Simulation-Based Assessment of Workers' Muscle Fatigue and Its Impact on Construction Operations

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Abstract: Construction workers are frequently exposed to excessive physical demands due to repetitive lifting and material handling while performing tasks. Consequently, many construction workers suffer from a significant level of muscle fatigue that may negatively impact a project's performance. Thus, evaluating the level of muscle fatigue prior to work and implementing appropriate interventions to reduce physical demands will help to prevent adverse effects of workers' fatigue on construction operations. Even though several research efforts have suggested methodologies to evaluate muscle fatigue, the extent to which workers' muscle fatigue would affect construction performance has not yet been fully studied. To address this issue, a simulation-based framework is proposed to estimate physical demands and corresponding muscle fatigue, and thus to quantitatively evaluate the impact of muscle fatigue during construction operations. Specifically, physical demands from a planned operation modeled using discrete event simulation (DES) are estimated through biomechanical analyses. Then, the proposed dynamic fatigue models estimate the level of muscle fatigue of each worker as a function of the estimated physical demands. Workers' strategies to mitigate muscle fatigue, such as taking voluntary rests, are, in turn, modeled in the DES to understand how muscle fatigue affects time and cost performance of the planned operation. As a proof of concept, a case study on masonry work was performed to demonstrate the usefulness of the proposed framework, describing the need for taking into account muscle fatigue for operational planning due to possible excessive physical demands. The results from the case study indicate that excessive physical demands beyond workers' capabilities result in reduction of time and cost performance. The proposed framework helps to better understand workers' response to physical demands by adding workers' capabilities as changing variables into traditional DES approaches, enabling pro-active management of human resources. Ultimately, the framework, which combines conventional interests on optimized operations in terms of time and cost with those of ergonomics, provides opportunities to take into account both workers' health and work performance in early design stages. **DOI: 10.1061/(ASCE)CO.1943-7862.0001182.**

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Introduction

Construction is labor intensive, involving manual handling tasks that are repetitive and physically demanding (Ng and Tang 2010). When workers are exposed to excessive physical demands without proper rest time, they suffer from a significant level of physical fatigue that could generate diverse detrimental impacts, such as productivity loss, human errors, unsafe actions, injuries, and work-related musculoskeletal disorders (WMSDs) (Sluiter et al. 2003; Toole 2005; Huang and Hinze 2006; Hallowell 2010). Therefore, assessing and reducing workers' physical fatigue at construction sites is important to ensure that fatigue does not create devastating impacts on the project performance. A systematic understanding and management of workers' fatigue in planned operations of which activities and resources are determined prior to work can greatly contribute to workers' productivity, safety, and health—all by taking proper action before severe fatigue takes place.

From a physiological perspective, physical fatigue can be defined as a loss of maximal force-generating capacity that develops during muscular activities, commonly referred to as muscle fatigue (Chalder et al. 1993). Metabolic demands in different muscle groups and corresponding localized muscle fatigue not only limit the acceptable workloads for manual handling tasks that are performed for short and intensive periods (Bhattacharya and McGlothlin 1996), but also contribute to cardiorespiratory (i.e., oxygen consumption) or cardiovascular (i.e., heart rate) responses, resulting in whole-body fatigue (Chaffin 1973). To manage workers' fatigue, evaluating muscle fatigue from planned operations should take precedence.

Previous research efforts to evaluate muscle fatigue during occupational tasks have focused on identification of potential health issues due to excessive physical demands by estimating muscle fatigue from given workloads. For example, one widely used method to predict muscle fatigue entails using fatigue models that mathematically represent physiological or mechanical mechanisms of fatigue (Liu et al. 2002; Xia and Frey Law 2008; Ma et al. 2009). These approaches aim to detect ergonomic risks due to muscle fatigue that may contribute to the development of WMSDs (Vøllestad 1997; Perez et al. 2014). Manifestations of muscle fatigue during occupational tasks are also associated with work-performance contributions to costs due to lost productivity. However, understanding the direct impact of muscle fatigue on time and cost performance is challenging due to the lack of a tool for modeling interactions

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between human aspects (i.e., muscle fatigue) and construction operations prior to work (Seo et al. 2015).

To address these issues, a simulation-based framework is proposed to estimate physical demands and corresponding muscle fatigue from the planned operation, and then evaluate the impact of muscle fatigue on construction operations. Specifically, a discrete event simulation (DES) model is combined with biomechanical and fatigue models to capture the interactive effects between muscle fatigue and planned operations. The planned construction operation is modeled at the work-element-level (e.g., placing concrete blocks, lifting drywall, etc.) in DES that represents a breakdown of construction work into the fundamental segments of work involving different levels of physical demands. The physical demands from each work element are then estimated using a biomechanical model, simulating varying physical demands from tasks over time. The fatigue models estimate time-varying changes of muscle fatigue under estimated physical demands from the biomechanical model, which, in turn, affects construction operations in DES. Such a comprehensive and cyclic representation of muscle fatigue and corresponding operational behaviors over time reveals the impact of muscle fatigue on construction operations and vice versa, thereby enabling a better understanding of muscle fatigue resulting from construction operations prior to work. In addition, a case study on masonry work is conducted to demonstrate how the proposed framework can be applied to the actual construction operation. Based on the case study, the benefits of the proposed approach are discussed in terms of understanding how workers' fatigue under given workloads affects construction operations.

Muscle Fatigue and Its Impact on Occupational Tasks

While performing physical tasks, it is hard to maintain muscular strength (i.e., maximum force-producing capacity) because sustained force exertions without sufficient recovery generate muscle fatigue that causes a decline in muscle power output (Chaffin et al. 2006). Fig. 1, which has been adapted from McGill (1997), illustrates the relationship between force exertions (i.e., physical demands) and reduction in muscular strength (i.e., muscle fatigue). To perform a physical task (e.g., lifting heavy objects), one needs to exert forces on muscles. The required forces should be less than a worker's physical capacity (i.e., muscular strength). However, as one performs the task repeatedly over time, muscles become fatigued, resulting in a reduction of muscle strength due to accumulation of fatigue substances on muscle fibers (dashed line in Fig. 1). If appropriate recovery time (e.g., rest time) is not provided, the forces required to perform the task become higher than the decreased muscle strength at some point. This is called fatigue failure (McGill 1997), and the time to fatigue failure is called the endurance time (Chaffin et al. 2006).

