Success factors to large-scale adoption of wearable technology for musculoskeletal disorders (MSDs) prevention: a case study

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Abstract. Wearable technology has been playing an increasingly essential role in the construction domain, especially for safety and health related research. Musculoskeletal disorders (MSDs) are one of the most prevalent health problems among construction workers due to the physical demanding feature of the construction work. To solve this problem, wearable sensing technology has been applied for MSDs prevention. However, the large-scale adoption of wearables has encountered challenges and barriers. This study firstly reviewed recent literature on the factors influencing wearable technology adoption and designed a survey based on the review to further investigate adoption barriers and strategies using our proposed MSDs prevention system as a case study. The results demonstrate that the discomfort and fatigue caused by wearing devices for a long period of time is the main concerns hindering wearable adoption in our case. Construction managers expressed concerns on the indirect costs of implementation and workers expressed their concern on the invasion of privacy. To address these concerns, strategies to promote wearable adoption identified in literature such as worker training and education and providing personalized features were discussed. This study provides insight into the factors contributing to the large-scale adoption of wearable technology for MSDs prevention from the application perspective.

1. Introduction

The advent of wearable technology has provided unprecedented opportunities for construction research. In recent years, wearable technology has been applied in the construction domain to measure kinematic movement, workers' cardiac activity, skin response, muscle engagement, eye movement, brain activity, etc. [1]. The capability of continuously measuring workers' physiological status and detecting potential safety hazards has made wearable technology an invaluable tool, especially for safety and health related research [2].

Safety and health are inherent problems for the construction industry due to it hazardous nature. The U.S. Bureau of Labor Statistics reported a total of 1,008 fatal work injuries from the construction industry in 2020, which ranked at number one among all industries [3]. In addition, even though many projects were shut down during the COVID-19 pandemic, the construction industry still recorded 174,100 total cases of injuries and illnesses in 2020 [4]. The severity of such safety and health issues in the construction industry has gained attention from both practitioners and researchers. To reach the zero-injury goal, extensive research efforts utilizing wearable technology have been made to tackle the safety and health problems in the construction industry.

Of the various safety and health issues, Musculoskeletal disorders (MSDs) is one of the most common ones. Performing construction tasks often requires workers to assume awkward postures. The repetition of awkward postures coupled with long periods of exposure will result in MSDs such as chronic back pains and over-exertion. In the United States, construction related MSDs account for 30% of workplace injuries [5], and construction workers have an 18% higher rate of MSDs compared to all private industries [6]. To solve this problem, wearable technologies have been playing an increasingly essential role.

The research presented in this study is part of an ongoing project aimed at developing a data-driven approach for mitigating the risk of MSDs among construction workers. In our previous study [5], the authors proposed a wearable inertial measurement unit (IMU) sensing system for MSDs prevention and conducted an end-user evaluation among construction workers and managers. The survey results suggest that wearable sensing is a promising approach for collecting motion data for MSDs prevention. However, there are some concerns to its large-scale adoption. This is in accordance with a few other research studies attempting to introduce wearable technology for construction safety and health. [6,7]. Ahn et al. suggested that the adoption of wearable technologies is faced with multiple challenges such as signal artifacts and noise in field measurement, variable standards in assessing personal safety and health risks, user resistance in technology adoption, uncertainty about the return on investment [1]. The IMU sensing system we proposed, albeit cheap and low discomfort, may still encounter problems that may hinder its adoption. Therefore, in this study, the authors attempted to investigate the factors prohibiting the adoption of wearable technology in the construction and propose feasible strategies to speed up the wearable technology intake.

To this end, this paper firstly provides a critical review of the wearable technology application for MSDs prevention. Based on the review, the authors designed a preliminary questionnaire survey to investigate industry practitioners' perception on our prototype IMU-based MSDs prevention system. The results serve as a case study to further understand the adoption barriers and drivers of large-scale wearable technology adoption for MSDs prevention. Then, this paper discusses the adoption strategies and provide recommendations to promote the adoption of wearable technologies for MSDs prevention.

