this study, 18 carts of this type with varying ages and tire types were tested; newer carts were generally in better condition (Table 1). The framing of the five-year-old carts was 10 kg lighter than that of the newer carts. To make the results comparable, an extra 10-kg load was added to the five-year-old carts during the experiment. Both pneumatic and solid tires were from the same manufacturer and had the same dimensions.

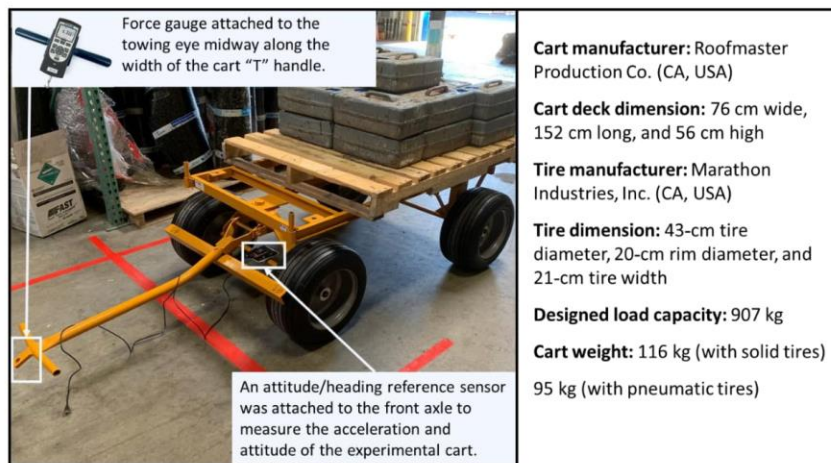


Figure 1. Instrumented cart.

Table 1. Experimental carts.

Cart Condition	Tire Type	Number of Carts Tested
Brand-new	Pneumatic	2
Brand-new	Solid	2
One-year-old (no noticeable structural damage)	Pneumatic	5
One-year-old (no noticeable structural damage)	Solid	5
Five-year-old (contaminated tires, broken/deformed bearings, warped axles, and loose turntables)	Solid (three years old)	2
Five-year-old (curved axles and loose turntables)	Solid (brand-new)	2

A digital force gauge (Series: DFS2, John Chatillon & Sons Co., Largo, FL, USA) with a maximum reading of 1000 N and a precision level of 0.0001 N was used to measure the required operating forces (ROFs) for cart maneuvering. As shown in Figure 1, the force gauge was attached to the towing eye midway along the width of the handle, and the force gauge was perpendicular to the handle while pulling. The force data were transmitted telemetrically to a personal computer at 36 Hz.

An industrial-grade attitude/heading reference sensor (Series: 3DM-CV5-25, Lord Sensing Co., Williston, VT, USA) was mounted on the cart’s front axle to gather accel-

ation and attitude data at 50 Hz to characterize the cart movement and to measure the required operating time (ROT). The positioning consistently oriented the  $x$ -axis vector of the sensor frame with the forward direction of the cart movement, and the  $z$ -axis vector was perpendicular to the cart frame. The resolutions for acceleration and attitude data were 0.05 mg and  $0.003^\circ/\text{s}$ , respectively.

#### Laboratory Track

An L-shaped track (Figure 2) was constructed to represent the common working conditions for cart operations. The track allows dynamic pulling activities in both straight-line (762 cm long) and turning motions (244-cm diameter). Tapes were used to mark a 122-cm-wide lane for cart operation.

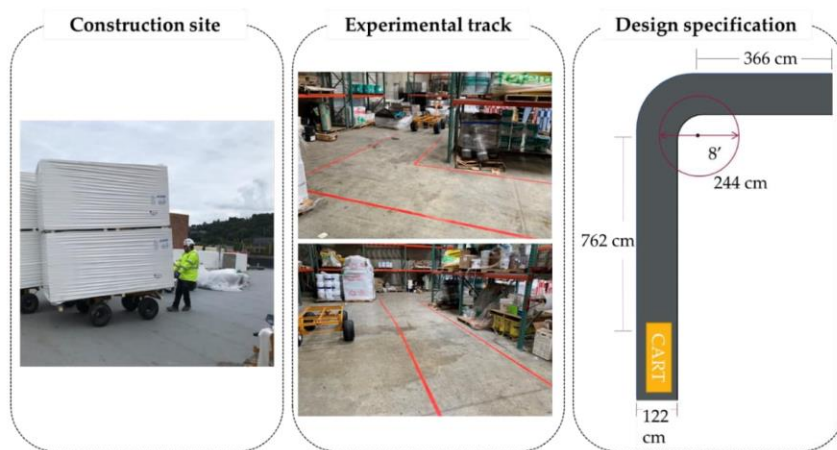


Figure 2. L-shaped track.

#### Subject

Individual differences are a known factor in OPP [23,32–35]. We controlled for individual factors by using a single subject. A male graduate student, aged 29 years, with a stature of 177 cm and a body mass of 88 kg, participated in the experiment. The anthropometric characteristics of the subject are representative of construction workers in the greater Seattle metropolitan area, based on a regional worker-profile survey [36]. The subject is healthy and free from any musculoskeletal problems. The subject visited five roofing jobsites to videotape and learn how workers operated carts. Then, he received 30 min of training on pulling techniques from two experienced workers and was given observational feedback in practice trials to ensure that identical pulling techniques were applied.

#### Experimental Procedure

The subject was instructed to pull a cart forward for 762 cm and then make a  $90^\circ$  turn with a 244-cm diameter, followed by a 366-cm straight pull to the marked finish point. The cart operations were performed from and until a standstill. The participant mimicked the pulling techniques of the roofers by pulling the cart symmetrically with both hands and without jerking motions. The handle was at the thigh level and the participant bent his back slightly (less than  $15^\circ$ ) when initiating and sustaining the cart movement. The cart-movement speed was subjectively controlled by the participant at an approximate walking speed of 2 m/s.

All of the trials were performed with three cart loads: 243, 356, and 469 kg, by combining a wooden pallet weighing 16 kg with 20 ballast weights, each weighing 22.7 kg. The ballast weights were loaded evenly onto the wooden pallet, which was placed on an experimental cart. All pneumatic tires were inflated to the recommended pressure. Good housekeeping was performed to ensure the track was free from debris and congestion. Each experimental setup was repeated at least three times until consistent ROF measurements were obtained: each measurement was within 15% of the others. A one-minute recovery time was given between trials and a three-minute rest was given between experimental setups to eliminate fatigue [23,37,38]. All 162 experimental trials (18 carts  $\times$  3 cart loads  $\times$  3 trials) were completed in five days.

### 2.1.2. Data Analysis

#### Data Management

The cart movement on the L-shaped track was divided into four phases: initial, sustained, turning, and stopping (Figure 3). The four motion phases were determined post hoc using forward-acceleration and angular-rate data collected by the attitude/heading reference sensor. The “Segmented” package in the R project [39] was employed to detect the breakpoints where the linear relations between the acceleration/angular rate and time changed (Figure 3). The mean force over the sustained and turning phases, which constituted the majority of the cart movement, was obtained as the primary outcome measure of the ROF for statistical analysis. The required operating time (ROT) to finish the course of motion on the track was recorded as a measure of productivity.

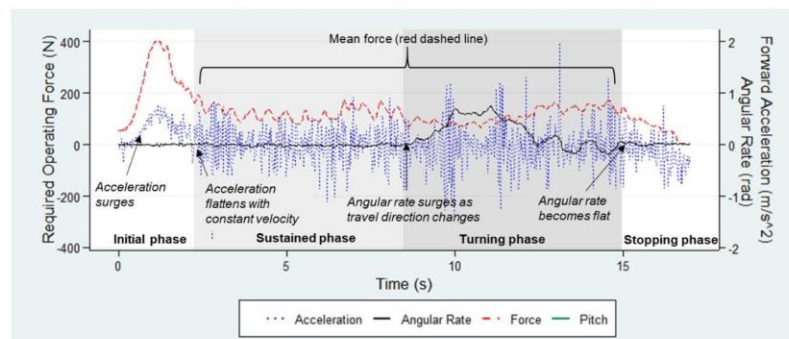


Figure 3. Sample trial with the L-shaped track.

