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A simulation and visualization-based framework of labor efficiency and safety analysis for prevention through design and planning

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ABSTRACT

Considering the physically demanding nature of manual tasks in the construction industry, an effective approach to mitigating ergonomic risks is to prevent the unsafe working conditions proactively during design and planning, also known as Prevention through Design (PtD). However, there is a lack of approaches for identifying the potential ergonomic risks of a proposed design that can effectively address designers' lack of familiarity with ergonomic risks and understanding of the PtD concept and its implementation. Furthermore, it is difficult to evaluate the impact of ergonomic interventions on productivity and vice versa using available tools. Thus, an integrated approach to PtD is proposed by developing a comprehensive framework that uses simulation modeling, coupled with Predetermined Motion Time Systems (PMTS) and ergonomic and biomechanical assessment, as well as workplace visualization, in order to incorporate both productivity and safety analysis into the design process. The results of implementing the proposed approach indicate its effectiveness in achieving optimum designs in terms of efficiency and safety by evaluating different scenarios of carrying out construction manual operations. The proposed framework also enables evaluating the relationship between safety and productivity from a physical perspective.

1. Introduction

The construction industry is identified as one of the most unsafe industries around the world [1]. Statistics indicate that the construction industry accounts for an average of around 20% of all workplace fatalities in Canada [2] as well as the US [3]. Considering the high rate of fatalities and injuries in the construction industry, one of the most effective approaches to improving the safety of construction workplaces is preventing these injuries proactively from the early design stage [4]. Previous studies have linked 42% of fatalities to the design for safety concept [5]. Accordingly, the Prevention through Design (PtD) initiative was implemented by the National Institute for Occupational Safety and Health (NIOSH) which aims to identify workplace hazards and risks during design to prevent and reduce injuries, illnesses and fatalities [6].

The concept of PtD can be highly effective in mitigating the occupational risks leading to Work-related Musculoskeletal Disorders (WMSDs) [7], which are the leading type of occupational injuries [8]. WMSDs account for about 34% of nonfatal injuries resulting in days away from work in the construction industry in the US [9] and for nearly half of all disabling injury claims in Canada [10]. Despite the prevalence of WMSDs in the construction industry and the potential of PtD-based approaches to mitigate WMSDs, less attention has been given to integrating ergonomic and biomechanical analysis into the design process, due to the lack of tools and approaches for identifying and evaluating the potential ergonomic risks of a proposed design that can effectively address designers' lack of familiarity with ergonomic risks [4,11,12] and understanding of the PtD concept and its implementation [1,13]. It is difficult to assess the biomechanics of a task which is not yet observable and without the existence of a physical workplace with the tools available in the construction industry. As the literature on PtD has been slow in addressing the technical principles of PtD [14], more tools and approaches are required to enable designers to effectively incorporate ergonomic evaluations into the workplace and process design [15]. Furthermore, safety performance is highly correlated to productivity [16] and ergonomic behavior in particular results primarily from physical conditions (e.g., human postures, repetitive movements, duration, forceful exertion) determined by production tasks (e.g., production rate, job procedures, and workplace layout) [17,18]. However, current approaches used in construction lack the concurrent integration of both production and safety into workplace and operation design and do not fully consider the high association

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between the two, especially in terms of ergonomic risks.

Thus, due to the lack of effective tools for incorporating ergonomic assessment into the design phase of construction operations, and the potentially high impact of actions of workplace and production designers on biomechanical exposure [19], this study explores an integrated approach to PtD that incorporates both productivity and safety into the design process. The scope of these PtD interventions includes design of workplaces (e.g., jobsite layout), operations (e.g., sequence of tasks), equipment and tools (e.g., height of workbench), material (e.g., shape and size of concrete blocks), human actions (e.g., body posture) and etc. The trade-off between ergonomic risk and the duration of manual activities, as the main element of productivity of manual operations, is also examined in this study. The proposed micro-level motion simulation approach combines discrete event simulation modeling of manual operations with ergonomic and biomechanical modeling of motions, which provides an effective means of evaluating various human motions potentially taking place in jobsites. Predetermined Motion Time Systems (PMTS) are integrated into simulation which enables calculating reliable job efficiency, experimenting with different scenarios of manual operations, and evaluating each scenario in terms of safety and productivity. Visualization of the workplace is also used in order to enable accurate and convenient extraction of the required inputs, facilitate the communication and execution of the design, assist with managerial decision-making, and promote training of workers and personnel. The proposed framework aims to enable an effective implementation of the safety in design concept in conjunction with efficiency analysis, in a simplified and user-friendly manner, which can be used by designers, without requiring extensive prior knowledge about the technical details of the different components of the system.

