Validation of a Predictive Equation for Recovery Time and Cumulative Fatigue

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Abstract*—Musculoskeletal disorders remain a leading concern in physically demanding industries, driven by repetitive tasks and high physical loads. Although existing ergonomic models help quantify risk for singular, repetitive tasks, industrial workplaces often involve different physical tasks that such models do not adequately address. This study validates a reformulated version of our previously published duty-cycle/maximum-acceptable-effort equation for back-involved tasks: by substituting a duty-cycle definition that includes both execution time and recovery time, we algebraically isolate the required recovery time and test whether the resulting break schedule prevents fatigue when four subtasks are interleaved over a one-hour protocol. Three participants completed lifting and lowering tasks of varying intensity and frequency, with recovery times calculated using a modified predictive equation. Objective indicators, including heart rate and endurance time, along with subjective ratings of exertion and task perception, were used to assess the validity of the model. Results showed minimal fatigue accumulation and consistent heart rate levels during the experiment, with only a 5% decline in endurance time. Participants perceived physical demand and effort to be moderate and recovery times adequate. These findings support the equation's application in multi-task contexts while highlighting the need for variation to mitigate task-related frustration in extended shifts. Additionally, how the equation can be used with exoskeletons is discussed.

Keywords—Ergonomic modeling, Musculoskeletal disorders, Recovery time estimation, Cumulative fatigue

I. Introduction

In many physically demanding workplaces, musculoskeletal disorders (MSDs) remain a leading cause of lost workdays, reduced productivity, and long-term disability [1], [2], [3], [4]. These injuries, often resulting from repetitive motions, sustained awkward postures, and high physical loads, pose a serious concern in sectors such as construction, manufacturing, logistics, and healthcare [5]. As work demands evolve with increasing pressure for efficiency and labor intensity, there is a growing need for evidence-based strategies that help mitigate biomechanical risks before injury occurs.

To address the growing risk of MSDs, various engineering and administrative interventions have been introduced [6], [7], [8]. Ergonomic redesign of tools and workstations, job rotation, and worker training remain essential components of injury prevention programs. More recently, wearable technologies such as passive or powered exoskeletons have gained attention as innovative solutions to reduce physical load on the body [9]. While these interventions can be effective, they are most impactful when guided by systematic risk assessment tools that can identify when, where, and for whom support is needed [10]. This underscores the importance of accurate, scalable methods to evaluate physical exposure during work tasks.

To support proactive risk management, researchers and practitioners have developed exposure assessment tools, including equations and tables that quantify safe task parameters based on physical intensity and repetition [11], [12], [13], [14], [15], [16]. Most existing risk assessment models have been developed and validated under controlled conditions involving single, repetitive tasks. However, in practice, workers often engage in a series of diverse tasks throughout the day, each with a different intensity and duration. This variability complicates the estimation of cumulative physical exposure and raises concerns about whether models built for single tasks can be reliably applied in dynamic settings. As job roles become more dynamic and task-switching more frequent, it is essential to examine how well current assessment methods capture the combined physical demands of multiple tasks. Therefore, a systematic validation of these models in multi-task contexts is necessary to enhance their accuracy, relevance, and application in occupational ergonomics.

To effectively assess physical exposure in jobs involving multiple tasks, existing predictive equations must be adapted to account for task variability across a work shift. Most current formulations are designed for single, uniform tasks and do not inherently accommodate the cumulative effects of alternating task demands, differing recoveries, or variable intensities [11], [13]. As a result, direct application of these models to multi-task scenarios may lead to inaccurate estimations of risk. Therefore, there is a dual need: first, to modify these equations to integrate

This project was funded by the Natural Sciences and Engineering Research Council of Canada in partnership with Alberta Innovates (Grant # ALLRP 567348 – 21).

multiple tasks in a time-weighted or cumulative manner, which has been suggested in previous studies [17], [18]; and second, to empirically validate their performance in realistic, multi-task environments. This approach will enhance the reliability of exposure assessments for diverse and dynamic work environments and multi-task activities.