#### Statistical Analysis

Experiment 1 employed two full-factorial designs. In Experiment 1a, we included three dummy independent variables for the cart condition to compare a one-year-old cart, five-year-old cart, and five-year-old cart after tire replacement against a brand-new cart (the reference category) and a continuous independent-variable cart load. Two multiple linear regression models were created to investigate the effects of the cart condition on the ROF and ROT under different cart loads. Because the five-year-old experimental carts (donated by our industry partner) were all equipped with solid tires, the tire type was controlled in Experiment 1a by using only carts (Table 1) that were equipped with solid tires.

In Experiment 1b, we included a binary independent-variable tire type (pneumatic and solid tires) and a continuous independent-variable cart load to estimate the association between the tire type and the ROF/ROT under different loads. The cart conditions (brand-new and one-year-old) were also included in the models as a precision variable to increase the precision of the estimate.

To understand how the changing ROFs are associated with the OPP risk, the ROFs were converted into capability percentages (CPs) by referencing the Snook Table [40]. Because cart operations are mostly performed by male workers in the construction industry, the CP denotes the percentage of the male population who are psychophysically capable of performing the experimental pulling task. The parameters needed for the Snook Table when calculating CPs included pulling at thigh height, 46 m pulling distance, and one pull every five min, which were determined through field observations. A multiple regression analysis was also performed for the CP.

For both ROF and CP, we reported regression coefficients ( $\beta$ ) to present the estimated change in the absolute value corresponding to the unit change in the independent variable, along with the robust standard error (s.e.) and  $p$ -value. The ROT was log-transformed to compare the relative percentage change in productivity. Backward elimination was applied to include interaction terms between the independent variables. All possible interactions were first fitted together to screen for significance, and only the terms that were significant at a level of 0.05 were included in the final models. All analyses were performed using the R Project software.

2.2. Results

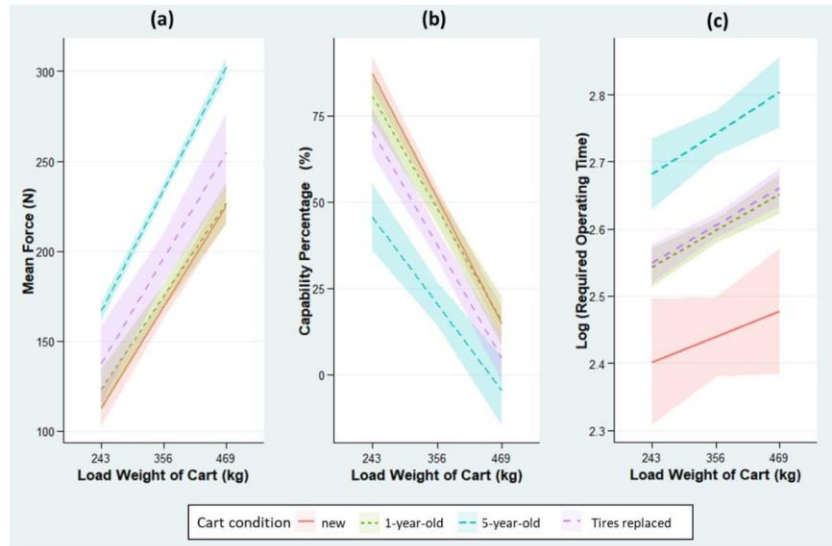
A total of 99 trials were conducted for Experiment 1a to examine the effects of the cart conditions on the cart operation under different loads. Table 2 summarizes the regression analysis results with the observed  $\beta$ , s.e., and  $p$ -value for the three dependent variables: ROF, CP, and ROT. The R-squared values for the three models are 0.83, 0.81, and 0.62, indicating the goodness-of-fit of the regression models. The estimated ROF, CP, and ROT for carts of different conditions are shown in Figure 4.

According to Table 2, both the cart condition and load are significantly associated with the ROF and corresponding CP, in most cases. A difference of 65.5 N in ROF (30.6% in CP) was found between the new and five-year-old carts, despite no significant difference between the new and one-year-old carts. Replacing the old tires on the five-year-old carts was effective in lowering the ROF (additional forces decrease from 65.5 to 27.1 N) with a moderate margin in CP (from -30.6% to -13.4%). In addition, the ROF increased as a cart was more heavily loaded, with an incremental increase of 0.487 N for every 1 kg increase in cart load, on average, for carts of different conditions.

Table 2 also shows that the cart condition and load are significantly associated with the ROT. The productivity of the cart operation degrades as the carts age: one- and five-year-old carts respectively require 17.1% and 35.4% more time to complete each trial, on average, than a new cart. Tire replacement on a five-year-old cart has proven effective in increasing the productivity (the extra percentage change in ROT decreases from 35.4% to 18.0%). Lastly, the ROT increases by 0.046% for every 1-kg increase in the cart load, on average, for carts of different conditions.

**Table 2.** Statistical results of Experiment 1a: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and  $p$ -values from the final models, featuring independent variables: cart condition (brand-new as reference category) and cart load (243 kg as baseline) and dependent variables: ROF, CP, and ROT. Bold fonts indicate  $p$ -values are less than our significance level 0.05.

Effect	Required Operating Force, ROF (N)			Capability Percentage, CP (%)			Percentage Change in Required Operating Time, ROT (%)		
	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value
Intercept	114	3.51	<0.001	83.6	1.95	<0.001	989	2.02	<0.001
Cart condition									
One-year-old vs. brand-new	5.76	4.61	0.215	-3.02	2.70	0.266	17.1	2.04	<0.001
Five-year-old vs. brand-new	65.5	4.61	<0.001	-30.6	3.52	<0.001	35.4	3.08	<0.001
Five-year-old after tire replacement vs. brand-new	27.1	5.98	<0.001	-13.4	2.21	<0.001	18.0	3.08	<0.001
Cart load (kg)	0.487	0.025	<0.001	-0.289	0.013	<0.001	0.046	0.008	<0.001

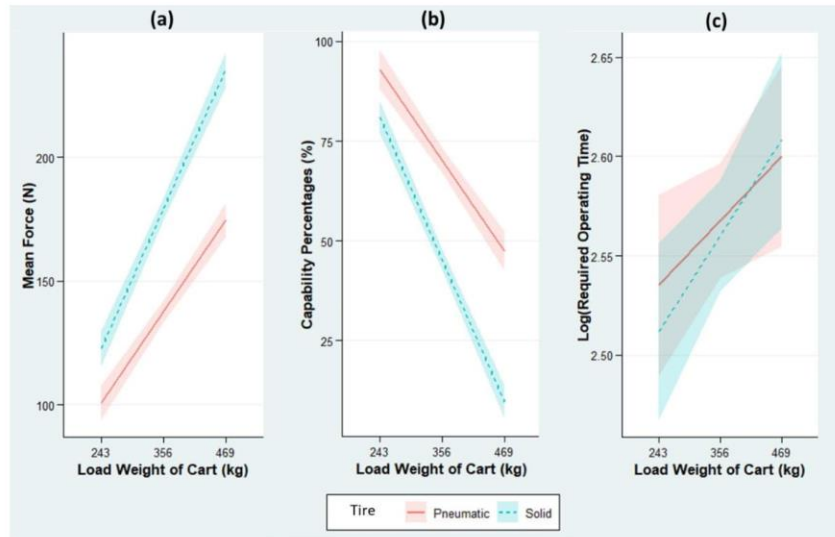


**Figure 4.** Estimated values: (a) ROF, (b) CP, and (c) ROT for carts of different conditions by fitting the actual measurements in Experiment 1a from the final linear regression models. The ribbons indicate 95% confidence intervals.

