Digital Twin Approach for the Ergonomic Evaluation of Vertical Formwork Operations in Construction

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Abstract –

Construction formwork activities are physically demanding and repetitive, increasing the risk of work-related musculoskeletal disorders. This study proposed a digital twin approach to evaluate the ergonomic risks associated with vertical formwork operations using steel formwork systems in Indian construction projects. The on-site observation captured the workers' postures, allowing for more reproducible and thorough evaluations. The researchers selected the significant postures, and the real scenario was replicated in a virtual environment and performed a simulation to evaluate the ergonomic risks involved in the tasks. The findings indicated that the workers were at high risk of developing musculoskeletal disorders in the trunk, neck, wrist, and arm during formwork operations which could result in long-lasting harm to the workers. The recommendations were provided based on the study findings, including changes in methods to avoid and reduce the signs of musculoskeletal disorder risk caused by the original operations. The study findings show how digital twins could be used to evaluate ergonomic risks associated with construction activities.

Keywords –

Digital twin; Vertical formwork; Construction workers; Health and safety

1 Introduction

Work-related musculoskeletal disorders (WMSDs) contribute to non-fatal occupational injuries in the construction industry [1]. Construction workers frequently suffer from WMSDs such as back pain, carpal tunnel syndrome, tendonitis, and sprains [2] due to physically demanding construction tasks involving prolonged awkward static/repetitive postures, long working hours, forceful exertions, and whole-body vibration [3]. Statistics reported that 41.2 out of every 10,000 employees experience WMSDs, which causes them to miss 12 job site work days in the U.S. [4]. Similar cases were recorded in Canada, indicating that 41.9% of all approved lost-time claims were attributed to WMSDs in the construction industry in 2008 [5]. In addition to causing work absenteeism, these WMDs could also result in permanent impairment [6] and place a significant financial strain on the construction industry owing to lost production and higher workers' compensation costs [7]. Workers at construction workplaces perform specialized tasks, including formwork and roofing, that require physical demands, thus overexerting various body parts. Prolonged overexertion's most common side effects include pain, sprains, strains, and discomfort [8].

Determining the workers' postures and workloads is the first step in reducing their negative influence. Generally, manual observations are used for this, and the data are analyzed quantitatively using ergonomic scales. However, this approach is time-consuming [9] and subjective to deliver accurate evaluations [10]. To overcome these challenges, developing measuring tools has become a priority in the era of Construction 4.0, seeking effective processes. For instance, Yan et al. [11] detect rebar workers' postures using Inertial Measurement Unit (IMU)-based wearable personal protection equipment (PPE) and alerts them about the risk involved with their actions. Similarly, several researchers (e.g., [12]) examined workload using biomechanical assessment tools). Although these methods illustrate the concept, they need the worker to have several sensors attached to their bodies, which may be physically uncomfortable and irritating and have a negative impact on productivity [9].

This study proposed a Digital Twin (DT) approach to evaluate ergonomic risks associated with construction activities, given the limitations of these methods. Kaur et al. [13] define DT as creating a digital replica of a physical object. It offers real-time monitoring, analyzing, simulating, optimizing, and forecasting throughout the lifecycle [14]. Data duplication and information silos can be avoided due to DT application [15]. From occupational health and safety perspective, DT is a virtual representation of the workplace, activities, and other elements used to forecast hazardous areas by simulating [16]. Wanasinghe et al. [17] reported that risks related to health and safety were reduced by optimizing offshore operations through DT in the oil and gas industry. Similarly, Ogunseiju et al. [8] proposed a DT framework to create awareness among carpenters regarding the ergonomic risks involved in their working postures.

Construction involves a wide variety of activities that require physical demands; hence, evaluating the ergonomic risks involved is necessary to prevent or reduce WMSDs. Compared to other construction activities, vertical formwork operations require a lot of physical demand [6] and have a chance of developing a high risk of WMSDs [19]. Labors and carpenters must carry large weights and squats to perform formwork operations, putting them at significant risk of WMSDs [20]. Formwork workers most frequently sustain low back, shoulder, hand, and wrist injuries and have a high prevalence of "sprains and strains" [21]. Numerous types of research have been undertaken on the causes and preventive measures of WMSDs in construction activities. However, only limited studies (e.g., [19]) reported the risk of WMSDs in formwork operations, especially traditional formwork.

The current study evaluated the ergonomic risks involved in vertical formwork operations while using steel formwork systems in Indian construction through the DT approach. First, a site observation was performed to understand the worker's nature of the job to understand how workers are associated with formwork activities. Second, video cameras were used to capture the working postures of workers involved in formwork operations. The researchers selected significant postures and created digital models for each working posture. Next, a simulation was performed to evaluate the ergonomic risks involved in the tasks. The proposed approach is significant from both a practical and theoretical perspective. Specifically, due to visualized results, construction workers and managers will benefit from an intuitive awareness of ergonomic risks.