2. Closely Related Work

2.1. Wearable Technology for MSDs Prevention in Construction

In previous research studies, wearable IMU sensors were commonly used for gait and posture monitoring which obtained varying levels of success [8-11]. Albeit useful, the posture monitoring capabilities of some of the commercially available IMU-based wearable devices generally do not cover construction workers' full-body awkward postures [12]. Picerno et al. reviewed wearable inertial sensors for human movement analysis and concluded that, even though IMU-based wearable devices have undergone a rapid transition from use in laboratory-based clinical practice to unsupervised, applied settings, "the successful use of wearable inertial sensing for assessing mobility, motor performance and movement disorders in applied settings will rely on machine learning algorithms for managing the vast amounts of data generated by these sensors for extracting information that is both clinically relevant and interpretable by practitioners. [13]" To better utilize the motion data obtained from IMU sensors for MSDs prevention, machine learning algorithms have been applied to automatically detect awkward postures [5, 11, 14, 15]. In our previous research [5], we developed a wearable sensing system that integrates IMU sensors for motion sensing, a deep neural network (DNN) model for posture recognition, posture-based ergonomics assessment models for MSDs risk assessment, and user interface for risk assessment feedback. The prototype system was tested among workers. The results showed that the proposed system was a promising approach for collecting data from construction workers because it was perceived to cause low level of discomfort and the posture-based MSDs risk assessment information had a high potential for improving the workers' safety awareness.

However, this IMU-based MSDs prevention system may encounter adoption barriers in practice. In general, some of the drawbacks of IMU sensors in application are that wearing multiple IMU sensors could limit workers' motions and obtrude on workers during various construction tasks [16] and wearing IMU sensors often requires indirect forms of attachments such as straps, belts, or other accessories to prevent detachment of sensors from the body when performing a given task [17].

There are other non-intrusive types of wearable devices that have been attempted for MSDs prevention. For example, a couple of recent studies have applied insole pressure sensors for gait/posture monitoring [17, 18]. This type of sensors can be worn inside participants' shoes and minimize intrusion during construction tasks. Antiwi-Afari et al. first introduced this type of sensors to the construction domain in their attempt to detect workers' awkward postures and achieved promising results [19, 20]. Since then, Anwer et al. adopted a fusion of insole sensors and biosensors to investigate the effects of different load carrying techniques on workers' physical status [18]. This type of sensors has the potential for MSDs prevention, but the research is still at early stage.

Another recent development in MSDs prevention is the introduction of wearable robotics/exoskeletons for MSDs prevention [7, 21]. Okpala et al. examined 11 wearable robotics and indicated that these robots could prevent about 60% of construction-related MSDs impacting different body regions and 30–40% of accidents associated with MSDs [6]. They also suggested that the adoption of this type of wearable technology could be problematic as they may cause issues in terms of the ease of use, the ease of learning, and comfort.

2.2. Wearable Technology Adoption Barriers

To accelerate the uptake of wearable technology, a few studies from other domains, like manufacturing and healthcare, have investigated the adoption challenges. Svertoka et al. reviewed the adoption challenges for industrial wearable devices [22]. They categorized the key challenges to adoption into five types, namely 1) data-related security and privacy issues; 2) economic concerns as a result of the high costs of some wearables and costs derived from compatibility issues with other technologies; 3) social resistance to accept new technologies among employees; 4) standard-related issues due to the heterogeneity of some of the wearable devices, which requires either application of the data fusion approach on the hardware level, or seamless integration on the protocol level; and 5) technological issues such as accuracy and connectivity problems. Even though these studies are focusing on industrial wearables, the findings are beneficial for wearable adoption in the construction domain. In the manufacturing domain, Zhang et al. investigated manufacturing workers' perception of using wearable inertial sensors surveying 31 workers who wore wearable inertial sensors for 15 days [23]. They found out that the workers considered the devices as generally comfortable to wear, not distracting, and not burdensome to use. The results suggest that IMU sensors may be suitable for extended use.

In the Architectural, Engineering, and Construction (AEC) industry, Nnaji and Awolusi investigated the critical success factors influencing wearable sensing device implementation [24]. They identified 25 success factors of wearable technology implementation from literature, including ease of use, effectiveness, leadership involvement, project size, etc. They then surveyed 416 practitioners to examine the relative importance and criticality of these success factors. The results suggest that contingencies such as organization type, organization size, technology maturity, organization experience could affect the adoption of wearable technology. However, regardless of the contingency, they concluded that strategies such as educating and training workers, promoting personalized wearables, and conducting detailed and continuous assessments of wearables are key to improve the implementation of wearable technology.

Based on the adoption barriers and adoption success factors identified in the review. We developed a survey to investigate construction workers' perception on our IMU-based MSDs prevention system and used the results as a case study to discuss the factors hindering the large-scale adoption of wearable technology on construction work sites.