A total of 126 trials were conducted for Experiment 1b to compare the difference between pneumatic and solid tires. The regression-analysis results are summarized in Table 3 and displayed in Figure 5. The R-squared values for the three models are 0.88, 0.87, and 0.40, indicating the goodness-of-fit of the regression models. The tire type is significantly associated with the ROF and CP; however, the measures of the association are dependent on the cart load, as we observe a significant interaction effect between the tire type and load. The intercept values estimate that pulling a 243-kg brand-new cart equipped with pneumatic tires requires 92.6 N, which is acceptable for 98.1% of the male population.

**Table 3.** Statistical results of Experiment 1b: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and  $p$ -values from the final models, featuring independent variables: cart condition (brand-new as baseline), tire type (pneumatic tire as baseline), and cart load (243 kg as baseline), an interaction term between the tire type and cart load, and dependent variables: ROF, CP, and ROT. Bold fonts indicate  $p$ -values are less than our significance level 0.05.

Effect	Required Operating Force, ROF (N)			Capability Percentage, CP (%)			Percentage Change in Required Operating Time, ROT (%)		
	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value
Intercept	92.6	3.0	<0.001	98.1	1.88	<0.001	1029	2.01	<0.001
Cart condition (One-year-old vs. brand-new)	11.7	2.79	<0.001	−7.30	1.82	<0.001	15.6	1.82	<0.001
Tire type (solid vs. pneumatic)	22.0	3.55	<0.001	−11.9	2.12	<0.001	−0.75	1.64	0.645
Cart load (kg)	0.326	0.023	<0.001	−0.201	0.017	<0.001	0.036	0.009	<0.001
Tire type $\times$ cart load	0.173	0.031	<0.001	−0.115	0.020	<0.001	-	-	-



**Figure 5.** Estimated values: (a) ROF, (b) CP, and (c) ROT for two tire types by fitting the actual measurements in Experiment 1b from the final linear regression models. The ribbons indicate 95% confidence intervals.

At this baseline cart load (243 kg), solid tires are estimated to require 22.0 N more force than the pneumatic tires, which is equivalent to an 11.9% decrease in CP. As the carts are more heavily loaded, however, the increase in ROF and decrease in CP become more rapid among carts with solid tires (Figure 5a,b). With every 1-kg load added to a cart, the ROT is estimated to increase 0.326 N ( $-0.201\%$  in CP) for pneumatic tires, while solid tires require an additional 0.173 N of force and impose a 0.115% extra risk (i.e.,  $-0.115\%$  in CP) over pneumatic tires. Finally, Table 3 shows that the productivity of the cart operation is not significantly associated with the tire type ( $p$ -value = 0.645).

### 3. Experiment 2

The objective of Experiment 2 was to uncover the main and interaction effects of physical environment-related factors (obstacle height, ramp slope, and space constraint) on the cart operation under different loads.

#### 3.1. Materials and Methods

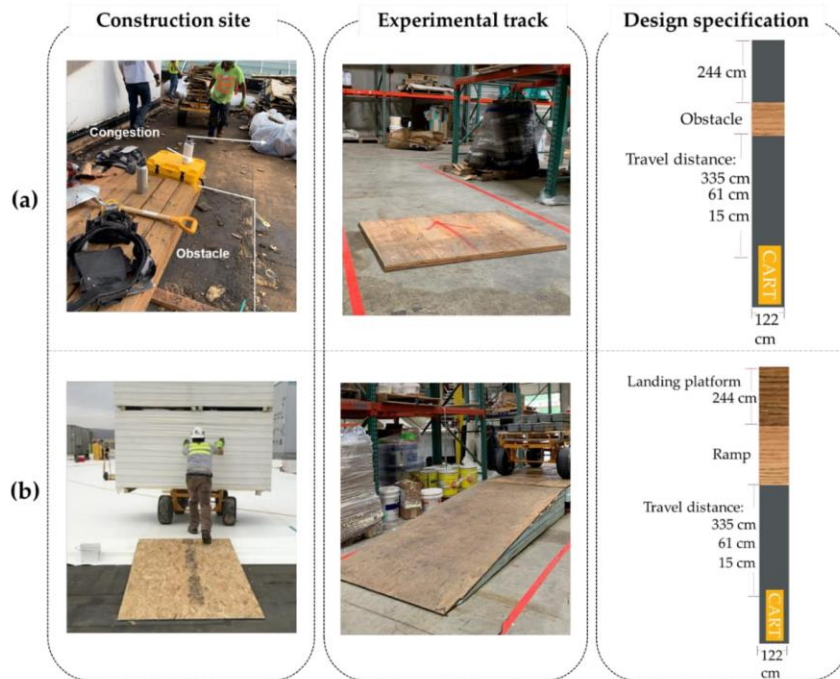
##### 3.1.1. Experiment Design

###### Apparatus

Four brand-new carts (two with pneumatic tires and two with solid tires) were tested in Experiment 2. The other deployed apparatuses were identical to those in Experiment 1.

###### Laboratory Track

Two laboratory tracks were created by the authors and two roofers to simulate the actual physical environments on construction sites. First, an obstacle track (Figure 6a) was arranged by mounting a 122 cm  $\times$  122 cm plywood board using anti-slip traction tape. The plywood boards came in three heights: 1.9, 3.8, and 5.7 cm. Second, a ramp track (Figure 6b) was built with two 244 cm  $\times$  122 cm plywood boards attached to insulation boards. The ramp came in three slope gradients: 4°, 8°, and 12°.



**Figure 6.** Laboratory tracks for Experiment 2: (a) obstacle track and (b) ramp track.

Three levels of space constraint were simulated by defining the travel distance (i.e., from the front axle of the cart to the closest edge of an obstacle/ramp): 335, 61, and 15 cm. The 335-cm travel distance simulated maneuvering a cart within an open space, which allowed the cart to build momentum and sustain a relatively constant velocity before contacting a ramp/obstacle. The 61-cm distance simulated a moderately constrained space and was determined by measuring the actual travel distances in congested passages, corners, and construction man-lifts. The worst scenario was 15 cm, when the front wheels almost contacted the edge of the ramp/obstacle, providing no space to generate momentum. All levels and interactions of the risk factors of interest were determined by 10 field observations and surveying 25 field workers in order to consider all possible working environments for cart operations.

#### Subject

The same as in Experiment 1.

#### Experimental Procedure

A cart was first placed upon a level surface with an obstacle/ramp located at a pre-defined distance (355, 61, or 15 cm) to simulate space constraints. The subject was requested to follow a set procedure: pull the cart over the pre-defined distance, then surmount the obstacle/ramp, followed by a 244-cm straight pull to a marked finish point. The cart operations were performed from and until a standstill. The entire experiment was conducted with five loads: 16, 129, 243, 356, and 469 kg. The subject mimicked the roofers' pulling technique by jerking to overcome an obstacle/ramp when within a moderately

(61-cm travel distance) or extremely (15 cm) constrained space. The other experimental details were identical to those in Experiment 1. All 963 experimental trials were completed in 25 days.

3.1.2. Data Analysis  
Data Management

The cart movement on the obstacle track was divided into initial and surmounting phases (Figure 7a). The two phases were determined post hoc using pitch data, which denote the angle between the longitudinal axis of the cart and the horizon. As surmounting an obstacle requires impulsive forces, the peak force during the initial and surmounting phases was recorded as the ROF. The duration of the initial and surmounting phases was collected as the ROT.