Fatigue failure indicates that forceful exertions beyond one's muscle capacity can result in significant detrimental effects on both workers' health and work performance (e.g., productivity). Repeated overexertion beyond one's muscular capacity may cause mechanical degradation of the tissues such as muscle damage (i.e., acute injuries). In the long term, muscle fatigue without sufficient recovery reduces the tissues' stress-bearing capacity as a result of an outcome of cellular changes, and thus may result in chronic conditions such as WMSDs (Kumar 2001). In addition, work performance (e.g., productivity) may also be affected by muscle fatigue, which can then cause a decrease in margin of maneuver (MM) (Durand et al. 2009). MM is an ergonomic concept that is defined as the possibility or freedom workers have to develop different ways of working in order to meet production targets without suffering adverse effects to their health (Durand et al. 2009). The level of MM can be determined by working conditions (e.g., production or quality target, work flexibility) and personal parameters (e.g., the person's physical capacity). Reduction of workers' capacity due to excessive physical demands (i.e., muscle fatigue) would decrease the MM at work, which, in turn, may jeopardize the balance between attaining production targets and preserving workers' health conditions (Durand et al. 2011). Accordingly, when workers recognize muscle fatigue (physical demands beyond muscular capacity), workers will apply appropriate work adjustment strategies (i.e., taking voluntary pauses or slowing down work pace) to cope with manifestation of muscular fatigue, which results in delay of work by sacrificing production targets.

Unlike machine-paced work such as manufacturing, construction tasks are self-paced, allowing workers a degree of autonomy in determining their optimal work pace or rest strategy (Xiang et al. 2014). As a result, a conflict between attaining production targets and preserving workers' health frequently occurs during construction operations as workers continuously try to adjust their work activity to match variations in their personal (e.g., fatigue or pain) and working conditions (e.g., available work time or MM) (Durand et al. 2009). Determining optimal operational designs to minimize this conflict is important for achieving performance goals, and thus requires comprehensive understanding of the effect of excessive physical demands (i.e., muscle fatigue) on planned construction

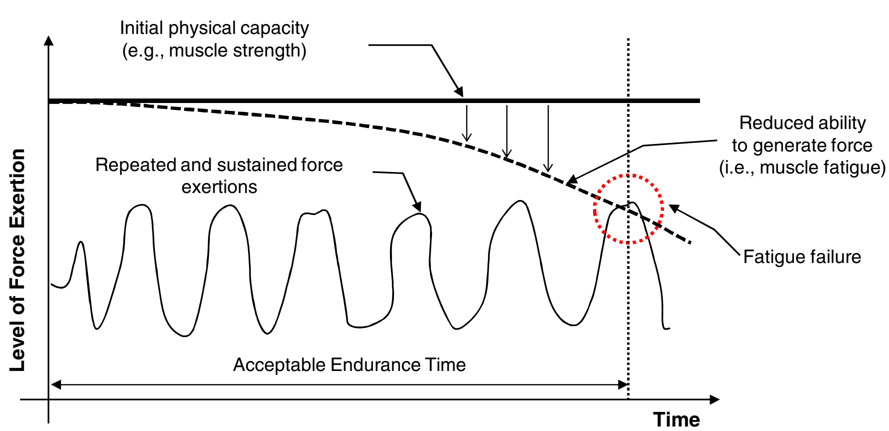

Fig. 1. Relationship between physical demands and muscle fatigue

operations not only to prevent health issues, but also to minimize unexpected productivity loss.

Previous Research Efforts Assessing Physical Demands and Muscle Fatigue

There have been several research efforts to measure physical demands and muscle fatigue during occupational tasks. Direct measurements during performing tasks or subjective evaluations after performing tasks are commonly used to quantify workers' physical demands from work and the degree of muscle fatigue (Vøllestad 1997; Abdelhamid and Everett 2002; Mitropoulos and Memarian 2012). However, estimating physical demands and muscle fatigue prior to work is challenging because there are no observable operations involved yet prior to work (Perez et al. 2014). In this section, a review on simulation-based or model-based approaches to estimate physical demands and muscle fatigue prior to work will be presented.

Methods to Assess Physical Demands Prior to Work

To estimate and evaluate physical demands prior to work, laboratory-based or virtual task simulation has been commonly used in ergonomic studies (Badler et al. 1993; Chaffin 2005; Reed et al. 2006; Nussbaum et al. 2009; Salvendy 2012). Laboratory-based simulation aims to evaluate ergonomic risks of occupational tasks at the stages of planning, scheduling, and designing by having subjects perform simulated tasks in the laboratory (Stanton 2006; Nussbaum et al. 2009; Salvendy 2012). While the subject simulates the task, a set of measures (e.g., anthropometric, kinematic, kinetic, electromyographic, etc.) are collected to estimate physical demands and corresponding ergonomic risks using physiological or biomechanical ergonomic assessment methods (Nussbaum et al. 2009). Recently, virtual visualization and simulation using digital human modeling (DHM) have provided proactive solutions for workplace ergonomic considerations, such as the ergonomic analysis of human posture and workplace design (Shaikh et al. 2004). This approach creates an avatar (i.e., virtual human), and inserts it into three-dimensional (3D) graphic renderings of workplaces, enabling a designer or engineer to investigate different design options of a product or a workplace in the early stages of the design (Reed et al. 2006; Chang and Wang 2007; Demirel and Duffy 2007). However, because developing laboratory-based or virtual simulations is time-consuming, these approaches focus on specific tasks with higher ergonomic risks at the workstation level that are feasible for experimental settings (Czaja and Sharit 2003; Chaffin 2005).

To understand physical demands at the system level in the early design phase, previous research efforts have used DES from an ergonomic perspective (Keller 2002; Neumann and Kazmierczak 2005; Kazmierczak et al. 2007; Neumann and Medbo 2009; Perez et al. 2014). DES has been recognized as a useful technique for analyzing operational design alternatives or optimizing resources with many applications in diverse industries including construction (Martinez and Ioannou 1999; AbouRizk 2010). DES is the representation of a system (e.g., sequence and times of the process) in which the state of resources (e.g., materials, equipment and workers) change at discrete points in time (Banks et al. 2005). Generally, the state of labor resources is modeled as a queuing system to determine the availability of resources, and occupied or waiting times for events as DES focuses on the optimization of resources or cost evaluation (Fishman 2001). However, combined with ergonomic methods to measure physical demands (e.g., subjective rating or biomechanical analysis), DES enables analysis of cumulative physical demands from the planned operations. For example, Keller (2002) estimated cumulative workloads by determining the workload of each task through subjective rating by experts and then adding up the workloads according to task scenarios from DES. Neumann and Kazmierczak (2005) suggested DES combined with biomechanical analysis to estimate musculoskeletal loads on a back and shoulders based on representative postures. Cumulative loads can be calculated by multiplying each task's load by its duration and summing up cumulative loads for tasks based on simulation results of DES (Neumann and Kazmierczak 2005). This approach, which has been applied and tested for manufacturing assembly systems, demonstrates great potential for the assessment of physical demands of alternative system configurations during a design phase (Kazmierczak et al. 2007; Neumann and Medbo 2009; Perez et al. 2014). Once cumulative physical demands from the planned operation are estimated, an analyst needs to determine whether or not the demands are excessive. This judgment generally relies on expert judgment (Keller 2002) or qualitative comparison of physical demands from diverse operational options (Kazmierczak et al. 2007). However, for objective evaluation, specific criteria are needed to determine if there could be potential health or performance issues due to excessive physical demands from the operations.

