Automation in Construction 95 (2018) 72–85

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

An integrated ergonomics framework for evaluation and design of construction operations

Alireza Golabchi[a], Xingzhou Guo[a], Meiyin Liu[b], SangUk Han[c,*], SangHyun Lee[b], Simaan AbouRizk[d]

[a] Dept. of Civil and Environmental Engineering, Univ. of Alberta, 9211 116th St., Edmonton, AB T6G 1H9, Canada
[b] Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward St., Suite 2340 G.G. Brown Building, Ann Arbor, MI 48109, USA
[c] Dept. of Civil and Environmental Engineering, Hanyang Univ., 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea
[d] Dept. of Civil and Environmental Engineering, Univ. of Alberta, 5-080 Markin CNRL Natural Resources Engineering Facility, Edmonton, Alberta T6G 2W2, Canada

ARTICLE INFO

Keywords:
Ergonomics
Sensing
Simulation
Visualization
Action recognition
Point cloud generation

ABSTRACT

Labor is one of the most critical resources in the construction industry due to its impact on the productivity, safety, quality, and cost of a construction project. Ergonomic assessment, as a tool and method for analyzing human activities and their interactions with the surrounding environment, is thus crucial for designing operations and workplaces that achieve both high productivity and safety. In construction, however, the constantly changing work environments and laborious tasks cause traditional approaches to ergonomic analysis, such as manual observations and measurements, to require substantial time and effort to yield reliable results. Therefore, to simplify and automate the assessment processes, this study explores the adaptation and integration of various existing methods for data collection, analysis, and output representation potentially available for comprehensive ergonomic analysis. The proposed framework integrates sensing for data collection, action recognition and simulation modeling for productivity and ergonomic analysis, and point cloud model generation and human motion animation for output visualization. The proposed framework is demonstrated through a case study using data from an off-site construction job site. The results indicate that integrating the various techniques can facilitate the assessment of manual operations and thereby enhance the implementation of ergonomic practices during a construction project by reducing the time, effort, and complexity required to apply the techniques.

1. Introduction

Since the construction industry is labor-intensive, worker activities can significantly affect the success of construction operations. Labor is one of the most crucial resources [1,2] and has the highest direct impact on the outcomes of a project, including time, cost, and quality [3]. Labor can account for nearly half the overall costs of a project [4] and is highly associated with construction productivity, which is one of the most important and frequently used performance indicators in the industry [5]. Furthermore, labor operations in construction involve physically demanding motions and tasks that frequently expose workers to risk in their working environments, leading to a rate of injuries and fatalities that are among the highest of any industry [6–8].

As an approach to human-oriented work design, ergonomics is the study of human interactions with the surrounding environment with the intent to improve human safety and well-being, as well as productivity [9–12]. An effective and comprehensive ergonomic analysis involves evaluating ongoing operations and proposing modifications and new designs that fit jobs and work environments to worker capabilities and limitations. Accordingly, the implementation of ergonomic principles can contribute to the success of a construction project by providing workers with comfortable working environments in which work procedures and tools are designed for safe and productive use. However, conducting an ergonomic analysis often requires extensive time and effort to yield reliable results as the data collection and evaluation involve human observations and measurements. This is particularly true in the dynamic environment of construction job sites, which involve many physically demanding manual tasks that create vast amounts of data to collect, analyze, and represent [13,14]. Furthermore, the variety of tasks and postures required of workers necessitates methods for

* Corresponding author.
E-mail addresses: alireza1@ualberta.ca (A. Golabchi), xingzhou@ualberta.ca (X. Guo), meiyin@umich.edu (M. Liu), sanguk@hanyang.ac.kr (S. Han), shdpm@umich.edu (S. Lee), abourizk@ualberta.ca (S. AbouRizk).

https://doi.org/10.1016/j.autcon.2018.08.003
Received 23 February 2018; Received in revised form 26 July 2018; Accepted 10 August 2018
0926-5805/

collecting and analyzing data that can address human error; the resulting low reliability of the analysis inputs and outputs make completing a meaningful ergonomic evaluation difficult [15–17]. Reliable and detailed visual representations of the analysis outputs can greatly improve the implementation of interventions or new workplace designs. Accordingly, the development and use of methods to automate, simplify, and increase the accuracy of data collection, analysis, and output representation could enable effective and comprehensive ergonomic evaluations. Furthermore, integrating such methods into an overall framework would potentially enhance the implementation of ergonomic practices at actual construction job sites by minimizing the need for experts, decreasing the time and effort required for analysis, and reducing the complexity of applying the various methods.

Therefore, this study proposes a framework to integrate different methods for evaluating and designing manual construction operations to achieve a more unified and reliable ergonomic analysis. The framework and its modules are presented with a focus on linking the different components together. A manual operation at an actual job site is then used to implement the proposed approach and evaluate its effectiveness.