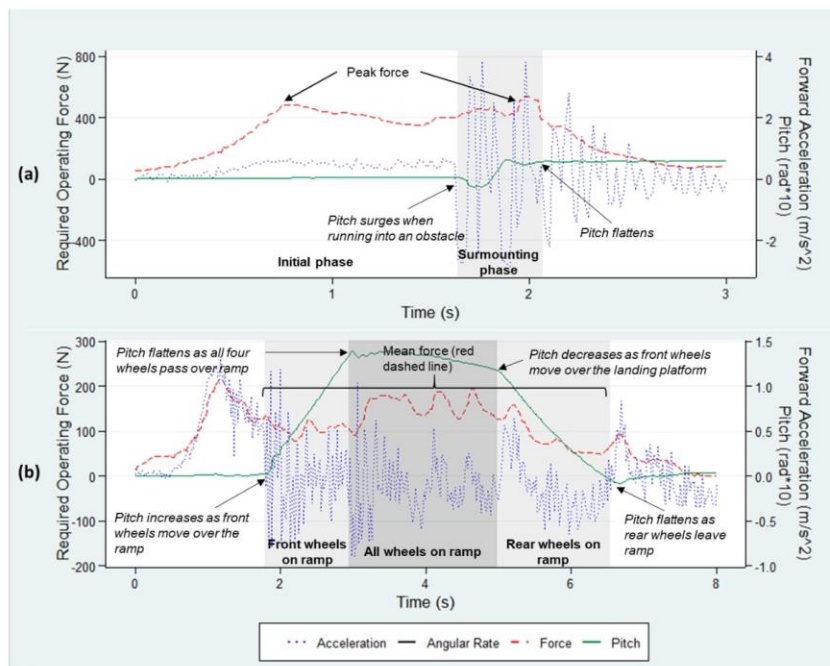


Figure 7. Sample trial data: (a) obstacle track within a moderately constrained space and (b) ramp track within a severely constrained space.

The cart movement on the ramp track was divided into three phases: front wheels on ramp, all wheels on ramp, and rear wheels on ramp. Similarly, the three phases were defined by detecting the change in the pitch with time (Figure 7b). The mean force and operating time over the three phases were recorded as the primary outcome measures for ROF and ROT, respectively.

Statistical Analysis

Experiment 2 employed respective full-factorial designs for the obstacle and ramp tracks. As an investigation of the effects of the obstacle height and space constraint on the cart operations under different cart loads, Experiment 2a included a continuous independent-variable obstacle height, two dummy independent variables for space con-

straints to compare moderate space constraints and extreme space constraints against *open space* (the reference category), and a continuous independent-variable cart load.

Experiment 2b was designed for the ramp track and included a continuous independent-variable ramp slope, two dummy independent variables for space constraint, and a continuous independent variable cart load. The tire type was included in both Experiments 2a and 2b as a precision variable. The parameters needed for estimating the CP were pulling at thigh height, 7.6-m pulling distance, and one pull every five min. The other technical details for data analysis replicated those of Experiment 1.

3.2. Results

Owing to the capacity constraint of the force gauge, 13 setups for Experiment 2a (obstacle track) were not tested. The remaining setups were tested over 501 trials. Table 4 summarizes the regression analysis results with the observed  $\beta$ , s.e., and *p*-value for the effects of the obstacle height, space constraint, and cart load on the ROF, CP, and ROT. The R-square values for the three models are 0.92, 0.89, and 0.96, indicating the goodness-of-fit of the regression models.

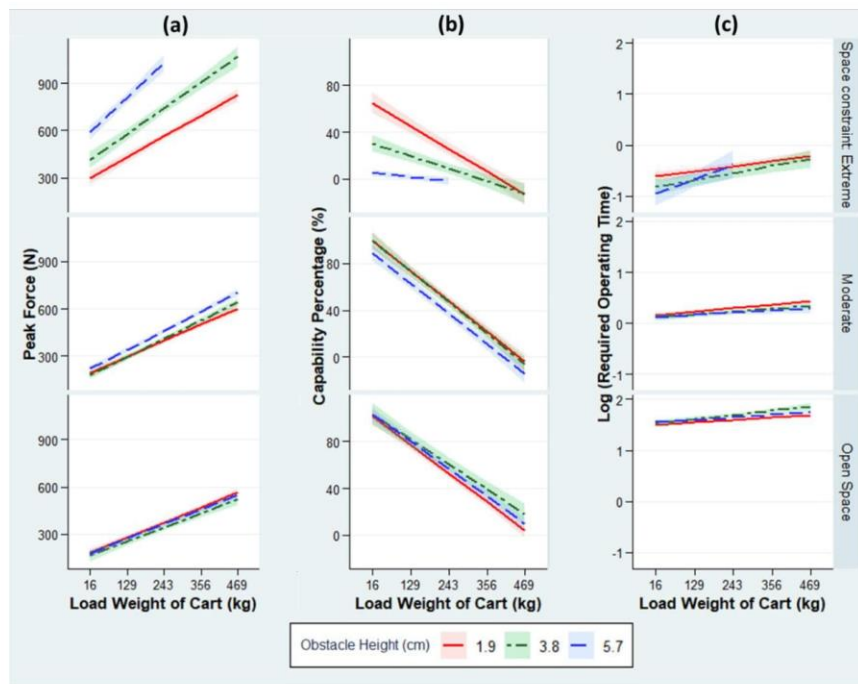
**Table 4.** Statistical results of Experiment 2a: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and *p*-values from the final models, featuring four independent variables: tire type (pneumatic tire as baseline), obstacle height (1.9 cm as baseline), space constraint (open space as baseline), and cart load (16 kg as baseline), interaction terms between the obstacle height and space constraint and between the cart load and space constraint, and finally dependent variables (ROF, CP, and ROT). Bold fonts indicate *p*-values are less than our significance level 0.05.

Effect	Required Operating Force, ROF (N)			Capability Percentage, CP (%)			Percentage Change in Required Operating Time, ROT (%)		
	$\beta$	s.e.	<i>p</i> -Value	$\beta$	s.e.	<i>p</i> -Value	$\beta$	s.e.	<i>p</i> -Value
Intercept	29.8	7.44	<b>0.008</b>	110	1.73	<b>&lt;0.001</b>	353	2.67	<b>&lt;0.001</b>
Tire type (solid vs. pneumatic)	60.5	5.91	<b>&lt;0.001</b>	−14.7	1.38	<b>&lt;0.001</b>	2.38	1.87	<b>0.003</b>
Obstacle height (cm)	25.0	2.23	<b>&lt;0.001</b>	0.996	0.523	0.057	−1.83	0.612	0.204
	Space constraint								
Moderate vs. open space	46.8	10.4	<b>&lt;0.001</b>	0.744	2.56	0.772	−75.5	2.21	<b>&lt;0.001</b>
Extreme vs. open space	190	15.2	<b>&lt;0.001</b>	−45.0	4.68	<b>&lt;0.001</b>	−88.6	2.36	<b>&lt;0.001</b>
Cart load (kg)	0.546	0.022	<b>&lt;0.001</b>	−0.210	0.005	<b>&lt;0.001</b>	0.071	0.006	<b>&lt;0.001</b>
Obstacle height × space constraint									
Obstacle height × Moderate vs. open space	2.03	4.59	0.569	−3.77	0.486	<b>&lt;0.001</b>	-	-	-
Obstacle height × Extreme vs. open space	76.8	5.99	<b>&lt;0.001</b>	−14.2	1.21	<b>&lt;0.001</b>	-	-	-
Cart load × space constraint									
Cart load × Moderate vs. open space	0.386	0.036	<b>&lt;0.001</b>	−0.028	0.007	<b>&lt;0.001</b>	-	-	-
Cart load × Extreme vs. open space	0.845	0.057	<b>&lt;0.001</b>	0.072	0.012	<b>&lt;0.001</b>	-	-	-

First, the obstacle height was found to be significantly associated with the ROF when overcoming an obstacle within an open space: The ROF is estimated to increase by 25.0 N for every 1-cm increase in obstacle height; however, the additional ROF does not lead to a significant difference in CP (*p*-value = 0.057). Second, Table 4 confirms the effect of the space constraint on the ROF and CP in the baseline scenario: when overcoming a 1.9-cm obstacle with a 16-kg cart, the ROF is estimated to increase by 46.8 N (insignificant difference in CP; *p*-value = 0.772) and 190 N (45% decrease in CP, *p*-value < 0.001) in moderately and extremely constrained spaces, respectively, as opposed to an open space. Third, the ROF increases by 0.546 N with every 1-kg load added to a cart when overcoming an obstacle within an open space.