Methods to Estimate Muscle Fatigue Prior to Work

As muscle fatigue is developed gradually in sustained force exertions and is associated with an ability to continue the task (Enoka and Duchateau 2008), it has been used as a measure of cumulative workload (Village et al. 2005). Muscle fatigue has been studied using a wide variety of models, protocols, and assessment methods (Vøllestad 1997). Electromyography is most often used to assess the level of muscle fatigue during or after task performance (Sommerich et al. 1993). In case of fatigue measurement prior to work, however, model-based measurement has been widely used (Vøllestad 1997; Perez et al. 2014). Most existing muscle fatigue models are based on the quantitative relationships between static (i.e., constant) workloads and maximum endurance time (MET) (e.g., time to fatigue) that are empirically derived from laboratory experiments (Hagberg 1981; Sato et al. 1984; Manenica 1986; Rohmert et al. 1986; Rose et al. 1992, 2000). However, due to the assumption of constant force exertions to estimate MET, these models are not suitable for evaluating fatigue during construction tasks that involve time-varying force exertions and irregular pauses (e.g., short breaks). To address this issue, dynamic fatigue models have been introduced to estimate the level of fatigue as a function of varying force exertions over time. For example, Liu et al. (2002) proposed a set of dynamic equations to describe the effect of muscle fatigue and recovery as a function of the number of motor units (MUs) being activated by the voluntary drive. Despite the ability to reflect varying voluntary efforts (i.e., force exertions), the application of this model is limited to theoretical studies on muscle physiology, neural control mechanisms, and clinical applications because it is difficult to specify the number of motor units during specific occupational tasks. Based on Liu et al.'s (2002) approach, Xia and Frey Law (2008) developed a mathematical muscle fatigue model that can predict muscle fatigue for complex tasks with varying intensities. This approach, however, has to specify diverse model parameters (e.g., the number of MUs to exert a certain level of forces, muscle compositions of body segments etc.) and inputs (e.g., angular velocity and joint angles for performing a task), and thus it is too complex to be used for occupational tasks. Compared with these models (Liu et al. 2002; Xia and Frey Law 2008), the dynamic fatigue model proposed by Ma et al. (2009) is more suitable for evaluating muscle fatigue during occupational

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tasks due to its applicability to any types of force exertions (e.g., both static and dynamic exertions) on specific body parts (e.g., upper limbs, back, or lower limbs) and simplicity of input data (i.e., muscle force). By defining muscle fatigue as a reduction of the maximum exertable force capacity of muscle, this model estimates the reduced capacity of muscle based on muscle force history on specific body parts (i.e., accumulated physical demands), and thus can detect fatigue failure described in Fig. 1. However, this model does not take into account fatigue recovery, which makes it difficult to be used to understand fatigue resulting from construction tasks. There is a significant amount of irregular pauses and short breaks in construction tasks, which can account for up to 31% of the total working time (Serpell et al. 1997).

For the use of fatigue models prior to work, estimation of physical demands from the planned operation is required. As described earlier, DES combined with biomechanical analysis can be a promising tool for estimating cumulative physical demands on specific body parts during the whole operation, and thus can provide input for fatigue models to investigate the level of muscle fatigue during the planned operation. For example, Perez et al. (2014) proposed a combination of DES, biomechanical analysis, and static fatigue models to estimate physical demands and then to calculate a corresponding fatigue rate, which refers to the relative degree of muscle fatigue levels for manufacturing assembly tasks. However, as this approach focused on detection of potential ergonomic risks due to muscle fatigue from diverse operational scenarios, it cannot capture the interaction between production system design and muscle fatigue. As described earlier, manifestation of muscle fatigue during work can result in delays of work to recover from fatigue that may affect the work performance of workers. Modeling of this interaction is not reflected in Perez et al.'s (2014) work, which makes it difficult to understand how excessive physical demands would affect operation performance, and how to optimize operational designs to achieve production targets without sacrificing workers' health. In addition, this approach estimated muscle fatigue under static conditions where the level of force exertions during each activity is constant, which may not be suitable for construction activities involving dynamic force exertions.

Research Methodology

This paper proposes a simulation-based framework for systematically assessing muscle fatigue and its impact on construction operations. This framework is intended to depict the relationship between cumulative physical demands and corresponding muscle fatigue as shown in Fig. 1, aiming to detect fatigue failures that result from excessive demands during the planned operation. One of the novel features of this framework is that the impact of excessive physical demands on construction operations can be simulated by modeling workers' behaviors to cope with muscle fatigue such as voluntary rests. In addition, both fatigue-generation and recovery processes are reflected in this framework, capturing the dynamics of muscle fatigue in construction that involves time-varying force exertions and irregular idling. Fig. 2 shows the overview of the proposed framework, which integrates DES, biomechanical and fatigue models to represent interactions between human aspects (i.e., muscle fatigue) and construction operations prior to work.

Modeling of Construction Operations Using DES

The first step of the framework needs to model the construction operation in DES. Different types of simulation modeling approaches have been used to understand the real system, and these include but are not limited to DES, system dynamics (SD), and agent-based modeling (ABM). Among them, DES is the most widely used modeling approach due to its process-centric approach that enables the quantitative analysis of operations and processes (Martinez 2009; Zankoul et al. 2015). By using DES as a simulation platform for modeling construction operations and workers' behaviors, the proposed framework helps to quantify the effect of fatigue on construction performance. However, one of the limitations of DES is that entities' behaviors at the individual level are predetermined while workers' behaviors should be dynamically determined by the current fatigue level in this framework. To address this issue, workers' physical demands and corresponding level of fatigue are externally modeled using biomechanical and fatigue models. Then, the strategy to mitigate muscle fatigue (i.e., tacking a rest to be recovered from fatigue) is combined into the DES by holding workers in queues such as idling when workers are in fatiguing conditions. These will be described in more detail in the following sections.