3. Research Methodology

This research is directed at investigating the adoption drivers and barriers of large-scale deployment of wearable sensor-based injury prevention system on construction sites. To achieve this goal, a three-step approach was chosen as illustrated in Figure 1.

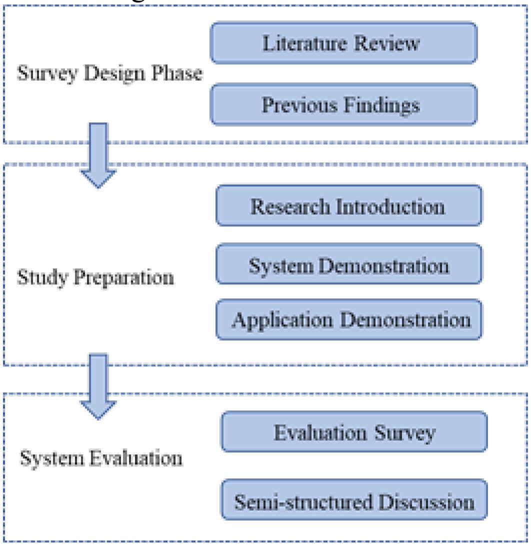

Figure 1. The 3-step research approach.

Firstly, a questionnaire survey was designed based on the review presented in the previous section and findings from our previous work. Three main types of adoption factors including physical factors, cognitive factors, and emotional factors were identified. Workers' perception of the proposed prototype system was evaluated with eleven questions using the five-level Likert scale.

The authors collected data from a construction site on the Pennsylvania State University main campus. Both construction workers and managers were invited to participate in this study. The subjects were given a brief introduction of this research and the proposed IMU sensor prototype workflow and functioning were demonstrated to the subjects in details with both an oral presentation and a video demonstration. The physical sensors were distributed to the participants for closer observation. In the last step, the evaluation survey was distributed to each participant. A brief semi-structured group discussion was conducted to further communicate participants' concerns with the proposed IMU-based MSDs prevention system.

4. Research Methodology

Forty-eight subjects participated in this study, including thirty-four construction workers from fifteen different trades and fourteen construction managers. The survey results are shown in Table 1. The main findings of the study are presented and discussed below.

Table 1. Evaluation survey results.

Category	Adoption Success Factors	Survey Item	Response[a]
Emotional Factors	Privacy	Q1: Invasion of privacy	3.167
	Distraction	Q2: Distraction from work	3.063
Physical Factors	Wearability	Q3: Device adaptable to body shape	2.667*
		Q4: Device weight	2.125*
	Comfort	Q5: Device easy to wear and take off	2.438*
		Q6: Device allowing natural movement	2.375*
		Q7: Device causing fatigue or discomfort	3.521*
	Durability	Q8: Device easy to clean	2.729*

		Q9: Device sturdiness	2.750
		Q10: Device securely attached to body	2.702*
Cognitive Factors	Ease of use	Q11: Device easy to use	2.417*

[a] Unpaired Wilcoxon Test for whether the subjects' response is different from "moderate level (3)" for each item, * 0.05 level of significance.

4.1. Main Concerns for Adoption

4.1.1. Fatigue or Discomfort. The survey results demonstrated that physical factors such as wearability (Q3-4) are not concerns for adoption (response score significantly lower than the moderate level). However, potential fatigue and discomfort (Q7) caused by wearing devices for long period of time is the biggest concern hindering wearable technology adoption for MSDs prevention (highest mean score 3.521 among survey items). This observation is in line with previous literature's statement [16, 17] on the drawbacks of wearing IMU sensors. But the recent development of wearable technology has enabled wearable devices to become smaller in size and has made wearing sensors less obstructive. The sensors in our proposed system are small and easy to wear. Instead, workers' main concerns of fatigue or discomfort may be a result of wearing sensors in a long period of time while performing physically demanding work. To solve this concern, one option is to apply less sensors. Chen et al. proposed a single IMU sensor based real-time walking gait estimation system for construction workers [25]. The data obtained from the single IMU sensor can be augmented through machine learning algorithms. The development in data augmentation can alleviate workers concerns from wearing multiple sensors for a long period of time.