2. Background

2.1. Limitations of manual observation–based ergonomic analyses

A complete ergonomic analysis involves evaluating the motions and postures of workers and the physical attributes of a job site to assess current work conditions and propose new designs for manual operations (e.g., safe motions) and workplaces (e.g., workstation dimensions). To carry out such an assessment, an ergonomist generally needs to complete three stages: (i) data collection, (ii) data analysis, and (iii) interpretation and representation of results.

Prior to data collection, the ergonomist has to plan the analysis process and define the strategy based on the particular conditions of the work being analyzed. After planning the procedure, which enables identifying the methods to be implemented and the required inputs for each, relevant data is gathered, traditionally, through observing the subjects (e.g., anthropometry, posture), their motions while working (e.g., leaning, bending), and the attributes of the work environment (e.g., workbench, tools, equipment). The inputs of an ergonomic assessment thus include various types of data, such as the distance between a worker and a necessary tool or material, or the joint angles between different body parts, which are often challenging to observe simultaneously. Typically, an ergonomist either visits a job site to collect the required data in real-time or uses video recordings to extract the inputs later [15]. In both cases, such a procedure results in subjectivity in the collected inputs introduced by the ergonomist's personal judgment [16]. Although this traditional approach can work effectively in static workplaces, such as offices and manufacturing assembly lines, it can produce unreliable data at construction job sites because of the variety of manual tasks performed, complexity of exposures, and constantly changing work environment [17,18].

After data collection is complete, the ergonomist uses the gathered data to conduct an ergonomic evaluation using tools such as ergonomic assessment checklists (e.g., RULA [19], ROSA [20]) and time and motion studies (e.g., MTM [21], MOST [22]). To complete this step, the ergonomist inputs the data into the tools, which use a set of predefined rules to produce the output of the analysis. For example, inputting a worker's posture (i.e., joint angles) along with the frequency and duration of exposure allows posture-based tools to report on the level of ergonomic risk associated with a task. Also, using inputs that describe working conditions (e.g., walking distance, motions involved), time and motion systems (e.g., predetermined motion time systems) provide the standard duration for a task [23]. However, similar to the challenges presented to data collection, manual analysis of construction tasks can be inefficient since job sites and the motions required change every day.

Following data analysis, the ergonomist interprets and represents the gathered data and analysis results to illustrate how any modifications should be implemented and address any discovered risks. Traditionally, this involves reports that reflect the ergonomist's conclusions from the analysis and state any modifications suggested by the outputs from the checklists and tools used. Typically, those reports include only whether the level of ergonomic risk associated with a task is acceptable, moderate, or unacceptable based on the inputs provided. Such reports are thus limited data representations that do not allow re-evaluation of the proposed changes and designs because of the difficulty of assessing a non-observable task on a job site that does not yet exist [24]. Furthermore, the traditional report-based approach does not offer managers a tool for practical decision-making, nor does it provide an effective means to accurately implement the proposed modifications or train the personnel involved. This approach also makes it difficult to effectively assess other ergonomic variables (e.g., clearance, vision) when modifying the design of a workplace.

Thus, the three stages of a thorough ergonomic analysis could be improved by adapting and integrating existing methods through automation to both enhance different aspects of the analysis and connect them to provide a more reliable and simplified assessment. The different stages of an evaluation, including data acquisition through sensing, productivity and safety analysis of the obtained data, and representation of the results through visualization, are shown in Table 1. For each stage, the research areas that could be beneficial for evaluation of manual operations and workplace design are identified as components of the framework, and both the input used for each component and its output are shown. The inputs and outputs show the

Table 1
Research areas, inputs, and outputs for different stages of evaluation and design of manual operations.

Stage	Research area	Input	Output	Example references in research area
Data acquisition (sensing)	Action recognition	Video/sensor recordings	Type and sequence of actions	Akhavian and Behzadan [25], Cheng et al. [26], Joshua and Varghese [27]
	Motion capture	Worker motion recordings	Worker motion-capture data	Han and Lee [28], Starbuck et al. [29], Ray and Teizer [30]
	3D reconstruction	Photo/video of job site	As-is point cloud model	Rashidi et al. [31], Fathi and Brilakis [32], Guo et al. [33]
Analysis	Simulation modeling	Action recognition	Operation efficiency Motion generation	Seo et al. [34], Golabchi et al. [23] Golabchi et al. [13], Golabchi et al. [35]
	Biomechanical analysis	Motion capture	Level of safety	Seo et al. [36], Mehta and Agnew [37], Golabchi et al. [38]
Representation (visualization)	Motion generation	Simulation modeling	Worker motions	Wei et al. [39], Taylor et al. [40], Golabchi et al. [41]
	Path planning	Start and end location of motion	Animation of worker motions	Yao et al. [42], Wu et al. [43], Pettré et al. [44]
	Visualization	3D reconstruction Motion generation	Complete virtual model	Al-Hussein et al. [45], Budziszewski et al. [46], Golabchi et al. [38]