Validation of adapted exposure assessment models should rely on both subjective and objective indicators of physical strain to ensure comprehensive evaluation. Participant feedback provides valuable insight into perceived exertion and task difficulty, capturing perceptual aspects of physical demand that may not be evident through measurement alone. At the same time, objective metrics such as endurance time and physiological responses offer quantifiable evidence of the body's response to cumulative load. In particular, heart rate serves as a critical indicator of fatigue and overall physical performance, reflecting cardiovascular effort during task execution and recovery [19], [20]. By triangulating these data sources, researchers can more robustly assess whether modified models accurately reflect the true physiological and perceptual impact of multi-task workloads.

In this study, we aim to validate the equation previously developed for a single repetitive back-involved task to be used for multiple tasks. Specifically, we validate a reformulated version of our previously published duty-cycle/maximum-acceptable-effort equation [13] by substituting a duty-cycle definition that includes both execution time and recovery time. This allows us to algebraically isolate the required recovery time (Equation 3) and test whether the resulting break schedule prevents fatigue when four subtasks are interleaved over a one-hour protocol. Participant attended an experiment with one-hour duration, during which they performed multiple back-involved tasks with different intensity and frequency levels. Participant feedback along with heart rate data was recorded for the validation and analysis.

II. Methods

A. Participants

Three participants (age: 28 ± 2 yr., height: 173 ± 6 cm, body mass: 72 ± 12 kg) were recruited for this study. All participants were able-bodied adults with no prior lower back injuries or disorders, and they signed a consent form after explaining the experiment. The study was approved by the research ethics board of the University of Alberta, ID: Pro00109264.

B. Calculation of Recovery Time

Previous equation developed for a single, repetitive task relates duty cycle to the intensity level of the task, equation (1) [13]:

$$MAE(\%) = (1 - DC^{n}) \times 100 \quad (1)$$

in which MAE is the maximum acceptable effort as a percentage of *MVE*, maximum voluntary effort, *DC* is duty cycle, and n is 0.22 for back-involved tasks [13]. DC is the percentage of time that an individual is engaged in doing the task, and thus can be expressed as equation (2) [17], [18]:

$$DC = \frac{t_{Exec} f}{t_{Rest} + t_{Exec} f} \quad (2)$$

where t_{Exec} is the time of task execution, *f* is the frequency, and t_{Rest} is the recovery time. By substituting equation (2) into equation (1), it can be reformed into equation (3):

$$t_{Rest} = \frac{t_{Exec} f}{(1 - MAE)^{4.167}} - t_{Exec} f \quad (3)$$

With this new form of the equation (1), recovery time can be calculated for any subtask, and therefore more than a single task can be assessed. Based on equation (3), recovery time can be calculated for any subtask as a function of effort (*MAE*), frequency (*f*), and the time of task execution (t_{Exec}).

C. Experimental Procedure and Data Collection

To validate equation (3) across multiple subtasks, participants completed four tasks: two lifting and two lowering. Data collection took place over two sessions on separate days. During the first session, measurements were taken for MVE, lifting and can be assessed.

