



Article

Rest Interval Modeling for Repetitive Lifting Using Task Characteristics

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Abstract

Overexertion, usually caused by manual material handling (MMH), often leads to work-related musculoskeletal disorders (WMSDs). These can be prevented during MMH tasks by redesigning them to include sufficient rest periods. Task characteristics play an important role in the redesign of the job. This study evaluated the effect of five task characteristics—weight, duration, frequency, distance, and angle of symmetry—at two levels on the maximum voluntary contraction recovery rate (Muscle Voluntary Contraction Recovery Time (MVCRT), defined as the time required for the muscle to recover to 80% of the initial Maximum Voluntary Contraction (MVC) value) of the muscles and developed a work-rest interval model based on these task characteristics. The results show that the weight and duration had a significant effect on MVCRT, increasing it by 32% and 21%, respectively. The interaction between frequency and distance also significantly impacted MVCRT. A simplified mathematical model was developed and validated by comparing a set of the model-generated data with experimental data. The simplified regression model demonstrated moderate predictive capability with an R^2 value of 0.52. The ANOVA shows no significant difference between the data. The study's results and mathematical models can be used during task design to reduce WMSDs. Because approximately 48% of the variability in MVCRT remained unexplained, direct application of the model to establish worker-specific work-rest intervals may result in underestimation or overestimation of recovery requirements. Therefore, the model should be interpreted as a preliminary estimation framework.



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Keywords: MVC; recovery time; manual material handling; task characteristics; rest intervals; repetitive lifting

1. Introduction

WMSDs are a significant cause of concern in industry. Musculoskeletal disorders (MSDs) include various degenerative and inflammatory conditions that affect muscles, tendons, joints, peripheral nerves, ligaments, and supporting blood vessels [1]. According to the World Health Organization, the leading causes of MSDs are forceful exertions, long-term repetitive tasks, poor work practices, and sustained uncomfortable postures [2]. According to the 2025 Liberty Mutual Workplace Safety Index [3], workplace injuries

continue to impose a substantial economic burden on U.S. industries, with overexertion involving outside sources remaining the leading cause of workplace injury costs and accounting for approximately \$13.7 billion annually, primarily due to manual material handling activities. Recent U.S. Bureau of Labor Statistics reports [4] also indicate that work-related musculoskeletal disorders and overexertion injuries continue to represent a major proportion of occupational injuries requiring days away from work in private industry settings. In the same report, the incidence rate of overexertion is higher than that of injuries from other events or exposures. The incidence rate of overexertion is 28.2, while falls, slips, and trips come next, with a rate of 23.9 cases for 10,000 workers. Contact with objects and equipment occurs at an incidence rate of 23.5, while the remaining causes of injuries are significantly less than these three factors. The incidence rates of different exposures are given in Figure 1.