The basic modeling element of the DES model is a *work element*. Construction operations are defined by collections of work tasks that can be further divided into work elements (Halpin 1992). For example, one of the examples of physically demanding construction operations, masonry work consists of several work tasks such as scaffolding, material preparation, and brick (or block) laying. The task of brick (or block) laying can be decomposed in to work elements (i.e., basic tasks) such as lifting drywalls or placing

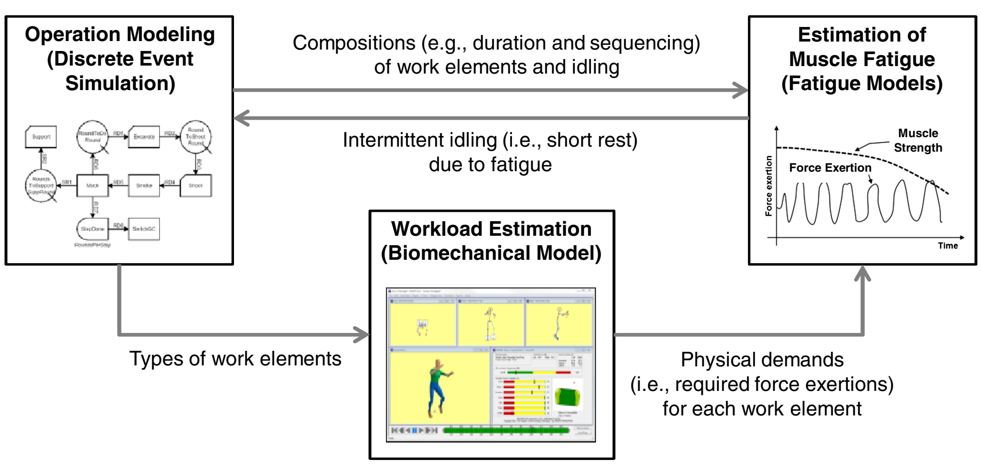

Fig. 2. Overview of proposed framework

bricks (or blocks) (Everett and Slocum 1994). As each work element generally involves different levels of physical demands, modeling the operation at the work-element level is helpful to capture dynamic changes of physical demands through biomechanical analysis in the next step.

To determine model behaviors, the work elements' attributes such as the duration or priority of a work element and the amount of resource that flows from one element to another should be further defined based on prior knowledge on the operation. Especially, the durations of defined work elements can be empirically determined through time-motion studies on existing operations (e.g., direct and continuous observation of construction operations) (AbouRizk and Halpin 1992). By simulating the DES model, the states of workers (e.g., types of work elements including idling of workers at specific moments) throughout the operation can be predicted.

Estimation of Workloads of Given Operations through Biomechanical Analysis

Once a DES model for the operation is developed, physical demands from each work element are estimated using a biomechanical model. Biomechanical modeling and analysis aims to estimate musculoskeletal stresses (e.g., muscle forces) required to perform a task as a function of postures, external loads, and anthropometric data (Chaffin et al. 2006). It provides an effective means to understand physical demands on the musculoskeletal system of human body during construction tasks (Seo et al. 2014).

The computerized biomechanical analysis tool *3DSSPP* was used to estimate physical demands from each work element (Chaffin et al. 2006). Using *3DSSPP*, physical demands from work (i.e., required forces to perform tasks) can be estimated as a percentage of maximum voluntary contraction (%MVC is the level of muscle forces compared to an individual's maximum muscle strength) that can be a direct input for the dynamic fatigue models. As muscle forces to be exerted on a group of muscles vary depending on postures, a collection of representative working postures is required to obtain reliable %MVC for specific work elements. Laboratory-based simulations of tasks and motion measurement using motion-capture devices [e.g., marker-based or inertial measurement unit (IMU)-based] can be used to collect data of working postures during occupational tasks. Physical demands from each work element are then added up according to the states of workers (i.e., working or idling) obtained from the DES, generating physical demands during the entire operation over time.

Estimation of Fatigue Using Dynamic Fatigue Models

Dynamic fatigue models aim to estimate muscle fatigue at a group of muscle level at specific body parts (e.g., shoulders, knees, or back) as a function of estimated physical demands from the previous step. The dynamic fatigue models consist of a fatigue generation model to estimate the reduction of muscle strength due to continuous physical demands (e.g., %MVC) and a fatigue recovery model to predict how much muscle fatigue (i.e., reduced muscle strength) can be recovered during nonworking time (e.g., rest or idle time).

The mathematical model developed by Ma et al. (2009) is used for the fatigue generation model in this study [Eq. (1)]. The model is based on the motor unit activation pattern on muscles of which force and movement are produced by contraction of muscle fibers, representing the process of fatigue generation in mathematics. This model was validated with 24 existing static models that estimate METs under isometric exertions by comparing the calculated METs, and qualitatively or quantitatively validated with three existing dynamic models by comparing specific model parameters (Ma et al. 2009). Eq. (1) can be explained as follows:

$$\frac{F_{\text{cem}}(t)}{\text{MVC}} = e^{\int_0^t -[F_{\text{load}}(u)/\text{MVC}]du} \tag{1}$$

where MVC = maximum voluntary contraction (maximum capacity of muscle); $F_{\text{cem}}(t)$ = current exertable maximum force (current muscle strength); $F_{\text{load}}(t)$ = forces required for the task (e.g., workloads); and t = current time (seconds).

$F_{\text{cem}}(t)$ describes the capacity of the muscle group (i.e., current muscle strength) while $F_{\text{load}}(t)$ means the forces that the muscle needs to produce to perform tasks at a time instant t. By dividing $F_{\text{cem}}(t)$ and $F_{\text{load}}(t)$ by MVC, which is a measure of force that can be exerted maximally by one's muscle group, both the current muscle strength and physical demands can be expressed proportional to one's MVC (%MVC), reflecting individual differences in muscle strength. As a result, the equation indicates that the current capacity of muscle strength can be determined by the negative exponential function of cumulative physical demands from work.

However, one of the critical limitations of this model is that this model does not reflect the recovery from fatigue during nonworking time (e.g., rest or idle time), which is essential to measure the impact of fatigue on work performance. To address this issue, a recovery model is proposed based on the physiological recovery rate on muscle groups as shown in Eq. (2). Empirical studies on recovery from muscle fatigue found that reduced muscle strength after fatiguing exertions can be recovered quickly in 5–10 min up to about 90%MVC while more than 30 min are additionally required to be fully recovered (Lind 1959; Mills 1982; Kuorinka 1988; Bogdanis et al. 1995; Fulco et al. 1999; Shin and Kim 2007). Especially, Mills's (1982) experiments on the recovery time for the hand and forearm showed it took about 10 min to be recovered from 40%MVC to 90%MVC. Based on this study (50%MVC recovery in 10 min), a 5% average recovery rate per 1 min is assumed for the recovery of up to 90%MVC. In addition, as 30 min are additionally required to be fully recovered from 90%MVC (10%MVC recovery in 30 min), a 0.3% recovery rate is assumed for the recovery from 90%MVC to 100%MVC:

$$F_{\text{cem}}(t_b) = [1 + \text{recovery rate} \times (b - a)]F_{\text{cem}}(t_a) \tag{2}$$

where $F_{\text{cem}}(t_a)$ = current exertable maximum force at start time a of nonworking time; and $F_{\text{load}}(t_b)$ = current exertable maximum force at finish time b of nonworking time.

As a result, the fatigue models quantify the current muscle strength as a function of time-varying values of physical demands. By comparing the current muscle strength with the physical demands from the operation, fatigue failure (i.e., physical demands beyond the current muscle strength) can be detected.