Fourth, the effect of the obstacle height was found to differ under different levels of space constraint, as we observed a significant interaction effect between the obstacle height and the space constraint. Specifically, the adverse effects of the obstacle height on the ROF and CP became significantly salient in an extremely constrained space (Figure 8a,b). According to Table 4, a higher obstacle (by every 1 cm) requires 76.8 N of additional force and imposes an extra 14.2% risk in an extremely constrained space, when compared to an open space.

In contrast, the adverse effect of the obstacle height on the ROF was not significantly stronger in a moderately constrained space than in an open space ( $p$ -value = 0.569), while a significant but minimal gap in CP (−3.77%) was found. Furthermore, the effect of the space constraint was found to differ under different levels of cart load. As the carts were more heavily loaded, the changes in ROF/CP became more rapid in a constrained space (Figure 8a,b). For every 1-kg increase in cart load, the moderate and extreme space constraints required an extra 0.386 N of force (−0.028% in CP) and 0.845 N of force (0.072% in CP), respectively, when compared to an open space.



**Figure 8.** Estimated values: (a) ROF, (b) CP, and (c) ROT for three obstacle heights by fitting the actual measurements in Experiment 2a from the final linear regression models, stratified by the space constraint. The estimated values are adjusted for tire type. The ribbons indicate 95% confidence intervals.

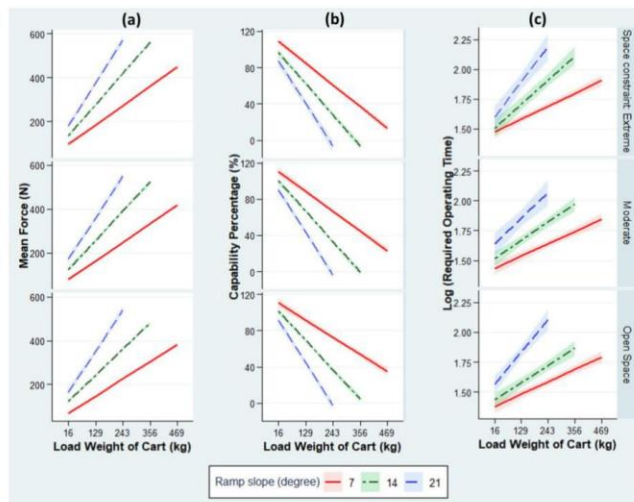
Finally, Table 4 suggests that the productivity of the cart operation is not significantly associated with the obstacle height ( $p$ -value = 0.204). The ROTs under different space constraints simply reflect travel distances and are not worthy of discussion.

Owing to the capacity constraint of the force gauge, 26 setups for Experiment 2b (ramp track) were not tested. The remaining setups were tested over 462 trials. The regression

analysis results are summarized in Table 5. The R-square values for the three models are 0.91, 0.89, and 0.50, indicating the goodness-of-fit of the regression models. The ramp slope is significantly associated with the ROF and CP; however, the measures of the association depend on the cart load, as we observe a significant interaction effect between the ramp slope and cart load. When overcoming a 16-kg cart, the ROF is estimated to increase by 10.3 N (−2.29% in CP) for every 1° increase in ramp slope. However, the detrimental effect of the ramp slope significantly escalates as the carts are more heavily loaded (Figure 9a,b). Table 5 shows that, with every 1-kg load added to a cart, the ROF is predicted to increase by 0.756 N (−0.196% in CP) for a 4° ramp, while a steeper ramp (for every 1°) requires 0.123 N of additional force and imposes an extra 0.03% risk.

**Table 5.** Statistical results of Experiment 2b: Regression coefficients ( $\beta$ ), robust standard errors (s.e.), and  $p$ -values from final regression models, featuring four independent variables: tire type (pneumatic tire as baseline), ramp slope (4° as baseline), space constraint (open space as baseline), and cart load (16 kg as baseline), an interaction term between the ramp slope and cart load, and dependent variables: ROF, CP, and ROT. Bold fonts indicate  $p$ -values are less than our significance level 0.05.

Effect	Required Operating Force, ROF (N)			Capability Percentage, CP (%)			Percentage Change in Required Operating Time, ROT (%)		
	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value	$\beta$	s.e.	$p$ -Value
Intercept	37.5	2.54	<0.001	119	1.46	<0.001	275	1.95	<0.001
Tire type (solid vs. pneumatic)	31.5	1.91	<0.001	−6.96	0.848	<0.001	4.24	1.29	0.0013
Ramp slope (°)	10.3	0.385	<0.001	−2.29	0.217	<0.001	2.19	0.335	<0.001
Space constraint									
Moderate vs. open space	19.2	2.31	<0.001	−3.92	0.988	<0.001	6.28	1.56	<0.001
Extreme vs. open space	41.5	2.27	<0.001	−8.76	1.05	<0.001	11.9	1.56	<0.001
Cart load (kg)	0.756	0.009	<0.001	−0.196	0.004	<0.001	0.098	0.006	<0.001
Ramp slope × cart load	0.123	0.003	<0.001	−0.030	0.001	<0.001	0.015	0.002	<0.001



**Figure 9.** Estimated values: (a) ROF, (b) CP, and (c) ROT for three ramp slopes by fitting the actual measurements of Experiment 2b from the final linear regression models, stratified by the space constraint. Estimated values are adjusted for tire type. The ribbons indicate 95% confidence intervals.

Table 5 also confirms the effect of the space constraints on the ROF and CP. After adjusting for other factors, the ROF is estimated to increase by 19.2 N (−3.92% in CP) and 41.5 N (−8.76% in CP) under moderately and extremely constrained spaces, respectively, when compared to an open space.

Finally, the impact of the ramp slope on the ROT is statistically significant, while the magnitude of the impact varies under different loads (Figure 9c). For the baseline cart load (16 kg), the ROT to overcome a ramp is 2.19% longer for every 1° increase in slope; however, the ROT gap between two ramps differing in slope by 1° grows increasingly wider as the carts are more heavily loaded (by 0.015% for every 1-kg increase in cart load).

#### 4. Discussion

This study assessed the main and interaction effects of the cart condition, tire type, physical environment-related factors, and load on the cart operation, using the roofing industry as the study context. Evidence was collected to uncover the ergonomic hazards that should be addressed to prevent overexertion injuries resulting from cart handling.

##### 4.1. Effect of Cart Condition

The results of Experiment 1a made it clear that operating a five-year-old cart was risky (placing an additional 30.5% of the male population at an elevated risk for overexertion) and non-productive (requiring 35.4% extra time to complete the experimental task). The malfunctions of old tires (contaminated tires and broken/deformed bearings) appear to explain 50% to 59% of the performance degradation, as we observed a 17.2% increase in CP and 17.4% decrease in ROT after tire replacements for five-year-old carts. Altogether, the findings suggested that tire replacement is a convenient administrative control worth considering; however, it is less effective than replacing the entire cart, when structural framing problems (warped axles and loose turntable) have developed causing excessive friction in axle shafts and vibration in the turntable.