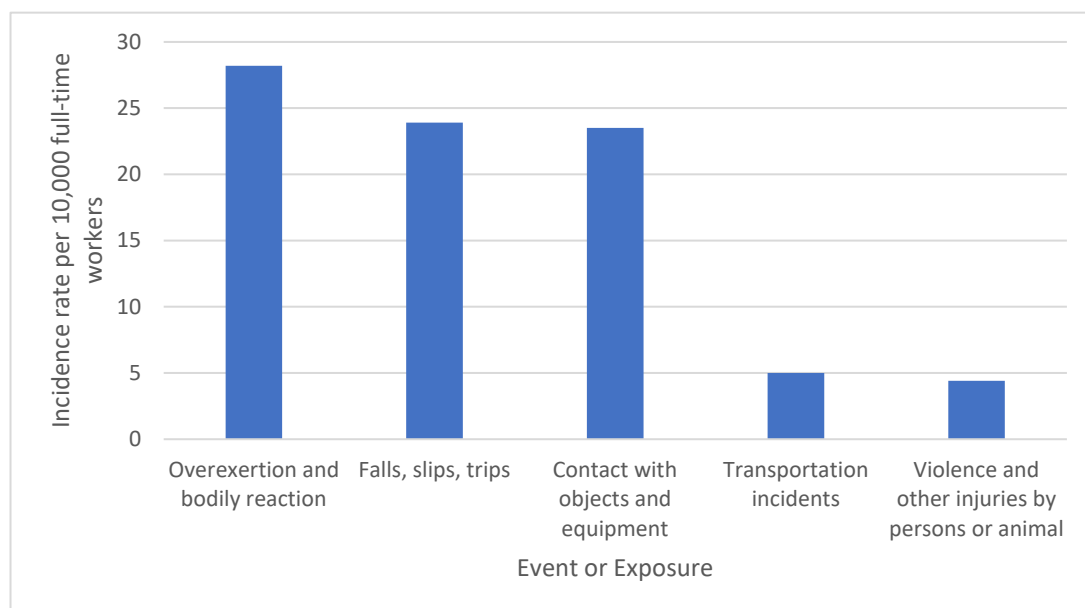


Figure 1. Nonfatal occupational injury and illness incidence rates for cases by exposure.

The consequences of overexertion are muscle fatigue and insufficient recovery time. According to Anderson and Chun [5], overexertion injuries are mainly caused by MMH tasks. MMH tasks are present in many industries; in most cases, substantial physical effort is required to perform a task. Workers performing MMH activities in most industries and occupations are at higher risk of WMSDs. Recovery from fatigue plays an essential role in preventing MSD. The most optimum way of reducing injuries is redesigning the job or task. However, not all tasks can be modified from the perspective of manual labor [6]. If jobs cannot be modified according to the worker's needs, the job should be redesigned with enough rest intervals between the tasks. Rajesh [7] classified tasks based on work environment characteristics. The work environment characteristics are task-related variables (intensity, frequency, the distance of lift), material-related dimensions (direction and load), and work system-related dimensions (equipment and layout). The jobs may be modified by changing the work environment characteristics. These characteristics can be used to redesign the work to match the worker's capabilities.

Many studies were conducted on the effects of task characteristics on workers' capability [8–13]. However, none of the studies have investigated the effect of more than three task-related variables on rest intervals. This study aims to examine the effects of five task characteristics and to build a mathematical model for designing a work-rest schedule.

2. Literature Review

2.1. Manual Material Handling and WMSDs

MMH encompasses activities like lifting, lowering, and transporting loads using human force [14]. MMH is a primary risk factor for WMSDs, often caused by improper lifting and muscle fatigue [15]. When muscle fatigue exceeds recovery thresholds, severe injury can occur, necessitating appropriate rest [16,17]. Strategies to prevent WMSDs include epidemiological, biomechanical, psychophysical, and physiological approaches [18]. The epidemiological approach examines job and workplace characteristics, historical data, and other sources to identify causes of injuries and the recurrence of medical problems in the population. The biomechanical approach finds the causes of WMSDs by investigating the human body's physical properties and factors to create a safe and injury-free environment. The psychophysical approach provides a task, situation, or environment acceptable to the participants. Finally, physiological parameters like $\dot{V}O_2$, EMG, Heart rate, or other cardiovascular load indicators determine the body's fatigue levels in a physiological approach. In their study, Ciriello and Snook [19] outlined three main methods of prevention of WMSDs in the lower back. The three main methods are worker selection, training, and ergonomics. While worker selection and training are common, ergonomics—matching work design to human capabilities—is the most effective method for providing a safe workplace [20].

2.2. Task Characteristics and MAWL

Ergonomic standards like the Revised NIOSH Lifting Equation and Snook Tables define safe working limits for workers for an MMH task [21,22]. The NIOSH equation was based on physiological, psychophysical, and biomechanical approaches. The equation was revised in 1991 to address some of the shortcomings in the previous equation. Asymmetric and coupling multipliers were added to the new equation. Psychophysical methods for the MMH task determine the Maximum Acceptable Weight of Lift (MAWL). Aghazadeh [20] used a psychophysical method to determine the MAWL. In his study, the participants performed an MMH task twice. An empty box was initially used, and then the participants were given a heavy box with weights and asked to adjust by adding and removing the weights until they reached a comfortable weight they could lift for 8 h. The weight average of the two trials was considered the MAWL of the participant. Chaffin and Park [23] conducted a research study on the MAWL of workers in electronics manufacturing companies. The research was conducted for five months on 135 workers. It was found that when the weight is lifted closer to the body, the MAWL should not exceed 35 lbs. If the load was lifted 20 inches from the ankle, the MAWL should be capped at 20 lbs. Garg and Banaag [8] studied the effects of symmetric angle, frequency, and lifting height in a repetitive task. Three angles of symmetry, namely 30, 60, and 90 degrees, were studied along with three frequencies of 3, 6, and 9 lifts per minute. The two lifting heights were from the floor to 81 cm and from 81 cm to 152 cm. The impact of the three task characteristics was studied on MAWL, static strength, rating of perceived exertion (RPE), and heart rate. The study found that the RPE and heart rate increased with an increase in the symmetric angle, while MAWL and static strength decreased. The frequency and height of lift had no significant impact on MAWL. Gallagher [9] studied the effect of posture, lift distance, and symmetry on MAWL, oxygen intake, and heart rate. The task variables' posture used stooping and kneeling, while the lift distance was 35 cm and 60 cm. The task was performed at either symmetric or asymmetric angles on eight male participants using a within-subject design for eight treatments. The study results found a significant asymmetric effect on the heart rate, and the physiological responses were lower in the case of kneeling. MAWL, which was obtained by the psychophysical approach, had higher values in asymmetric