Modeling of Interactions between Muscle Fatigue and Operations

Once fatigue failure is detected, workers may want to adjust work to mitigate muscle fatigue. For example, they may want to slow down work pace or change postures to reduce muscle forces exerted at fatiguing body parts. However, these strategies still expose workers to certain levels of physical demand, and changing postures may lead to even higher risk of injury due to reduced postural stability (Kumar 2001). This paper adapted voluntary rests as a fatigue mitigation strategy by workers to recover from muscle fatigue. Specifically, when fatigue failure occurs, these voluntary rests are added in the DES model by hindering the onset of the following work element, and thus making workers stay in the queue. This model behavior

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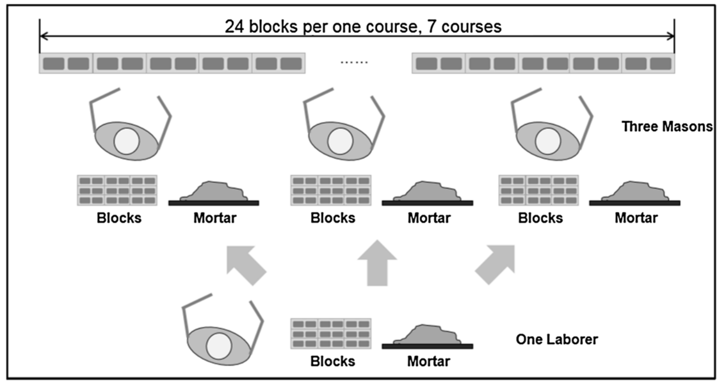
(a)



(b)

Fig. 3. Site conditions (image by authors): (a) site photo; (b) site layout

results in the delay of work, increasing both total duration and cost. As a result, this framework can evaluate the impact of muscle fatigue on time and cost performance due to excessive physical demands during the planned construction operations.

The duration of voluntary rests that workers would take could vary depending on their level of muscle fatigue. Bonen and Belcastro (1975) found that subjects would choose optimal recovery time that allows them to be recovered from fatigue at the fastest rate when they can determine the duration of rests during intensive exercise. Seiler and Hetlelid (2005) also found that self-selected recovery duration is subjectively determined to maintain expected performance level during interval training. Based on these findings, it is assumed here that the duration of voluntary rests are determined by the gap between the current level of muscle strength after finishing the preceding work element and the desired level of muscle strength by workers. For example, as workers can perceive their own level of muscle fatigue, they may want to take a rest until their muscle strength is recovered sufficiently enough to exert forces for the next task (at least 10%MVC higher than the following physical demand).

Case Study on Masonry Work

The proposed framework is applied to a case study to demonstrate the usefulness of evaluating muscle fatigue and its impact on construction operations. The operation for the case study is masonry work for building a three-story research complex, located at the north campus of the University of Michigan. Site conditions obtained from this project served as basic conditions for developing a DES model for masonry work. As shown in Fig. 3, the masonry work was to build a concrete block wall with 7 courses and 24 concrete blocks [$15.2 \times 20.3 \times 40.6$ cm ($6 \times 8 \times 16$ in.) (width × height × length)] per course. A crew for this operation consisted of three masons and one laborer. The masons took a major role in masonry work such as cutting and laying blocks, or installing rebar if needed while the laborer performed supportive tasks, mainly material-handling tasks [e.g., preparation and distribution of material (e.g., blocks and mortar)]. Total work duration for building the concrete block wall was about 54 min including about 4 min of idle time (e.g., chatting with coworkers).

The case study examines how different operational plans affect workers' muscle fatigue, and in turn, time and cost performance of the masonry work. First, by changing crew composition (i.e., the number of masons and laborers), the optimized resource plan (i.e., crew composition) was selected to minimize time and cost without consideration of muscle fatigue as in the typical DES analysis. Then, we also simulated the operation using the crew composition that is optimized only for time and cost by considering fatigue effects on the operation simulation. Through comparison between simulation results without and with consideration of muscle fatigue, potential conflicts between achieving performance targets and preserving workers' health are described. Specifically, the case-study model focuses on shoulder muscle fatigue because shoulder pain is one of the frequently reported musculoskeletal disorders by masonry workers due to heavy lifting, working above shoulder level, and repetitive movements (Goldsheyder et al. 2004; Faber et al. 2009).

DES Model Development

To develop a DES model for this masonry work, tasks by masons and laborers are divided into work elements based on observations as presented in Table 1. While masons perform the work elements M1, M2, and M6 once for each course, M3 to M5 are repeated for the next blocks to complete the full course of concrete blocks. Material handling tasks by laborers are to deliver mortar (L1) and concrete blocks (L2) to masons. It was assumed that there are enough materials prepared, and thus the laborers just deliver materials to masons, who have the least amount of material first to prevent them from becoming idle due to lack of materials during this operation. The duration of each work element was determined based on time-motion analysis of the observed operation.

Based on these assumptions and descriptions on the masonry work operation, a DES model for this masonry work operation was constructed in *STROBOSCOPE* (State and Resource Based Simulation of Construction Processes) (Martinez 1996) as shown in Fig. 4. *STROBOSCOPE* is a programmable and extensible

Table 1. Work Elements for Masonry Work

Crew member	Work element
Mason	M1. Setting up (e.g., setting a string for reference)
	M2. Spreading two parallel lines of mortar using a trowel
	M3. Lifting and laying a concrete block onto the mortar lines
	M4. Tapping the top of the block to level it and collecting the excessive mortar mix that squeezes out from under the block
	M5. Spreading mortar at the side of the block just laid on
	M6. Rechecking each block for level and alignment when the course has been completed
Laborer	L1. Delivering mortar
	L2. Delivering concrete blocks