A comparison between the results of Experiments 1a and 1b suggested that pneumatic and solid tires could have different rates of wear and tear. In Experiment 1a, we only tested carts with solid tires and found insignificant differences in CP between brand-new and one-year-old carts (Table 2). However, after including carts with pneumatic tires, we found in Experiment 1b (Table 3) that one-year-old carts presented a 7.3% higher injury risk than brand-new carts did, on average, over the two types of tire ( $p$ -value < 0.001). This finding implies that pneumatic tires could deteriorate more rapidly and thereby need more attention in routine maintenance.

Compared to the narrative descriptions of the adverse effects of cart deterioration in prior literature [16–18], our numerical evidence can be more powerful when persuading practitioners to replace aged equipment in a timely manner [41,42]. The evidence is also more business oriented by providing important data (i.e., changes in health outcome and productivity) for practitioners to perform cost-effectiveness analyses of preventative replacement. We envision the evidence as providing broader implications for roofing and other industries in which heavy-duty carts are utilized and deteriorate fairly quickly.

##### 4.2. Effect of Tire Type

We identified the differences between pneumatic and solid tires, which were overlooked by prior studies. The pneumatic tires consistently outperformed the solid ones across all experimental conditions with a moderate margin in CP (L-shaped track: −11.9%, obstacle: −14.7%, and ramp: −6.96%) and a minimal margin in ROT (L-shaped track: insignificant, obstacle: 2.38%, and ramp: 4.24%), which could be ascribed to the light weight of the pneumatic tires. The larger difference in ROFs on the obstacle track could be attributed to the fact that a pneumatic tire has a greater resilience allowing it to better conform around obstacles.

Furthermore, Experiment 1b identified an interaction effect between the tire type and cart load on the ROF/CP, implying that the advantages of pneumatic tires become

increasingly salient under a higher cart load. Our results supported the use of pneumatic tires, especially when transporting heavier loads. However, it should be noted that the advantages of pneumatic tires are modest, and can be offset by the labor and administrative costs caused by flat-tire downtimes.

#### 4.3. Effect of Physical Environment-Related Factors

When it comes to physical environment-related factors, this study was unique and did not simply replicate the past works performed in the contexts of healthcare, waste collection, aviation, and manufacturing [19–22]. We carefully varied the degree of each physical environment-related factor and the interactions among factors to mimic the actual working conditions at construction sites. Retrospectively, we found this experiment design to be critical in generating results that could reliably inform practice.

Previous studies have not examined whether a space constraint increases the force required to overcome an obstacle/ramp, although its detrimental impact has been confirmed when moving carts along a straight line or making a turn [23,27]. In this study, Experiment 2a surprisingly demonstrated that the space constraint was the strongest risk factor when surmounting obstacles. This factor also considerably amplified the adverse effects of both obstacle height and cart load on the cart operation.

In an open space, a larger obstacle barely presented any additional risk under the different cart loads (Figure 8) because the open space allowed the operator to build sufficient cart momentum to overcome an obstacle. In a constrained space, however, the operator could not depend on the cart's inertia of motion; rather, a much greater force is needed to not only overcome the obstacle, but also initiate the cart movement.

Our findings indicated that any evidence that overlooks space constraints as a risk factor will substantially underestimate the injury risk of overcoming an obstacle and, therefore, is unreliable when informing workspace-layout planning. Practitioners are recommended to reserve an open space in the work station to ensure that the travel distance from a cart to any obstacle is larger than 61 cm.

Experiment 2b highlighted the ramp slope as the strongest predictor of ROF, CP, and ROT when overcoming a ramp, suggesting that practitioners should build gentler ramps for cart operations. Furthermore, the detrimental effect of the ramp slope was stronger for carts with heavier loads. This could be due to the heavier carts lose momentum more easily on steeper ramps and operators need to constantly apply a much larger force to initiate the cart movement [23]. This finding unveiled a complex interaction effect between the ramp slope and cart load on the cart operation, challenging the prior observation [43] that the ramp slope has a simple linear association with the ROF. This means that past research findings [19,20] that were obtained at lower cart loads (20–100 kg) can underestimate the risk of injury when overcoming a ramp at higher cart loads. Overall, our study results support the notion that experimental studies should sufficiently consider the levels of variables and their interaction effects to provide insights into the mechanics of cart operation [6] and generate reliable evidence for applications [31].

#### 4.4. Effect of Cart Load

Although the cart load has been studied by almost all the above-mentioned literature, this research contributed to the evidential understanding of this risk factor by assessing its effects at a higher range and thoroughly exploring how its effects vary in relation to the cart condition, tire type, and physical environment-related factors. Hence, the research results have practical implications for operating heavy-duty carts in dynamic and complex working environments. Practitioners can refer to Figure 4, Figure 5, Figure 8, and Figure 9 to quickly search for the safe load under a certain circumstance or to find the at-risk threshold of a physical environment-related factor, given a fixed cart load. In general, cart load has a greater effect on CP (L-shaped track:  $-0.289\%$ , obstacle:  $-0.210\%$ , and ramp:  $-0.196\%$  for every 1-kg increase in cart load). Despite being statistically significant, the

effect of cart load on ROT is rather minimal (L-shaped track: 0.046%, obstacle: 0.071%, and ramp: 0.98%).

Moreover, we confirmed that the cart load can modify the effects of the tire type, ramp slope, obstacle height, and space constraint, contradicting previous observations that the cart load is linearly proportional to the operating forces [10] and physiological demands [43].

#### 4.5. Limitations and Future Directions

Similar to many previous studies [5,23,44], our practical implications were made, based on the psychophysical limits of the measured hand forces. Although the validity of the psychophysics-based Snook Table has been repeatedly confirmed after its inception [16,45,46], we still see the potential of using advanced instruments (e.g., surface electromyography) and biomechanical analyses to provide more accurate results for risk assessment. For example, an increase in the cart load or ramp slope not only required a larger hand force, but also prolonged the exertion duration of the cart operation; however, we only considered the force when assessing the OPP risk because of the restrictions of the Snook Table. Furthermore, the pulling/pushing speed has been found to be a factor that can influence the shear forces and moments within the lumbar spine [6,47]. Without considering this factor, our study could underestimate the OPP risk, especially for experimental conditions in which a constrained space was involved that required jerking motions.

The generalizability of the research findings may be limited because we controlled the individual factors in the experiment by selecting an anthropometrically representative subject who adopted the most common pulling/pushing techniques. Another way to control individual differences is to deliberately select subjects and then adjust individual factors in the statistical analysis. But thus far, the causal mechanisms of individual factors on OPP remain unclear, refraining us from applying this method. Alternatively, a large subject pool could be obtained for the full randomization of individual factors, which, however, overcomplicates and distracts the experiment design in which the factors of interest are already highly varied. This methodological choice is also constrained by the cost and difficulty of recruiting field workers.

Because of the research subject limitation, our results only represented the best estimates; the actual effects of the factors we tested may vary from one person to another. Starting from the premise that administrative controls are more effective and attainable than individual changes during a workplace intervention, this study focused on the cart condition, tire type, physical environment-related factors, and load, rather than individual factors.

Future research can certainly be built on this study to characterize and assess how individual differences might influence the OPP risk. For example, what is the best pushing/pulling technique that cart operators should use to negotiate with physical environment-related hazards? Some findings on pulling/pushing techniques can be found in the literature [23,27,34,35]; however, they are far from being conclusive.