lifting tasks. The participants had higher MAWL values at lower lifting heights than at higher ones.

2.3. Work-Rest Cycles

Work-rest cycles are defined by resting frequency, duration, and intervals, and are essential for fatigue recovery [24–26]. Early formulas by Lehman [27] and Murrell [28] used energy expenditure to calculate rest. However, many models [18,29,30] assume that low-intensity tasks (below 5 kcal/min or 33% VO_2 max) require zero rest. This is a significant limitation, as repetitive low-intensity work still accumulates fatigue [31,32]. A study was conducted by Kopardekar and Mital [33] to evaluate the effect of three rest intervals on workers. The three treatments used were 5 min of break after 30 min of work, 10 min of break after 60 min of work, and no break for 120 min of work. The 5 min break after 30 min of work was sufficient, while no break and 120 min of work led to the most significant number of errors compared to the other two treatments. Dababneh and Swanson [34] conducted a study to see the impact of extra breaks on traditional workers. Two different breaks were compared, with workers getting a break of 9 min after 51 min of work and 3 min of break after every 27 min. The study found that a 9 min break was more effective than the 3 min break. The researchers concluded that the best way to schedule breaks depends on the task demands, duration, and cycle time. Balci and Aghazadeh [35] compared the three different work schedules of a video display terminal (VDT) user in their research. The performance and perceived level of discomfort were measured among ten subjects for the schedules. The three schedules used were 10 min of rest for 60 min of work, 5 min of rest for 30 min of work, and micro-breaks for 2 h of work. The micro-breaks were 30 s after 15 min, a more extended break of 3 min within an hour, and 14 min after 2 h of work. The micro breaks were better as they decreased the level of discomfort among the users and increased their speed, accuracy, and performance. A study was conducted by Bahmani Bahman Beiglou [36] to determine the optimum rest periods for lifting tasks using perceived exertion, heart rate, and physical strength in a manual lifting task. The task was performed for a fixed duration of 20 min. The rest intervals for the study were 5, 10, 15, and 20 min. Fifteen minutes of rest was optimal over the rest intervals compared with heart rate elevation, physical strength, and perceived exertion. Prabhakar [37] compared the effect of different rest intervals on the EMG recovery of the Biceps muscles, heart rate, and perceived exertion in his research. The treatments of no rest (0), 5 min, 10 min, and 15 min were used for the study. The task was performed for 10 min, followed by rest treatment, then continued for another 2 min. The results showed that participants should be given at least 5 min of activity, and 10 min of rest was optimum for the task. Surface EMG sensors were positioned on the belly of the biceps muscle following standard muscle preparation procedures to improve signal acquisition consistency and reproducibility.

2.4. Electromyography (EMG) in Fatigue Modeling

EMG is a non-invasive tool used to identify muscle fatigue by measuring reductions in contraction ability and shifts in signal frequency [16,25,38,39]. A study was conducted by Kroon and Naeije [40] to look at the recovery of the maximum voluntary contraction (MVC), endurance time, and the root mean square during the exercise of the biceps brachii. Studies show that exercise-induced fatigue has long-lasting physiological effects, sometimes detectable for days [41,42]. The study showed that exercise had a long-lasting impact on the physiological parameters impacting the EMG signal. Masuda et al. [38] researched the effects of contraction types on muscle fiber contraction. Their study showed a decrease in the median frequency of the muscles in both static and isometric contractions. Ahmadi et al. [41] used EMG to investigate heavy eccentric effects on the biceps. There were

significant alterations in the EMG reading for up to seven days after the heavy exercises. The study also found that the change in EMG muscle readings is not a functional marker of muscle damage. Banks and Aghazadeh [42] evaluated the effect of progressive fatigue on lower back muscles using EMG during a manual lifting task. The study estimated the average weight for lift as 15.95 kg based on the psychophysical approach. The study found that muscle fatigue progressed based on the duration and repetition of the task.