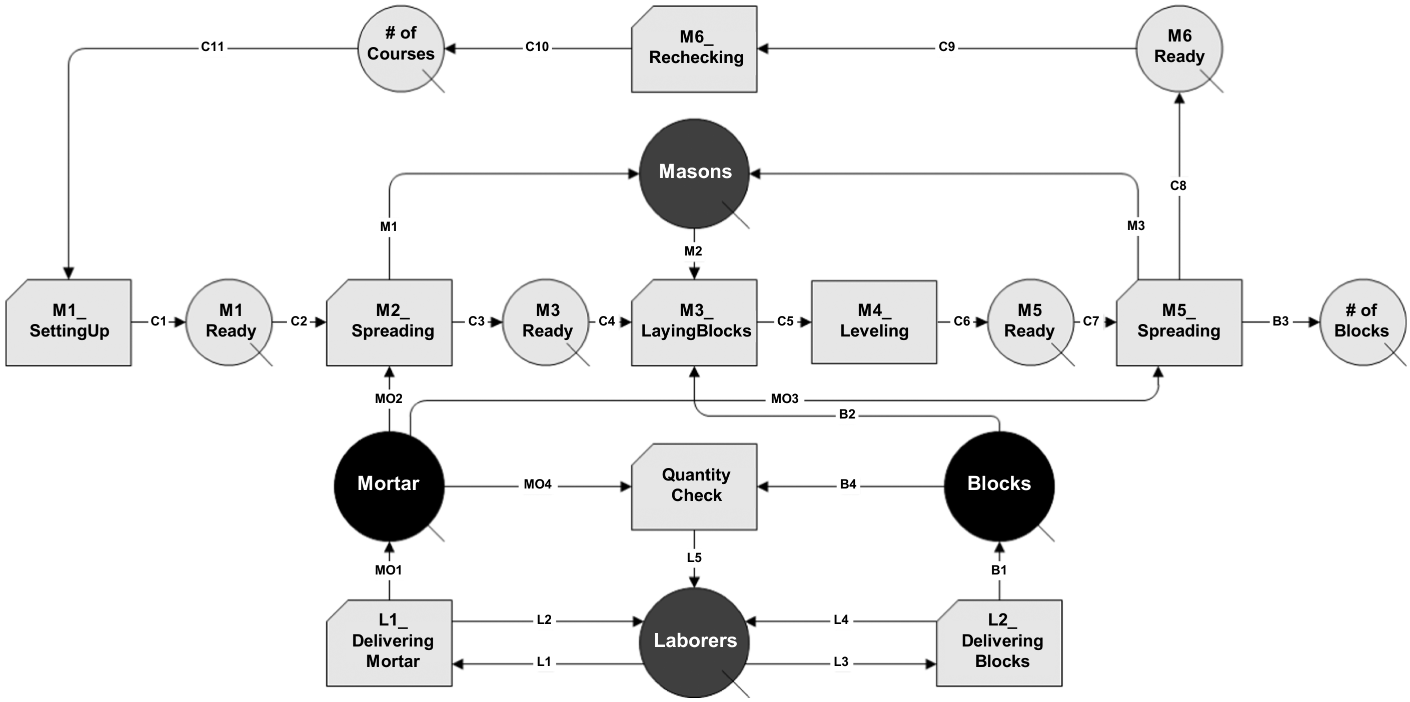


Fig. 4. DES model for masonry work

simulation system designed for modeling complex construction operations in detail and for the development of special-purpose simulation tools (Martinez and Ioannou 1999). Work elements by masons and laborers are modeled independently, but resources such as concrete blocks and mortar are shared by both masons for resource consumption and laborers for resource production. The total simulation time to build the wall with the same crew composition (i.e., three masons and one laborer) of this case operation was 48 min while the actual duration was 54 min from the field observation. However, about 4 min of idle time such as chatting with coworkers that was not associated with the operation were found from the observation, which was not considered in the model. If this idling is excluded, the model performed well to represent this masonry work, showing 4% of the difference in working time (48 versus 50 min). Though it is only one instance, it can be a good reality check of the developed DES model.

To identify the optimal design for this operation without considering the effect of muscle fatigue, the model was then simulated again with varying crew compositions. Table 2 details time and cost performance (e.g., total duration, labor productivity, and cost rate) by varying the numbers of masons and laborers. The results imply that adding an additional laborer would not reduce total duration in this operation as work progress is determined by masons, and

Table 2. Simulation Results according to Different Crew Compositions

Crew combination		Simulation results		
Number of masons	Number of laborers	Total duration (h)	Labor productivity (blocks/h/person)	Cost rate (labor cost) ($/block)
1	1	1.74	48.2	0.81
2	1	1.05	53.6	0.75
3	1	0.81	51.7	0.80
1	2	1.74	32.1	1.17
2	2	1.05	40.2	0.97
3	2	0.81	41.3	0.96

material supply by one laborer is sufficient not to delay the work progress by masons. As a result, a crew with two masons and one laborer is recommended for this operation because this crew shows the highest productivity and the lowest cost rate [hourly labor costs for masons and laborers are obtained from RS Means (2015)]. However, if the objective is to choose the fastest completion, a crew with three masons and one laborer can be chosen.

Biomechanical Analyses on Work Elements

Biomechanical analyses were performed to estimate physical demands from each work element using *3DSSPP*. To collect working postures required to perform biomechanical analyses on work elements, laboratory experiments were conducted in a controlled environment. Five experienced masons were recruited in order to examine postural variations of their working techniques as they performed block-laying tasks at a comfortable pace. Masons' motions were collected using an inertial measurement unit (IMU)-based motion capture system. Working techniques for each work element were similar except for lifting techniques. In some cases, masons lifted and laid a concrete block with one hand, but typically, both hands were used; accordingly two-hand lifting was considered to be a representative lifting technique because it is recommended to reduce ergonomic risks during lifting tasks (Cheung et al. 2008). Hand loads were estimated based on what types of objects (e.g., blocks, mortar, trowel, or shovel) workers were handling.

Table 3 shows average physical demands on shoulders as %MVC to perform work elements from biomechanical analyses based on collected motion data and estimated hand loads. To compute %MVC, the 50th percentile of workers for anthropometry (e.g., height and weight) and muscle strength were assumed. For example, when laying a concrete block (M3), which is the most physically demanding work element performed by masons, a mason has to exert muscle forces on shoulders up to 35% of maximum muscle strength. The other work elements required force exertions less than 10%MVC. Work elements by laborers are more physically demands than the ones by masons because delivering

Table 3. Average Physical Demands (% MVC) from Work Elements

Work element	Physical demands (%MVC)
Masons (%)	
M1	5
M2	10
M3	35
M4	5
M5	10
M6	10
Laborers (%)	
L1	35
L2	40

mortar (L1) and concrete blocks (L2) involve heavy material lifting, showing 35%MVC and 40%MVC, respectively. Based on the physical demands for each work element from biomechanical analyses and duration and sequencing of work elements from DES, total physical demands by both masons and laborers during this operation were obtained.

Evaluation of Muscle Fatigue for Different Crew Compositions

To examine how muscle fatigue due to excessive physical demands affects the operation of masonry work, the level of muscle fatigue by workers (i.e., a mason and a laborer) was evaluated for different crew compositions using the proposed dynamic fatigue models. Fig. 5 shows physical demands and corresponding muscle fatigue for a mason and a laborer according to different crew compositions when voluntary rests to recover from fatigue are not considered. The dashed line indicates current exertable maximum forces (% MVC), which refers current muscle strength, while the solid line means forces required for the tasks (%MVC), which refers to physical demands from the operation. Based on the previous simulation results from the DES model that did not take into account muscle fatigue impact (e.g., Table 2), it was found that the crew with two masons and one laborer or with three masons and one laborer can achieve the best performance in terms of time or cost. However, when muscle fatigue is taken into consideration, the laborer could experience fatigue failure in both crew compositions due to excessive physical demands from work elements (e.g., delivering mortar and concrete blocks) while the masons would not become fatigued before finishing the operation. As mentioned earlier, forces required for the tasks (%MVC) beyond current exertable maximum forces (%MVC) indicates fatigue failure that may result in health issues such as WMSDs.