4.1.2. Indirect Costs. Another main concern raised from the semi-structured interview is the indirect cost associated with adopting the wearable device. Even though the direct cost of the sensors were presented to the participants in the study preparation phase, construction managers were still concerned with the indirect costs. The introduction of a new technology will inevitably induce costs in training and require additional human resources to assist implementation. The managers were concerned that "the total cost may not be worth the investment". This concern of return on investment was also observed in Ahn et al. [1]'s review. As Nnaji and Awolusi pointed out, sufficient implementation budget is a successful factor for wearable adoption [24]. To promote the large-scale adoption of wearable-based MSDs prevention approach, practitioners need to understand the cumulative financial benefits of adopting this approach in the long term. As mentioned in the introduction section, MSDs are one of the most common health problems among construction workers. According to Middlesworth, the direct costs of MSDs are $20 billion a year and the indirect costs (lost productivity, product defects, etc.) of an MSDs case can be up to five times the direct costs [26]. As Ahn et al. suggested, the financial benefits estimated from one or two business cases would foreseeably promote decision makers in adopting more wearables for MSDs prevention [1].

4.1.3. Privacy Issues. In previous studies [1, 27], perceived privacy risk was identified as a main factor influencing wearable technology adoption among construction workers. In our survey responses, privacy is the second highest concerns in terms of wearable adoption. Moreover, during the semi-structured discussion, workers were questioning who will have access to the data and how secure the data would be. One worker even commented that, "Wearing such devices would make me feel watched." However, the problem might not be so severe for MSDs prevention. For our proposed posture monitoring system, the mean response in terms of privacy concerns (Q1) is not significantly higher than the moderate level. This might be because our proposed system only records posture data from the workers, which may not be invading workers' privacy as much as other types of wearables such as biosensors. To help alleviate the privacy concerns, the scope of data collection and the data sharing scheme must be clearly communicated with the workers.

4.2. Adoption Strategies

4.2.1. Worker Education and Training. In our study, we observed the effect of education and training on worker's acceptance of the proposed wearable system. During the study preparation phase and the semi-structured discussion, both managers and construction workers showed great interest in learning more about the proposed system and how wearable sensors work for injury prevention in general. Several participants explained that their concerns of the wearable sensors stem from their lack of understanding on how the technology works. Though the oral presentation and video explanation, most participants comprehended the purpose of the proposed wearable system and learnt how it works. Thus, in the survey, the participants scored ease of use (Q11) as one of the lowest concerns in terms of wearable adoption. In fact, Nnaji and Awolusi identified that worker education and training is one of the key strategies to improve the implementation of wearables [24]. Education and training could help workers understand the effectiveness of the wearables and become more willing to adopt the technology. In addition, through education and training, workers could avoid the indirect costs induced by the improper use of the devices.

4.2.2. Providing Personalized Features In the semi-structured discussion, a couple of participants expressed that they are more prone to adopt personalized wearable devices than "one-size fits all". In terms of physical aspect, a more personalized fit would help avoid discomfort and fatigue issues caused by wearing devices in a long period of time, which is a major concern as highlighted in the previous section. Moreover, participants suggested their injury history should be considered in the MSDs prevention system. On one hand, the sensors should avoid being attached to body parts that sustained previous injuries. On the other hand, past injuries are major factors to consider for MSDs prevention. The injury history could be used to generate personalized feedback to participants. In addition, Nnaji and Awolusi suggested that personalized wearables could differentiate sensitive physiological information to workers and non-sensitive information to managers [24], which may help address the data privacy concerns.

5. Conclusions and Further Research

This study served as part of an ongoing project aimed at developing a data-driven approach for mitigating the risk of MSDs among construction workers. The proposed IMU-sensor based MSDs prevention system is faced with the same problem of large-scale adoption as many of the wearable technologies developed in the research domain are. To investigate the barriers of large-scale adoption of wearable devices for MSDs prevention, a survey was distributed among 48 construction practitioners. The results revealed that the potential discomfort and fatigue caused by wearing devices for a long period of time is the main concerns hindering wearable adoption. Other noticeable concerns include indirect costs of implementation and invasion of privacy. To solve these problems, strategies such as worker training and education and providing personalized features were discussed. The survey results are only preliminary evidence on the potential of the proposed MSDs prevention system.

To further investigate the large-scale adoption barriers of wearables, the authors will conduct experiments where workers wear the proposed device for longer periods of time on construction sites. More factors influencing the wearable sensing device adoption would be investigated.

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