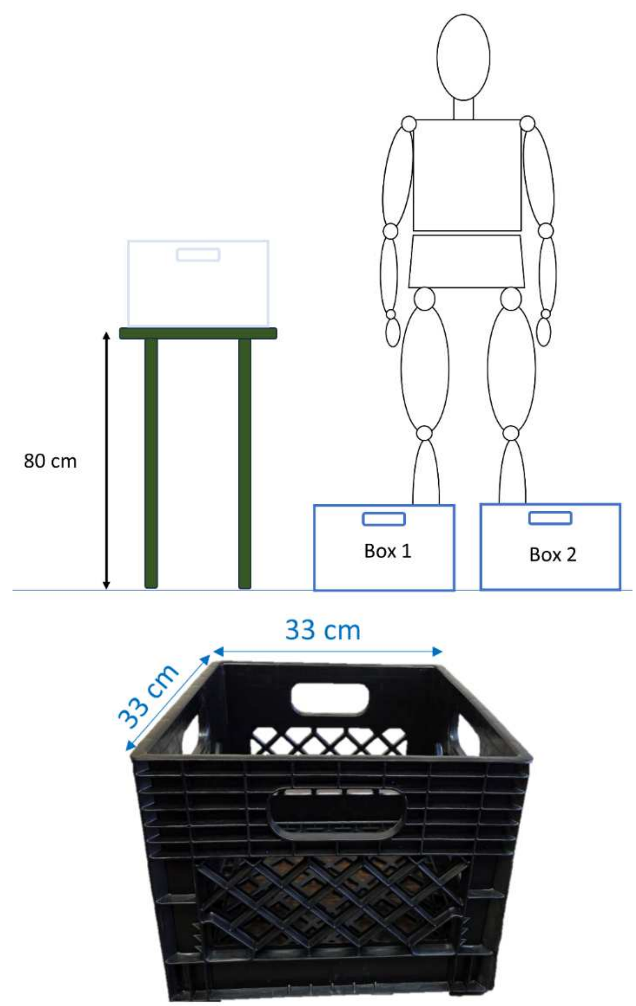

Fig. 1. (a) Experimental Setup (b) Milk crate used for lifting and lowering

Based on equation (3), recovery time can be calculated for any subtask as a function of effort (*MAE*), frequency (*f*), and the time of task execution (t_{Exec}).

D. Experimental Procedure and Data Collection

During the first session, measurements were taken for MVE, lifting and lowering durations, and endurance time under a resting condition. For the MVE assessment, participants lifted or lowered a milk crate (Fig. 1) containing a sand-filled bag, allowing the total weight to be adjusted as needed. Participants were instructed to report the maximum weight they could voluntarily lift or lower while experiencing no pain. The lifting and lowering durations were determined by averaging the time taken to complete these tasks using two different loads (20% and 40% of each participant's MVE), with each condition repeated three times.

To measure the endurance time, participants lay on a bench (Fig. 2) with their hip region supported at the edge while holding a 5 kg weight. They were instructed to maintain the position until they experienced pain or fatigue in their back muscles. Using the measured MVE and lifting/lowering durations, an individualized experimental protocol was designed for each participant. The protocol used MAEs between 20% and 40% of MVE, with each task repeated 1 to 3 times per cycle. A sample calculation is provided in Table I.

Fig. 2. Endurance time test. Hip is supported at the edge of the bench, and the participant holds a 5 kg weight in their hands close to the chest.

TABLE I: SAMPLES OF RECOVERY TIME CALCULATION

Task	Effort (%MVE)	*f* (per cycle)	Task duration (s)	Total Recovery time (s)	Total time per repetition (s)
Task 1 lift	40%	4	2.75	81.43	23.11
Task 2 lower	20%	2	3.1	9.51	7.86

As shown, the recovery time for each repetition of each task was calculated. A program was developed using MATLAB (R2023a, The MathWorks Inc., Massachusetts, USA) to deliver auditory cues, guiding participants through the experiment. The program instructed participants when to perform a task (lifting or lowering) and when to rest, based on the pre-calculated recovery time. This cycle continued for one hour. Prior to the experiment, participants' heart rates were recorded under resting and a light activity (walking) conditions to serve as baseline measurements. During the experiment, heart rate was monitored every five minutes using an Apple Watch (Apple inc, USA) for comparison.

Following the experiment, participants repeated the endurance task and rated their perceived fatigue using Borg's scale (1–10). They also completed a questionnaire that included the following questions:

1. Rate the task based on the following criteria (0: very low – 100: very high):
   - How mentally demanding was the task (mental demand)?
   - How physical demanding was the task (physical demand)?
   - How hurried or rushed was the pace of the task (temporal demand)?
   - How hard did you have to work to accomplish the task (effort)?
   - How discouraged, irritated, stressed, and annoyed were you (frustration)?
2. Was the recovery time enough/more/less? (yes/no)
3. Would performing similar tasks for 8 hours lead to fatigue for you? (yes/no).