## 5. Conclusions

Overexertion in pulling and pushing constitutes more than 11% of work-related musculoskeletal disorders in the construction industry. Through a series of laboratory experiments, this study enhanced the evidential understanding of how the cart condition, tire type, physical environment-related factors, and load could interact to influence the overexertion risk and productivity during cart handling. Specifically, we confirmed that using aged carts increases the injury risk by 30.5% and decreases the productivity by 35.4%. Also, pneumatic tires consistently outperform solid ones in both ergonomic and productivity performance. Our study further identified and quantified the interaction effects between tire type and cart load, between space constraint and cart load, between obstacle height and space constraint, and finally between ramp slope and cart load. Based on our enhanced understanding, we propose a set of principles for administrative controls

(cart maintenance and preventative replacement, tire selection, workplace-layout planning, and load restrictions) that could be tied to the operational context in the roofing industry. For one, we suggest the roofing companies to pay more attention to the routine maintenance of aged carts, especially those with pneumatic tires. On the other hand, we recommend field workers to build gentle ramps, reduce obstacles, and keep an open space for cart handling. Our research results can be readily incorporated into a company's training materials, job-hazard analysis, job-specific safety plan, and safety-inspection checklist. We envision this study as increasing practitioners' awareness and understanding of how to ergonomically operate carts, thereby reducing overexertion injuries and their economic burden on our society. Future research could consider using advanced instruments and biomechanical analyses to examine the individual differences in cart operations and provide more accurate results for risk assessment.

**Author Contributions:** Methodology, Z.Z. and K.-Y.L.; data collection and analysis, Z.Z.; writing—original draft preparation, Z.Z.; writing—review and editing, K.-Y.L. and J.-H.L.; project administration, K.-Y.L.; funding acquisition, K.-Y.L. and Z.Z. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** This study was approved by the University of Washington Human Subjects Division (HSD) for the exempt status due to its no more than minimal risk to research subjects.

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## APPENDIX C – TRAINING HANDOUTS

# 1

## Inspect Carts Prior to Use

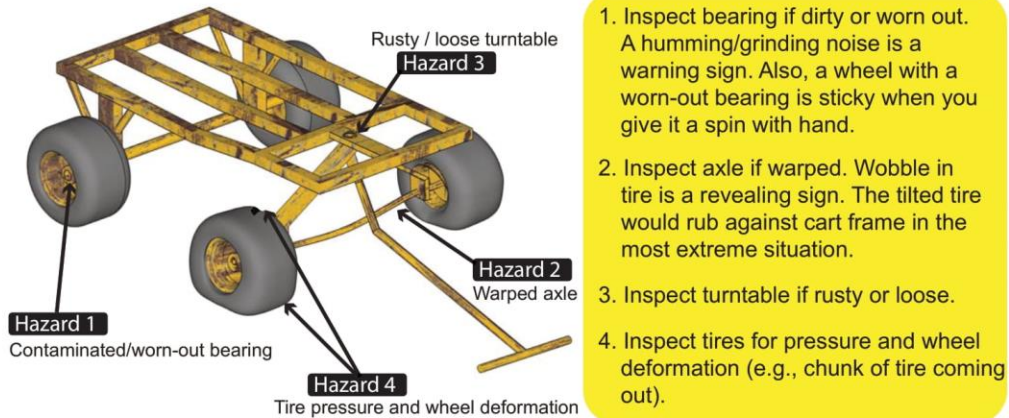
### Hazard:

As a heavy-duty equipment, material carts could deteriorate fairly quickly and develop structural problems. The use of aged carts could greatly increase the risk of injury and decrease the productivity.

CART CONDITION	SAFETY PERFORMANCE	PRODUCTIVITY PERFORMANCE
	4 out of 10 men can safely handle this cart (500-lbs load) 	
	8 out of 10 men can safely handle this cart (500-lbs load) 	A well-maintained cart moves 35% faster than an aged cart does 

### Control Measures:

- Inspect carts prior to use and report to supervisor when carts are not in good repair
- Avoid leaving loaded cart stationary overnight.



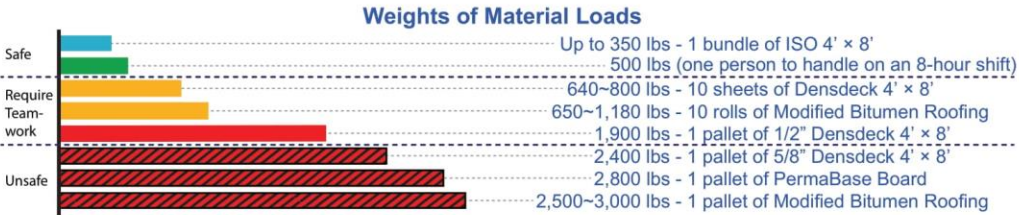
Using a cart in good condition cannot fix all problems because of other ergonomic hazards which can cause overexertion during cart handling. Please refer to following pages for ways to address these hazards and create an ergonomic workplace for cart handling.

# 2

## Teamwork and Job Rotation

### Hazard:

8 out of 10 workers can handle a 500-lb cart load during an 8-hour shift without becoming unusually tired. However, most bundled materials exceed this load capacity. If teamwork and job rotation are used, there is a lower chance for a worker to get hurt.



**WARNING:** Avoid moving the whole pallet when it is heavier than 2000 lbs. This will overload the cart, damage the roofing system you are installing, and wear yourself out.

### Control Measures:

- Perform job rotation so pushing/pulling is no more than 2 hours per day.  
*Keep in mind that job rotation allows workers to develop different skill set and help them become more productive.*



- Perform 2-person, 3-person or 4-person pushing/pulling as suggested by the table below.  
*Keep in mind that teamwork can encourage workers to watch out for each other, build a habit of reaching out for help, and develop a sense of unity as they go towards the same goal.*

Materials			Flat Surface	Ramp or Space with constraint
<p>10 rolls of Modified Bitumen Roofing</p>	<p>10 sheets of Densdeck</p>	<p>2 bundles* of ISO</p> <p><small>* Stacking bundles creates falling-object and struck-by hazard.</small></p>	<p><b>2-person</b></p>	<p><b>3-person</b></p>
<p>1 pallet of Perma Board</p>	<p>1 pallet of Modified Bitumen Roofing</p>	<p>1 pallet of Densdeck</p>	<p><b>3-person</b></p>	<p><b>4-person</b></p>

- Team leader to signal start and stop to minimize exertion and maintain control of heavy loads.
- Arrange loads evenly and balance the loads. If load obstructs view, use a spotter.
- Face the cart and use both hands to get it moving. Do not walk backwards unless going up ramps.
- Keep your back straight. Do not twist your body while pulling/pushing.

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Contact Dr. Ken-Yu Lin: 206-616-1915

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# 3

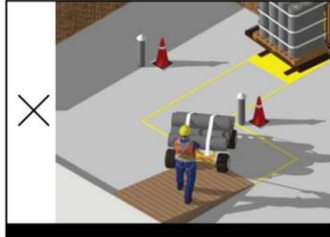
## Site Planning & Housekeeping

### Hazard:

Space constraints could come from physical restrictions of the site or bad workspace setups. Pulling a cart in a tight space requires higher precision and will increase the risk of overexertion. Poor material handling can also result in other type of injuries such as falling from height.

#### Setup workspace

Plan the workspace setup and select the best possible path of movement to avoid space constraints.



#### Narrow passage

Add one more worker to team when the space is tight.



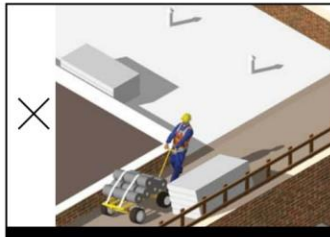
#### Housekeeping

Keep good housekeeping when space is tight. Allow at least 2 feet of run before rolling up an incline or over an obstacle.