2 Background

In 2002, Michael Grieves' presentation on " Product Lifecycle Management" later became "DT" [22]. According to Grieves and Vickers [23], DT is a collection of virtual information models intended to completely represent an existing physical product. The basic framework of DT is illustrated in Figure 1, which involves mapping the virtual worker to the actual worker through the interchange of data and information. DT generally consists of the physical element, its virtual model, and the information that flows between these physical elements and the virtual model [8]. The National Aeronautics and Space Administration (NASA) applied the concept of DT for the first time in 2010 on the Apollo program to enable mirroring or twinning of the state of the real spacecraft during the mission [14]. Since then, many researchers have defined DT. For example, Tao et al. [24] stated that DT consists of a physical product, a virtual product, and connected data that connects the virtual and physical products.

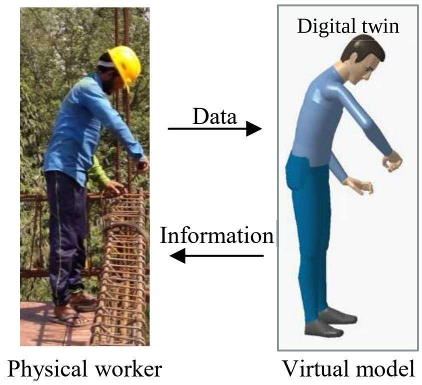

Figure 1. DT model – adaptation of Grieves model [23]

In the past decade, industry interest in DT has grown due to the rapid advancements in emerging technologies. This technology has been mostly adopted in healthcare, manufacturing, and aviation. Particularly in industries like manufacturing, DT technology has advanced significantly. For instance, Zhuang et al. [25] introduced a supervision system based on DT for product assembly shop floors. The findings indicated that by connecting the actual physical assembly with the digital representation, the real-time data capture of the assembly shop floors was able to provide smart manufacturing. The DT could identify the causes of product defects and analyze manufacturing bottlenecks [26]. In healthcare, the individuals' digital representation, including personal information like emotional status, activity data, and health data, may help understand one's well-being and factory working conditions. This can result in upskilling and the greatest production performance through ultrarealistic training programs, improving employees' physical and psychological wellness [27]. In the aviation sector, to secure and monitor data while producing aircraft components, Mandolla et al. [28] merged digital twin and 3D printing.

With the increased interest in DT, researchers in the construction domain explored the potential of DT and discussed how the technology might be used to enhance productivity [29]. Researchers further stated that DT optimizes asset performance by monitoring and diagnosing the asset's condition using simulations and historical data [30]. Although the definitions of Building Information Modeling (BIM) and DT appear similar, construction researchers have drawn attention to the differences between the two concepts. BIM and DT differ in the technology, purpose, and stages of the project life cycle [31]. Volk et al. [32] stated that BIM can be used for constructability analysis, site safety management, and clash detection and does not function as real-time data. However, Khajavi et al. [31] claimed that to create a real-time view, extracted data from BIM could be an essential component to creating the DT of a building. Recently, Opoku et al. [33] argued that the DT primarily focuses on the operation phase, where BIM is mainly applied in the design and planning stages. With the potential of real-time monitoring, a DT-driven framework was proposed by Kan and Anumba [34] to improve workforce health and safety.

In summary, DT technology is used in various industries, including construction. Few studies have focused on the applications of DT for construction site safety; however, there is limited research on the application of DT for ergonomic evaluation for construction activities [8,20]. This study aimed to propose a DT-based approach for the ergonomic assessment of vertical formwork operations focusing on improving the health and well-being of construction workers.

3 Methodology

Several observational methods enable researchers to record and assess WMSD risk based on worker postures, and observation causes less interruption to worker task performance [19]. Therefore, an on-site observation was conducted to achieve research objectives. Manual observation or video recordings can be a basis for observational methods [35]. The present study used manual and video recordings to collect field data to allow for more reproducible and thorough evaluations. The study was performed on commercial construction projects in northeast India. At the time of the study, the workers at construction sites were associated with vertical formwork operations (panel assembly and panel erection) using steel formwork systems. The worker's task was to assemble formwork panels and lift the assembled panels manually (see Figure 2) to the place for erection.

Figure 2. Workers lifting assembled panels to erect

The workers then erect the panels around the rebar and lock them with bolts and nuts. Figure 3 shows the workers erecting formwork panels around the rebar. The weight of the panel (108 kilograms) and panel dimensions were gathered from site supervisors. Researchers observed that workers mostly use their upper body and were involved in the repetitive nature of the work and awkward postures. Once the manual observation was performed, a video camera was used to capture the working cycle postures while performing the worker's routine tasks.