The reason for asking 8 hours in the last questions is that this is a typical shift duration.

III. RESULTS

The mean MVE was 19.25 ± 9.5 kg across both lifting and lowering tasks. Additionally, the average task duration was 2.75 ± 0.35 s and 2.9 ± 3.5 s for lifting and lowering, respectively.

Heart rate values for rest, walking, the experimental conditions are presented in Fig. 3. The average heart rate during rest was 70 ± 19 BPM, while walking resulted in an average of 93 ± 8 BPM, representing a 32% increase compared to rest. During the experiment, heart rate fluctuated but showed no consistent increasing or decreasing trend. The average heart rate during the experiment was 99 ± 23 BPM, only 4% higher than walking on average.

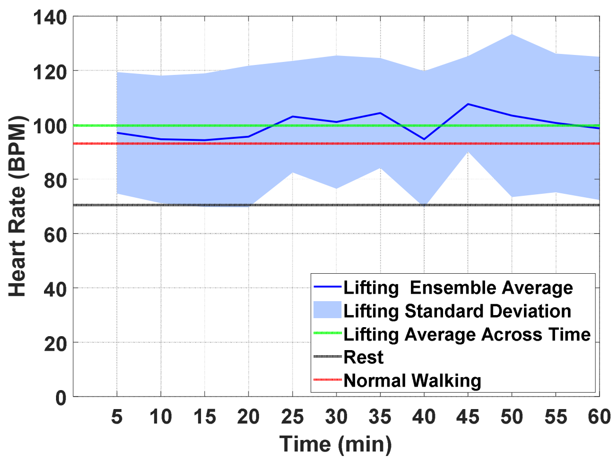

Fig. 3. Change in heart rate during the experiment and its comparison with rest and walking heart rates.

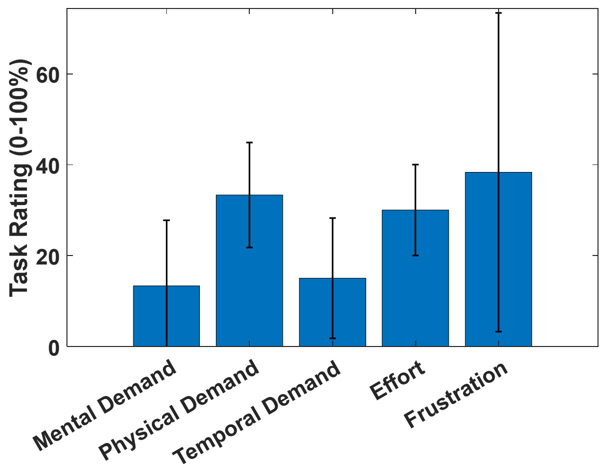

Fig. 4. Task rating in different aspects after one-hour experiment (mean ± standard deviation).

Endurance time before the experiment was 78.3 ± 20.5 s, while it decreased by only 5% after the experiment (74.6 ± 20.4 s).

Participants did not find the task to be mentally (13%) or temporally (15%) demanding. The perceived physical demand and required effort were rated at 33% and 30%, respectively. The task was reported to be moderately frustrating, with an average frustration level of 38% (Fig. 4).

All participants found the recovery time to be enough, with one of them indicating that it was more than what is needed. Additionally, for an 8-hour shift, participants found that tasks to be frustrating due to the repetition nature of it.

IV. Discussion

This study aimed to validate an ergonomic equation, originally developed for single tasks, for multiple subtasks. Both objective measurements, heart rate and endurance time, as well as subjective rating during multiple lifting and lowering tasks were recorded for the validation. Both objective and subjective assessments show the validity of the equation for multiple tasks. However, there are some concerns that need to be considered when the equation is applied for long shift.