2.5. Summary and Research Gap

While task characteristics significantly impact MAWL and energy expenditure, existing rest allowance models focus primarily on aggregate energy expenditure. There is a notable lack of research integrating specific task characteristics into a rest allowance model for lifting. This study aims to fill that gap by determining rest interval models based on these characteristics.

3. Methods and Procedures

3.1. Participants

The experiment involved 32 male university students. Female participants were not involved in the experiment since they changed the protocol with different weights, as the lifting standards were defined differently for males and females. One of the experimental aims was to develop a model; therefore, having different measurement data sets causes difficulty in the analysis phase. The participants signed an informed consent form approved by the LSU Institutional Review Board (IRB) before the experiment. The participants' ages ranged from 20 to 43 years, with an average of 25.03 years, and a body mass index (BMI) of 25.31.

The present study focused only on male participants to maintain consistency in the lifting conditions and task parameters during model development. However, the authors acknowledge that physiological differences between males and females may influence muscle fatigue and recovery characteristics. Therefore, future studies should include female participants and evaluate gender-specific responses to improve the generalizability of occupational rest interval models. Symmetric lifting conditions referred to lifting tasks performed without trunk rotation, whereas asymmetric lifting conditions involved angular deviation during load handling. Commercially available wearable monitoring devices may also provide practical opportunities for future real-time occupational fatigue and recovery assessment applications. Participant anthropometric factors, including height and body weight, may additionally influence lifting posture, lifting distance, and lifting angles during manual material handling activities and should be considered in future investigations. The use of only male university students may limit the applicability of the proposed mathematical model to female workers and older employees because physiological characteristics, muscle strength, fatigue responses, and recovery patterns may differ across demographic groups. Consequently, additional validation involving female participants and older worker populations is necessary before broader occupational implementation of the model.

3.2. Tools and Equipment

The tools and equipment used in the study were Delsys Bagnoli version 4.3 EMG software and hardware, a wooden test platform with Adjustable levels of shelves, a wooden box with metal weights, a handgrip dynamometer, a static arm lift measurement dynamometer, a Nautilus treadmill (Nautilus, Inc., Vancouver, WA, USA), and a Gym Boss timer (Gymboss LLC, Clair, MI, USA) application for indicating the frequency.

Delsys Bagnoli EMG (Delsys, Natick, MA, USA), a data acquisition system, was used along with the software to acquire and process the data. The EMG signals were acquired at a sampling frequency of 1000 Hz, and surface EMG sensors were positioned on the belly of the biceps brachii muscle during data collection. The EMG system was an 8-channel wired device that could simultaneously acquire data from 8 muscles. An image of the Delsys Bagnoli EMG system is shown in Figure 2.

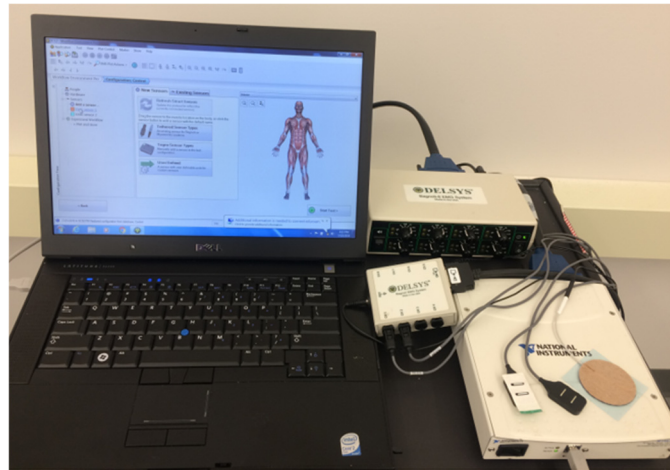


Figure 2. Delsys Bagnoli EMG.

A wooden platform with adjustable shelves was used during the lifting task. The lower shelf was set to the average knuckle height of 76 cm from the ground, and the top shelf was adjusted according to the treatment. Figure 3 shows the image of the lifting platform.