Figure 3. Workers erecting formwork panels around the rebar

The recorded videos were transferred to the computer over USB following the observational methods. Selected videos were divided into segments to select the significant postures for the analysis, as shown in Figures 4 and 5. The reason behind choosing these postures was that workers were repeatedly using the same postures while lifting the formwork panels throughout their tasks cycle. The literature (e.g., [20]) pointed out that the workers involved in formwork operations mostly use their upper body and only minimally involve their legs.

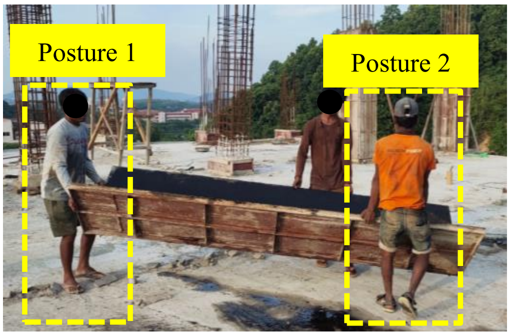

Figure 4. Panel lifting

The selected postures were transferred to CATIA V5 software to perform simulations and risk assessment.

CATIA V5 is a digital human modelling (DHM) software with a module for simulating individuals, enabling precise manual work modeling [9]. CATIA V5 replicates the real working environment of the worker's task (see Figure 6). The simulation was performed based on four following essential steps: (1) setting up a virtual environment that replicates the same workplace; (2) creating a DHM for actual workers; (3) data implementation and operations refining when necessary (e.g., grasping an object, lifting, handling, etc.); and (4) run the simulation. The ergonomics evaluation was carried out after the simulation had been completed.

Figure 5. Panel erection

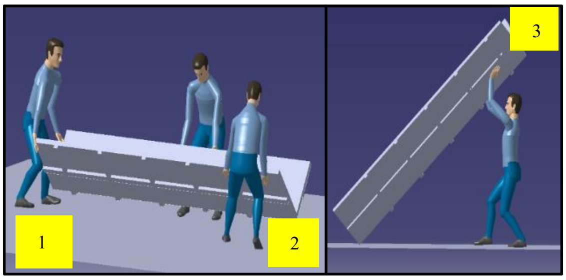

Figure 6. The virtual working environment of worker's tasks for postures 1-3

As previously mentioned, during formwork operations, workers mostly use their upper body parts, and hence, RULA (Rapid Upper Limb Assessment) is a suitable method for ergonomics study under the scenario depicted [5]. RULA, based on the work of McAtamne and Corlett [36], is integrated with the DHM module of the CATIA V5 software. The postural and biomechanical load requirements of workers' tasks/demands on the upper extremities, trunk, and neck are considered by the RULA ergonomic assessment tool. The final RULA score represents the WMSD risks for the evaluated job task. The RULA score ranges between 1 and 7, and the cut points and descriptions of the RULA level of WMSDs are as follows [37]: score 1-2 – acceptable posture; score 3-4 – further investigation and change may be needed; score 5-6 – further investigation and change soon; and score 7 – investigate and implement change. It should be noted that the Human Model in CATIA V5 does not display which body parts are less comfortable. Figure 7 illustrates the methodological framework of the present study.

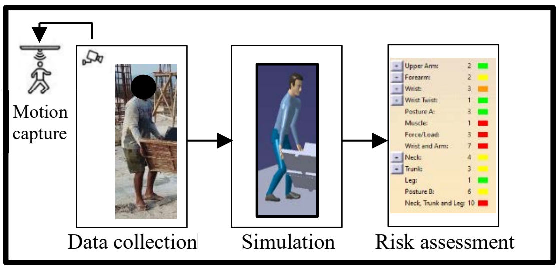

Figure 7. Overview of research methodology

4 Results and discussion

The overall RULA score for three postures is summarized in Table 1. The studies revealed that the postures were awkward, and the workers were at high risk of developing WMSDs. It can be seen in Figure 4 that the workers lifting panels stretch their upper body, causing muscle fatigue. The RULA analysis for both postures 1 and 2 are shown in Figures 8 and 9. It was observed from both these figures that the upper body parts, such as the wrist, arm, neck, and trunk, show red color, indicating that these postures experience muscle fatigue while lifting panels.