#### Stored materials

Avoid space congestion by keeping hallways and passages clear of materials.



Reminder for foreman: Please share photo examples with crew!

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# 4

## Reduce Obstacles

### Expansion/Control joint

**Hazards:**

Expansion/Control joints are a common obstacle for cart movement.

**Control measures:**

- Cut expansion/control joint to ensure cart pathway is free of obstacles.
- When an obstacle is immovable, set up a ramp to bridge the gap created by the obstacle.

### Old roofs

**Hazards:**

Old roofs create obstacles for cart movement.

**Control measures:**

- Ensure cart pathway is clean and free of debris.
- Keep an open workspace to allow at least 2 feet of run before rolling over an obstacle. In a tight space, operators cannot depend on cart momentum to overcome an obstacle.

### Poorly set-up ramp

**Hazards:**

Poorly set-up ramps create obstacles which are ergonomic hazards and can result in slip/trip incidents.

**Control measures:**

- Ramps should be stable with a smooth running slope and landings. Even a 3/4" obstacle could stop a cart especially when the tires are small.

Uneven running slope built with DensDeck and ISO



Loose or unsecured ramp materials create gaps



Uneven bottom landing

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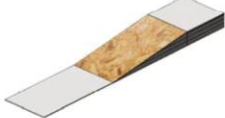

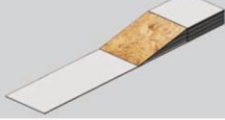

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# 5

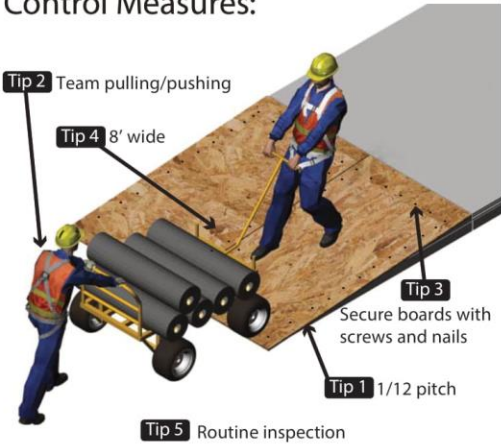
## Properly Set Up Ramps

**Hazard:**

A 1/12 pitch ramp presents little additional risk compared to a flat surface, but a ramp soon becomes a hazard when it reaches 2/12 pitch or higher. A steeper ramp will slow you down. In addition, poorly set up ramps often come with gaps, obstacles, and ridges that could cause slip/trip incidents and strain injuries.

RAMP	SAFETY PERFORMANCE
Flat floor 	8 out of 10 workers can safely handle it with a 500-lb load 
1:12 pitch 	7 out of 10 
2:12 pitch 	3 out of 10 
3:12 pitch 	None 

**Control Measures:**



1. Extend ramp length or lower ramp rise, so the slope is less than 1/12 pitch.
2. When a steeper ramp is inevitable, add one more worker or reduce the cart load. A buddy system can also prevent a struck-by incident when the cart rolls down the ramp.
3. Plan ahead and get sufficient materials to build a ramp. Secure plywood boards with screws or nails to stabilize the ramp. Remove gaps, obstacles, and ridges to make a smooth running slope and landings.
4. Ramp should be at least 8' wide.
5. Check the ramp routinely for debris, wear, or damage to remove slip/trip hazards.

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## APPENDIX D – PLANNING TOOL

# Planning Tool for Material Cart Handling

Instructions:

Following the 4 steps below to expand your safety plan and reduce the risk of manual cart handling.

Check the items listed in each step and follow the training sheets to get the control measures in detail for a specific hazard.



### STEP 1: BIDDING

a. Consider the following questions when bidding on a job (e.g., add the following questions to SSSP request form and go over them with PM/estimator during the Download meeting):

What types of materials will be used on this job? Are there lower weight options (e.g., alternative lightweight or small sized materials)? Find weights of common roofing materials in the table below.

Material Type	Weight	Risk level	
1 bundle of ISO 4' × 8'	up to 350 lbs	LOW	
-----	500 lbs	LOW	safe load
10 sheets of Desdeck 4' × 8'	640~800 lbs	MEDIUM	
10 rolls of Modified Bitumen Roofing	820~1,180 lbs	MEDIUM	
1 pallet of 1/2" Densdeck 4' × 8'	1,900 lbs	HIGH	
1 pallet of 5/8" Densdeck 4' × 8'	2,400 lbs	HIGH	
1 pallet of PermaBase Board	2,800 lbs	HIGH	
1 pallet of Modified Bitumen Roofing	2,500~3,000 lbs	HIGH	

b. What physical restrictions could be on site?



Clearance smaller than 2' on each side



Obstacles bigger than 3/4" in a cart's pathway



An incline steeper than 1:12

c. Is it possible to use mechanical devices for material moving on this job, instead of manual carts?

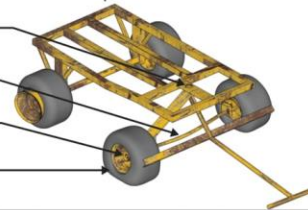
- Forklift
- Motorized cart
- Motorized push-puller
- Others



*If it is only possible to use manual carts, please review the items in "d"*

d. Are carts properly maintained before use? Here is a checklist for cart condition inspection.

- Rusty/loose turntable \_\_\_\_\_
- Warped axle \_\_\_\_\_
- Contaminated/worn-out bearing \_\_\_\_\_
- Tire pressure and deformed wheel \_\_\_\_\_






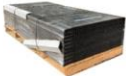






## STEP 2: PRE CONSTRUCTION

- a. During the pre-con meeting and walk-through, revisit the abovementioned questions to:
  - i. Confirm the hazards associated with cart handling
  - ii. Brainstorm control measures
  - iii. Put them in writing. Find a template that you can use for your JHA and SSSP.
- b. In the job hand-off meeting, go over the identified hazards and corresponding control measures. Also, ensure the following questions will be considered by PM, superintendent, and foreman:
  - i. What is the material delivery schedule on this job? What measures can you put in place to prevent delay in material delivery?
  - ii. How many material carts will be needed on the project?
- c. Review training records to check whether foreman and workers need training on how to properly implement the control measures:
  - i. What training will be needed? Who will be responsible? When will it take place?
  - ii. Helpful resources:
    - Animation videos - [Slow and steady wins the safety race!](#) - [Safety is a marathon, not a sprint!](#)
    - Seven Tips for Using Four-Wheel Carts in the Roofing Trade [PDF](#)
    - Toolbox Talk.

## STEP 3: ON THE JOB

- a. Share the plan on material delivery schedule, staging area, and cart pathway with the GC and other contractors in the area to avoid any conflict that could cause ergonomic hazards.
- b. Conduct safety inspection to ensure the control measures are implemented correctly:
  - i. Ramp set-ups
  - ii. Housekeeping
  - iii. Proper body and team pushing/pulling for moving materials. Refer to the chart below to find the suggested team size.

Materials			Flat Surface	Ramp or Space with Constraint
 2 bundles of ISO	 10 rolls of Modified Bitumen Roofing	 10 sheets of Densdeck	 <b>2-person</b>	 <b>3-person</b>
 1 pallet of Perma Board	 1 pallet of Modified Bitumen Roofing	 1 pallet of Densdeck	 <b>3-person</b>	 <b>4-person</b>

## STEP 4: LOOK BACK

- a. At the end of the project, meet with PM and foreman to discuss:
  - i. Whether the control measures helped or did not help to minimize manual materials handling?
  - ii. What equipment, work practices, or actions they would recommend for future projects?