Figure 3. Lifting platform.

A wooden crate was used to hold the weights for each trial. The crate's measurements were 45.5 cm × 30.5 cm × 20.5 cm. The crate had two handles installed on both sides, cushioned by a racquet grip. Different kinds of weights were used to fill the wooden crate. The image of the crate and weights is shown in Figure 4.



Figure 4. Wooden crate used for lifting.

3.3. Experimental Design

The experiment used a two-factorial block design. The study specifically employed a full two-level factorial block design that included all possible combinations of the five task characteristics, resulting in 32 treatment combinations. Aghazadeh [43] and Aghazadeh and Amini [44] used this design in their studies. The five task characteristics had two levels of interaction. They included the weight of lift (L), frequency of lift (F), duration of lift (D), distance of lift (H), and angle of lift (A). The number of possible combinations of treatments was 25, equaling 32 treatment combinations. Each participant was assigned only one treatment combination. The block design would prevent the carry-over effect if the participant performed multiple treatments. The participants were randomly assigned to each treatment.

The statistical analysis focused on the main effects, two-factor interactions, and three-factor interactions. The fourth- and fifth-order interactions were not included because these higher-order interactions are generally considered to have negligible practical importance in applied ergonomics experiments and were therefore incorporated into the residual error term for testing the lower-order effects. The pooled higher-order interactions were used as the ANOVA error term because the experimental design assigned one participant to each treatment combination, resulting in no independent within-cell replication error term.

From the snook table [22], it was determined that 8 kg could be lifted to 76 cm (which was closest to their value of 70 cm of vertical distance) by the 90th percentile of the healthy males at 12 lifts per minute. Thus, 8 kg was considered the lower limit. The upper limit was set at 12 kg based on the snook's table, with the lift frequency reduced to 6 lifts per minute. The closest value in the Snook table was 10 kg at a lift every 9 s. Since the higher frequency was halved, equivalent to a lift every 10 s, the next highest value in the Snook table was considered. The next highest value was 12 kg for a lift every 14 s. In his study, Gallagher [9] used 35 cm and 60 cm as the distance for the lift. 35 cm was used as the lower lift distance for the experiment, and the upper distance was doubled to 70 cm. The heights were adjusted from knuckle height. The corresponding value for 35 cm from the Snooks table was 13 kg for the 90th percentile (25 cm was considered the closest value to 35 cm). Thus, 20 kg was still above 13 kg to create a clear distinction for studying the effect. As mentioned in the literature review, Garg and Banaag [8] used three angles of 30, 60, and 90 to study symmetry. Gallagher [9] also classified the task based on symmetry. In the current study, the task was divided into symmetric and asymmetric. Symmetric lifting refers to lifting without trunk rotation, whereas asymmetric lifting involves angular deviation during load handling. The symmetric task (0°) was considered the lower value for the

symmetric angle, while 90° was taken as the higher value. The independent variables and their value are given in Table 1.

Table 1. Task-Related Independent Variables of the Study.

Variable	High Level	Low Level
Weight (kg)	12	8
Frequency (Lifts/min)	12	6
Duration (min)	10	5
Distance of lift (cm)	70	35
Angle of Lift (degrees)	90	0

MVC was the response variable, signifying the measure of strength. The MVC decreases with the exertion of the muscles. As the muscles relax, they recover and gain contraction power. According to Schwendner et al. [45], the muscles should return to 80% of the initial MVC value to recover. This threshold has also been used in previous muscle fatigue and recovery studies to represent functional recovery of muscle performance during repetitive occupational tasks [46,47]. Stull and Clarke [46] reported that approximately 84% of MVC was recovered following short-duration handgrip exertion, while Stokes et al. [47] observed recovery behavior using an 80% MVC threshold during muscle fatigue assessment. Similarly, this paper looked at the time taken by the muscles to reach 80% of their initial MVC value, which was called MVCRT. The 80% MVC threshold was adopted as an operational recovery criterion based on previously published ergonomic and physiological studies rather than as a criterion for complete physiological recovery. However, the authors acknowledge that residual fatigue below full MVC recovery may accumulate during prolonged work shifts and repeated lifting activities. The MVCRT was calculated after each trial. The nature of the task had an impact on muscle strength. The strength expended, in turn, determines the time taken by the muscle to recover.

3.4. Procedure

The task involved lifting from the knuckle height to the height allocated based on the participant's treatment. Figure 5 explains the experimental protocol.