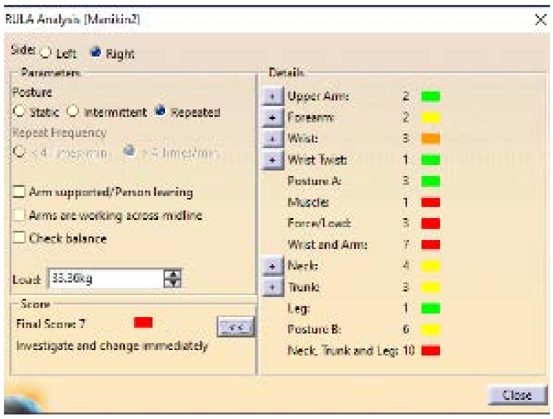

Figure 8. RULA score for posture 1

Similarly, the worker erecting panels had to stretch the upper parts of the body (see Figure 5). Figure 10 depicts the RULA analysis of posture 3, and the upper body parts, including the upper arm and wrist, exhibit a red color, which denotes that these body parts become fatigued from erecting panels.

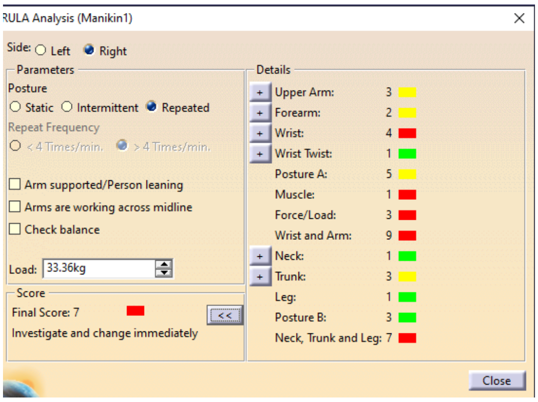

Figure 9. RULA score for posture 2

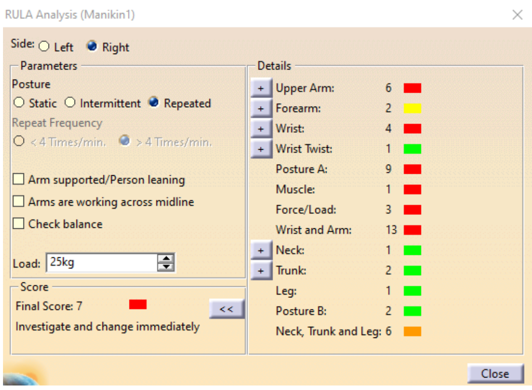

Figure 10. RULA score for posture 3

The overall RULA score is 7 for all the postures indicating that the postures could cause musculoskeletal disorders if it lasts for long time and hence, investigation and changes must be undertaken immediately for the outcomes obtained [30].

The neck, trunk, wrist, and arm are revealed to be the areas with the most risk in all the postures. The analysis made it clear that the workers were at a high risk of developing WMSDs when they repeatedly performed panel erection and lifting tasks.

Table 1 RULA score for vertical formwork operations

Posture	Score	Risk level	Action to be taken
1, 2 and 3	7	High	Investigate and change immediately

Formwork system manufacturers should introduce ergonomic interventions to prevent WMSDs. Based on the study findings and resources provided by National Institute for Occupational Safety and Health (NIOSH; 38) and Gambatese and Jin [19], the recommendations below may aid in preventing WMSDs that occur during formwork operations.

- Construction organizations should try to minimize lifting and overreaching requirements for their formwork workers by providing lifting devices, including hoists and hand tools.
- To reduce wrist-related disorders, formwork system manufacturers should provide handles or grips into formwork components without unnecessarily increasing the weight.
- Manufacturers should design ergonomic tools to eliminate the need for form workers to outreach and bend. For instance, extension clamps could be included in tools to allow users to do these activities while standing up, without elevating their shoulders, and with minimal bending.
- To avoid repetitive activities for an extended period, rotate workers among various tasks during a shift. The research team observed on the job site that employers frequently allocate form workers one or more specific form components at the beginning of the workday; rotating workers between tasks is extremely uncommon.

5 Conclusion

This paper proposed a DT approach to evaluate the ergonomic risks associated with vertical formwork operations. The virtual replica of actual workers allows for performing an ergonomic risk assessment. The study findings indicated a high risk of WMSDs in the trunk, neck, wrist, and arm during formwork operations. Based on the findings, the recommendations, including changes in methods, were provided to formwork system manufacturers to prevent WMSDs among form workers. It is expected that the recommended practices could minimize WMSDs if they are executed. The study findings demonstrate the potential of DT for evaluating ergonomic risks associated with vertical formwork operations. This study adds knowledge to the existing literature on enhancing workers' health through DT techniques. Future research could adopt DT technologies to evaluate the WMSD risks in other formwork systems, such as plywood and aluminum. The DT's potential for reducing further workplace hazards in other construction activities should also been examined.

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