Previous studies have demonstrated a strong correlation between fatigue and heart rate [19], [20]. Moreover, heart rate measurements obtained using Apple Watch have been shown to be accurate [21], [22]. In this study, heart rate was used as an indicator to monitor fatigue levels during the experiment. To establish a baseline for comparison, heart rate was also recorded during resting and walking conditions. As shown in Fig. 3, heart rate during the experiment remained relatively stable, with fluctuations but no clear increasing or decreasing trend. This suggests that fatigue did not accumulate over the course of the experiment, and participants' performance remained consistent. While the average heart rate during walking was 32% higher than at rest, the average heart rate during the experiment was only 4% higher than during walking. This small difference indicates that the recovery periods provided between trials were sufficient to prevent significant fatigue, and that participants finished the experiment with a fatigue level comparable to that of walking alone.

Changes in endurance time were consistent with the observed heart rate data. On average, participants' endurance time decreased by only 5% following the experiment. This minor reduction further supports the conclusion that participants did not experience significant fatigue and that the recovery periods provided were adequate.

As mentioned in the Methods section, the effort level, or MAE, for each task was set between 20% and 40% of the MVE. As shown in Fig. 4, participants rated the perceived effort and physical demand of the task at approximately 30%, aligning well with the intended effort range. This demonstrates that participants were able to accurately perceive and report the level of effort exerted during the experiment.

Although participants did not report the task to be mentally or temporally demanding, they reported frustration as the most significant challenge, particularly when asked about performing it over a full shift (eight hours). During the experiment, participants repeatedly performed four tasks over the course of one hour. The repetitive nature of the task was commonly cited as a primary source of frustration, surpassing even the perceived physical demand. This consistent feedback among participants highlights the importance of incorporating task variation and minimizing repetition to reduce frustration and improve long-term task sustainability for workers.

As assistive technologies such as exoskeletons become increasingly integrated into industrial settings, it is important to consider how these devices influence the inputs to existing ergonomic equations. Exoskeletons are designed to offload a portion of the biomechanical demands placed on the user, thereby reducing the muscular effort required to perform a task. In the context of our model, MAE represents the percentage of MVE that can be safely sustained at a given duty cycle. While exoskeletons do not change MVE itself, they reduce the effort (numerator in the MAE ratio) by assisting with load support. For instance, if an exoskeleton reduces effort by 25%, which can be up to 61% based on the task and type of exoskeleton as reposted in [23], substituting this adjusted MAE into equation (3) allows us to predict shorter required recovery times or higher allowable external loads. The second way of integrating exoskeletons into this ergonomic model is the exponent n in the original equation.

This study has several limitations that should be addressed in future research. First, while the current findings provide promising evidence for the validity of the ergonomic equation in multi-task scenarios, the number of participants was limited. Increasing the sample size in future studies would strengthen the statistical power and generalizability of the results. Second, as assistive devices such as exoskeletons are increasingly used in industrial environments, future work should focus on integrating the support provided by these technologies into ergonomic models. This would involve adapting or extending existing equations to account for the reduced biomechanical load experienced by users. Lastly, the current validation focused exclusively on lifting and lowering tasks. To ensure broader applicability, future studies should assess the equation's validity across a wider range of tasks commonly performed in occupational settings, such as pushing, pulling, or overhead work.

CONCLUSION

This study validated the use of a modified ergonomic equation, originally intended for single, repetitive tasks, for assessing recovery needs across multiple subtasks in a one-hour experimental setting. Both physiological measures (heart rate, endurance time) and participant-reported perceptions supported the equation's accuracy and effectiveness in managing fatigue during variable tasks. The recovery times calculated using the adapted model were sufficient to prevent fatigue buildup, as demonstrated by stable heart rate trends and minimal decreases in endurance capacity. Participants also confirmed the perceived effort aligned with the modeled intensity levels. However, reported frustration, particularly concerning long-term repetition, underscores the importance of task variation for sustainable work design. While the equation is effective for short-term multi-task planning, additional consideration is needed when applying it to prolonged shifts. Future research should explore integrating psychological demand and longer-term fatigue to further refine predictive exposure models in real-world occupational settings.

ACKNOWLEDGMENT

We acknowledge that this project was funded by the Natural Sciences and Engineering Research Council of Canada in partnership with Alberta Innovates (Grant # ALLRP 567348 – 21).

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