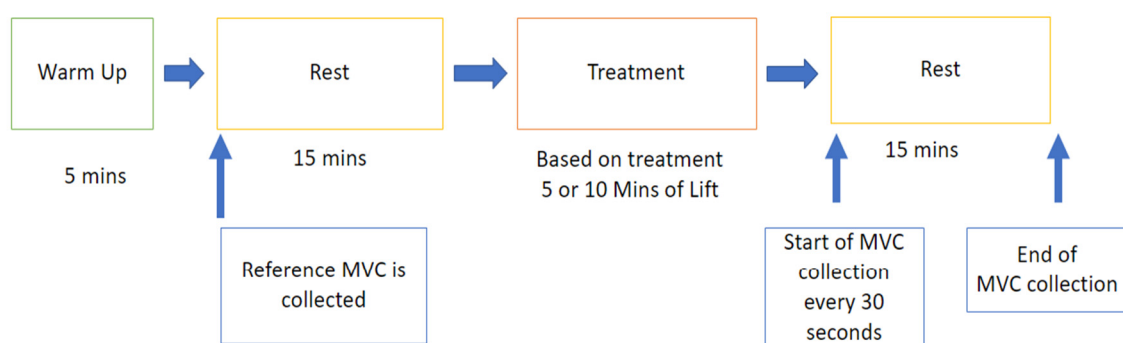


Figure 5. Experimental Protocol.

The participants were also shown a demonstration of the safer way of lifting. The participants then warmed up on the treadmill for five minutes at three mph to prevent any injuries during the lifting. The participants were asked to relax for 15 min while the EMG sensors were set up and placed on the biceps brachii muscles in both hands. The biceps brachii muscle was selected because the controlled repetitive lifting task involved upper-extremity load handling and repeated elbow flexion, while future studies should also evaluate lumbar erector spinae and trapezius responses for broader MMH fatigue

assessment. The MVC data were collected by asking the participants to exert their maximum force for three seconds, and five samples were taken on the dominant hand. At the end of 15 min of rest, the participants began lifting based on the assigned treatment. The participants lifted the crate with weights at the signal from the frequency timer. The participants performed the lift while a helper lowered the crate to the initial position at each lift's end. Figure 6 shows the participants lifting from a lower level to a higher level. Once the task was completed, the participants were asked to rest for 15 min while exerting the MVC every 30 s. Figure 7 shows the participant performing an MVC exertion. The MVC reference value was determined from the peak muscle activation segment obtained during the MVC recording procedure rather than from averaging the entire 30 s recording duration. The figure also illustrates the lift distance and lift angle considered during the experimental lifting tasks. The study focused on the biceps brachii because this muscle was directly involved in the repetitive lifting motion and provided a consistent indicator of upper-extremity fatigue and recovery across all treatment conditions. However, the authors acknowledge that manual material handling tasks also involve other load-bearing muscles, including the lumbar erector spinae and trapezius, and future investigations should incorporate multiple muscle groups to provide a more comprehensive assessment of fatigue and recovery responses. Although the lumbar erector spinae and other trunk muscles are important contributors during manual material handling activities, the present study focused on a single muscle group to maintain a controlled experimental protocol and to develop an initial recovery-time model based on a consistent physiological measure. The authors acknowledge that monitoring additional load-bearing muscles would provide a more comprehensive assessment of fatigue during lifting tasks and should be considered in future investigations.

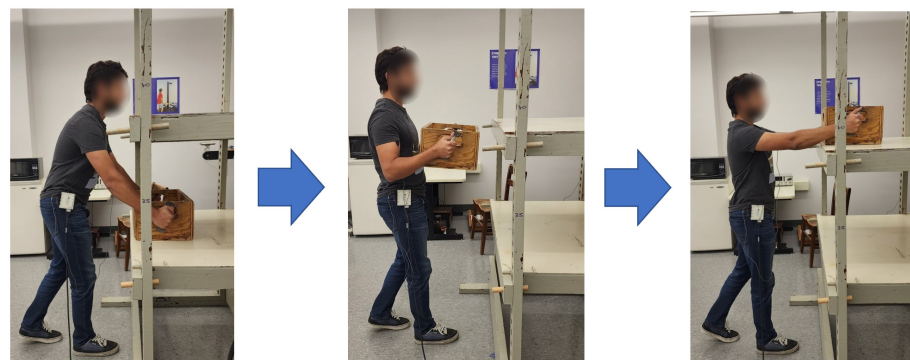


Figure 6. Participant lifting from a lower level to a higher level.