2. Background

The concept of design for safety, defined as considering construction safety during the design of a project [5], is accepted as a critical intervention to enhancing the safety of construction workers [20]. The concept dates back to 1985, where the International Labor Office (ILO) acknowledged the need for designers to consider construction safety in workplace and operation design [21]. The need for such intervention has been increasingly recognized since then [22]. For example, 60% of fatal accidents in the construction industry were found to be the results of shortcomings in early design and organization of work [23]. Although many studies have tried to apply the concept of design for safety, which has recently led to the PtD initiative, in different aspects of construction [24–26], not many studies have focused on incorporating principles of ergonomic safety into construction workplace design. Some researchers in the construction industry have worked on adapting ergonomic analysis for improving worker safety and preventing injuries using different approaches such as motion sensing and tracking [27–31], assessment tools [32], and participatory ergonomics [33,34]. Despite the effectiveness of the previous studies in evaluating ergonomic risks, more research is required to investigate the correlation between ergonomic safety and productivity of operations from a design perspective, which is critical for effective implementation of ergonomic considerations in PtD and taking into account the impact of ergonomic interventions on efficiency and vice versa.

Previous research on the correlation between construction productivity and safety has been indecisive in articulating the correlation [16]. On one hand, some studies have indicated a positive correlation between safety and productivity [35–37]. For example, Hinze [38] theorized the Distraction Theory, which asserts that a worker will have higher efficiency if the distractions of a known hazard are minimum and the efficiency is low when there is a high level of focus on the distractions posed by the hazards. On the other hand, some studies have also found out a negative correlation between safety and productivity [39–41]. For instance, Evans et al. [42] investigated workers' perception of productivity climate and concluded that workers who perceived a stronger climate for productivity reported higher number of accidents. They conducted 526 surveys where more than half of the participants responded that there is a negative association between productivity and safety as focusing on efficiency increases risky behavior. In terms of ergonomic safety, although improving the working conditions that result in less ergonomic risks can lead to improved efficiency due to higher level of comfort, some safety interventions suggested by ergonomists and safety practitioners, such as slower pace of work and more rest allowances, can also result in lower productivity [19]. Also, production demand explicitly affects safety performance as generating work pressure that gives rise to hazardous situations and adversely affects ergonomic behavior, which combine to increase exposure to accidents [17,43,44]. Thus, there is a need for tools and approaches that not only incorporate ergonomic considerations into the design phase to enable effective and convenient implementation of PtD, but also enable examining the impact of modifications in production and ergonomic design on both safety and productivity. Therefore, this study aims to examine the integration of ergonomics and efficiency analysis into the design process and provide a framework for planning efficient and safe operations concurrently.

3. Research framework

In order to enable concurrent analysis of the safety and efficiency of operations, this research suggests a micro-level motion modeling and simulation approach. The proposed framework is shown in Fig. 1. A proposed design is first visualized in order to enable reliable measurement and observation of the required inputs for the simulation, in addition to enabling effective communication and implementation of the design once it is finalized. Discrete event simulation modeling is then used to model the manual operations in a motion level. PMTSs in conjunction with ergonomic assessment methods are incorporated into the modeling elements of the developed simulation template, which enables inputting data regarding the method of carrying out the manual task and its attributes (e.g., walking distance, difficulty of grasping an object) as well as the physical exertion on the body (e.g., weight of object, position of arms). The system is developed such that any designer can conveniently model manual operations, even without detailed knowledge about the mechanics of PMTSs and ergonomic evaluation methods, using simple design data (e.g., location of material, shape of equipment, job sequence). The design is then evaluated in terms of efficiency and safety and is modified to examine the impact of the various attributes and compare different designs and scenarios. Biomechanical analysis is also used for the ergonomic safety evaluation in order to provide a more accurate and reliable analysis of the ergonomic risks and facilitate achieving safe motions. Among the different scenarios, the optimal design in terms of both safety and efficiency is selected and the visualization of the design is used for perception, communication, and implementation of the design. This study focuses on the integration of the efficiency and safety analysis through simulation and visualization, and builds upon previous studies and existing literature for some components of the comprehensive framework.

3.1. Workplace visualization

Obtaining reliable data regarding the physical attributes of a jobsite is essential for effective analysis of manual operations, as the dimensions and geometry of different elements of the workplace has a major impact on both the efficiency and safety of a manual task. Acquiring these inputs in case of existing workplaces requires significant amount of time and effort, and in case of non-existing workplaces which are still in the design stage, it is difficult to carry out the analysis without any reference, as it is challenging to perceive the design of a non-existing workplace and assess different possible scenarios. Thus, a visual representation of the workplace can facilitate extracting the required inputs for analyzing the design and also improves the reliability of the