Fig. 6 shows how muscle fatigue can affect work performance during masonry work with a crew composition of three masons and one laborer. As described earlier, the laborer could experience fatigue failures due to excessive physical demands at the beginning of the operation (about 11.6 min) [Fig. 6(a)]. Whenever fatigue failures occur, the laborer may want to take voluntary rests to recover from muscle fatigue, which can decrease work performance of the operation [Fig. 6(b)]. Unexpected idling due to the laborer's muscle fatigue results in the increase of total duration from 48 to 54 min because the masons also have to wait until materials are provided by the laborer. As a result, due to the impact of muscle fatigue by the laborer, work progress can be delayed about 12.5%, resulting in reduced labor productivity (9.7%) and increased cost rate (10%).

Discussions

The case study on masonry work demonstrates how the proposed framework can be applied to actual construction operations. As found in the case study, excessive physical demands beyond an individual's physical capacity may result in both health and performance issues even during a short-term operation (i.e., less than 1 h). However, masons and laborers are generally exposed to more workloads than the ones handled in the case study (i.e., 56 blocks per mason) during a whole day [a typical production rate per mason is 150 blocks per day (RS Means 2015)]. Thus, more-severe adverse effects on performance and ergonomic risks caused by excessive physical demands are expected when the analysis is expended to a longer operation (e.g., days and weeks).

As this study primarily focuses on the methodological development and demonstration of the proposed framework, testing the accuracy of the fatigue recovery equation [Eq. (2)] and its impact on time and cost performance is beyond the scope of the paper.

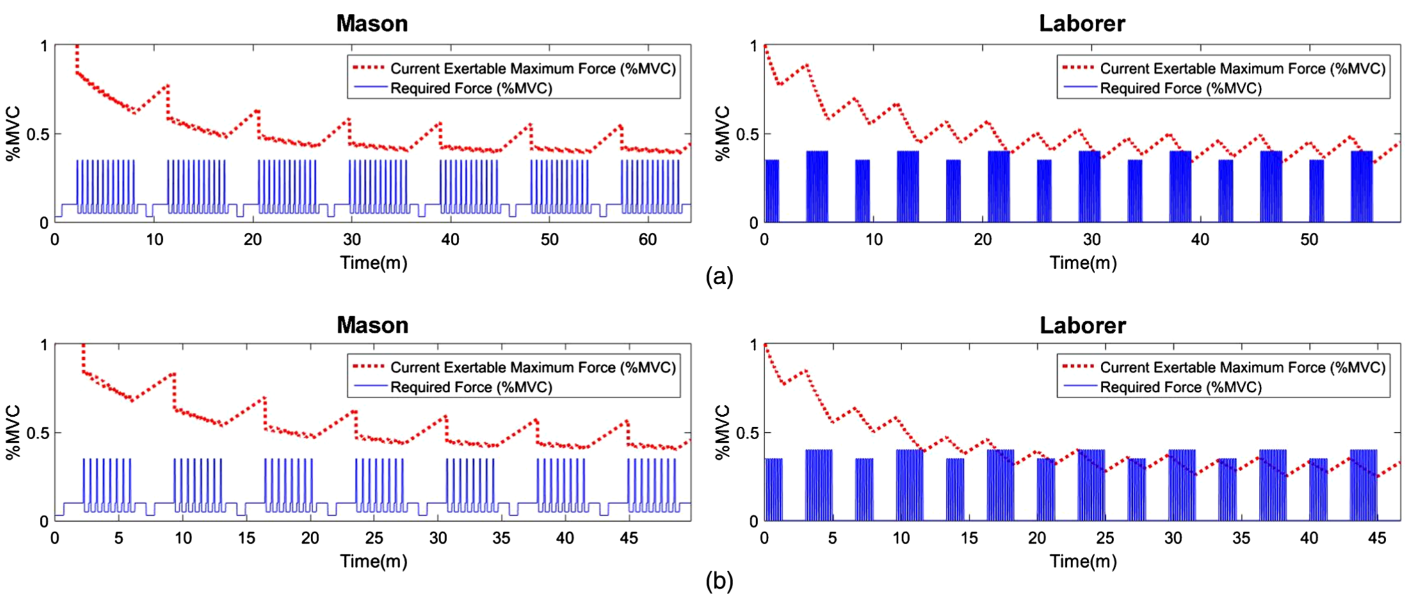
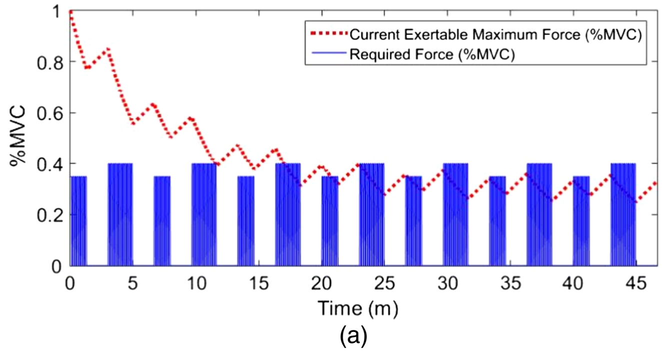


Fig. 5. Fatigue evaluation for masonry work with different crew compositions: (a) two masons and one laborer; (b) three masons and one laborer



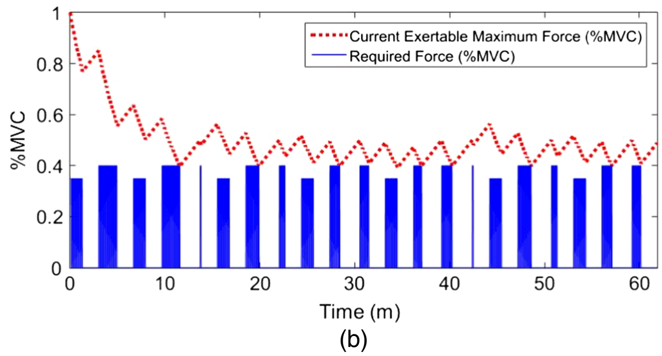


Fig. 6. Impact of muscle fatigue on work performance (crew composition: three masons and one laborer): (a) simulation result without considering idling due to muscle fatigue; (b) simulation result when considering idling due to muscle fatigue

This framework goes beyond Neumann and Kazmierczak's (2005) or Perez et al.'s (2014) approaches from a methodological perspective, enabling estimation of varying physical demands and corresponding muscle fatigue generation and recovery using comparable measures (i.e., %MVC), and thus to identify potential impact of muscle fatigue on construction operations. This novelty of the proposed framework is of importance for construction tasks involving different levels of physical demands (e.g., work intensity and duration) and irregular rests/pauses.

Evaluation of muscle fatigue in early stages of the design of the construction operations is important because it can provide a great opportunity to mitigate occupational health risks such as WMSDs (Nussbaum et al. 2009). When the planned construction operation is expected to have fatigue failures, a manager may want to redesign work places and tasks. Considering limited resources for redesigns, it is important to set a priority of work elements to be redesigned. Estimating physical demands (%MVC multiplied by duration) from work elements using the proposed framework can provide criteria to determine the target work element for intervention. In the case study on masonry work, it was found that delivering concrete blocks by laborers is the most physically demanding work element. In terms of design of workplaces, reducing the distance between a pile of concrete blocks and the wall, if site conditions allow, can reduce the duration for material delivery, contributing to decreased physical demands. In addition, providing appropriate guidelines or training on working techniques can also help workers minimize physical demands from work. For example, asymmetric load carrying such as one-handed carrying may have a greater injury potential compared to symmetrical carrying techniques, especially when transporting loads of 20% of bodyweight or more (Devita et al. 1991). Laborers who carry heavy materials such as mortar and concrete blocks are recommended to distribute hand loads symmetrically or to carry them interchangeably using left and right arms (Drury et al. 1989; Devita et al. 1991). As described previously, understanding potential ergonomic issues due to muscle fatigue from the planned construction operations helps to develop ideas for effective ergonomic interventions prior to work.

The proposed framework can also serve as a tool for optimization of construction operations considering workers' physical capacity. DES has been a useful technique for construction operation modeling to develop better project plans, optimize resource usage, reduce costs and duration, or improve overall project performance in construction (Martinez and Loannou 1999; AbouRizk 2010). For building accurate models that represent construction operations, modeling of resources and their state is one of the important elements because operations can be sensitive to resource properties (e.g., size, weight, and cost) that are allocated to specific activities (Martinez and Loannou 1999). Resources in construction generally refer to materials, equipment, and labor, all of which have a set of constant attributes in DES, for example, an amount of materials required for one cycle of an activity, or working capacity of equipment or labor. However, unlike other resources, there is significant variability in human capacities, which are affected by physical demands from work (Chaffin et al. 2006). However, consideration of human aspects such as fatigue has been seen as the missing link in discrete event simulation (Baines et al. 2004). As the case study found, selection of optimized operational scenarios in terms of time and cost are not necessarily optimal decision-making when considering limited human capacity. Given constraints regarding human aspects, specifically limited physical capacity, the DES that considers reduced physical capacity of workers during construction operations enables managers to experiment with diverse alternatives for resource allocation (e.g., number of workers and crew compositions) to prevent unexpected performance loss due to excessive physical demands. For example, in the case study presented earlier, the operational scenario with the crew of three masons and one laborer may result in unexpected delay of work (e.g., 12.5% of increased total duration) due to muscle fatigue by the laborer, showing the cost rate of

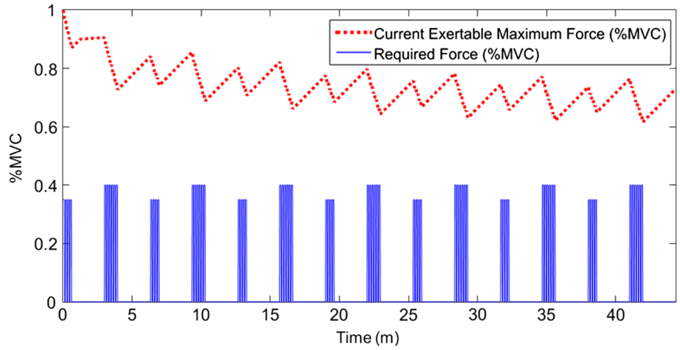


Fig. 7. Simulation result when adding one more laborer (three masons and two laborers)

$0.88/block [Fig. 6(b)]. To prevent unexpected delays by the laborer, adding one more laborer (e.g., three masons and two laborers) is recommended, even though the cost rate could be slightly increased up to $0.96/block (Fig. 7). As described in this example, understanding of muscle fatigue and its impact on work performance can support decision making when designing construction operations.

If an additional resource like an extra laborer is not available, the detection of fatigue failures during construction operations can be still useful by pursuing the optimal work–rest schedule that provides appropriate duration of rests in a timely manner (Kopardekar and Mital 1994). In construction, work–rest schedules are generally determined just based on working time without considering variations of physical demands according to types of operations. Using the proposed framework, fatigue failures due to excessive demands can be detected, thus enabling the right timing of rests for workers to be provided. In addition, simulating diverse scenarios for duration and frequency of rest breaks in the DES model, the optimal work–rest schedule that permits recovery from muscle fatigue without jeopardizing the work progress can be determined.

The proposed framework aims to understand localized muscle fatigue at specific body parts in the perspective of biomechanical demands (e.g., muscle forces) from work. However, contractile process to exert forces in muscle also requires a great deal of energy that refers to metabolic demands (i.e., energy demands) (Sahlin et al. 1998). When the metabolic demands from prolonged physical activities exceed an individual's capacity to produce energy, workers could experience whole-body fatigue, which also significantly affects work performance (Waters et al. 1993). Especially in construction where long work hours are common, accumulative effects of metabolic demands such as energy depletion could be also critical to work performance (Hallowell 2010). Alvanchi et al. (2011) investigated the impact of working hours and overtime on workers' performance on the basis of human energy consumption and found that almost 20% of productivity loss could exist depending on the amount of metabolic demands. Further studies are needed to reflect workers' fatigue at the whole-body level in the proposed framework.

Conclusion

This paper introduces a new approach for modeling interactions between human aspects (i.e., muscle fatigue) and construction operations. The proposed framework estimates physical workloads by combining DES and biomechanical analysis, predicts the level of fatigue under estimated workloads using dynamic fatigue models, and then evaluates the impact of muscle fatigue on the planned operation. A case study on masonry work was performed to demonstrate the usefulness of the proposed framework. Specifically, the results from the case study indicate that the optimized operational scenario only for time and cost performances may expose workers excessive physical demands, and thus an unexpected delay of the operation due to workers' muscle fatigue could be observed. This implies that incorporating muscle fatigue into the operational design phase provides systematic understanding of the trade-off between time and cost performances and ergonomic risks. As a result, this approach has great potential as an effective means to design optimized operations considering limited human capacity, as well as to assess potential ergonomic risks due to excessive physical demands.

As this framework is built on validated models (e.g., DES, biomechanical and fatigue models), it is outside the scope of this research to validate each step in the framework. However, this framework requires integration of different models that may result in unexpected model behaviors. A validation for fully integrated models will be further needed to identify potential issues due to interacted model behaviors. Even though several limitations and research challenges remain, they do not negate the potential application of this framework. If workers' fatigue due to excessive physical demands from operations could be evaluated in the early design stages, it would open the door to not only more proactive management of ergonomic aspects in the design of construction operation, but also optimization of construction operations considering workers' physical capacity. Ultimately, the proposed framework provides opportunities to take into account both workers' health and work performance in early design stages.

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