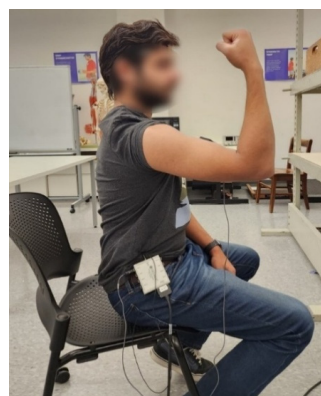


Figure 7. Participants performing the MVC.

3.5. Data Processing and Analysis

The Mean Absolute Value (MAV) is calculated in the software and exported as an Excel file. MAV was used as the EMG amplitude measure for tracking recovery over time and identifying when the muscle recovered to 80% of the initial MVC value. The MVC value was determined from the first 30 s of the data. The data in each Excel file is analyzed to determine the time taken after the trial to achieve 80% of the MVC value, called MVCRT. ANOVA was used to assess the effect of task characteristics on the MVCRT, while multiple regression analysis was employed to find the interaction effects of the factors. The backward variable selection method was used to build the model. The processed EMG amplitude data obtained from the manufacturer-provided acquisition software were used to evaluate MVC recovery characteristics and determine the time required to recover to 80% of the initial MVC value. The analysis focused on recovery trends derived from the processed EMG output data.

4. Results

4.1. Task Characteristics and Interaction

An ANOVA test was performed to test the significance ($p = 0.05$) of each task characteristic of the MVCRT. The test results are tabulated in Table 2, where an asterisk marks significant factors. The weight significantly impacted the recovery times, followed by the lift duration. The recovery time for the weight increased by 32.5% from lower to higher levels, while the recovery time increased by 21% for the duration. Frequency was insignificant at a 95% confidence level, but the effect was greater than distance and angle.

Table 2. MVCRT for Task Characteristics.

Parameter	Levels	Mean (S.D.)	<i>p</i> -Values
Weight	8	148 (31.91) s	0.0024 *
	12	196 (39.41) s	
Frequency	6	165 (39.51) s	0.17
	12	180 (46.51) s	
Duration	5	156 (38.21) s	0.0131 *
	10	189 (42.01) s	
Distance	35	170 (48.61) s	0.71
	70	174 (38.31) s	
Angle	0	171 (40.61) s	0.71
	90	174 (46.81) s	

* *p*-Value < 0.05.

The graphs showing the mean for each characteristic between the two levels are shown in Figure 8 below. The weight and duration had the highest slopes compared to distance and angle, which had similar slopes.

An ANOVA test was performed for the two-factor interactions, and the results are presented in Table 3. Only the interaction between frequency and distance had a significant *p*-value of 0.0351; all the other interactions did not significantly affect the recovery times. The non-significant weight-by-duration interaction suggests that the combined influence of these factors was not substantially different from their individual effects within the present conditions, while frequency and distance showed smaller independent effects relative to weight and duration. The graph showing the interaction between frequency and distance is shown in Figure 9.

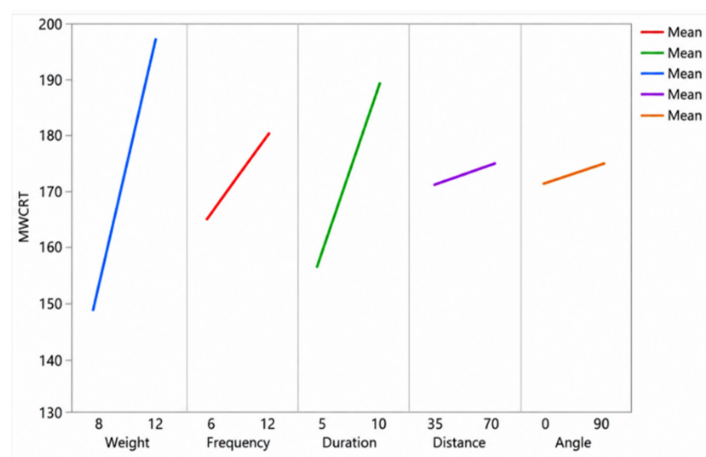


Figure 8. MVCRT vs. Task Characteristics.

Table 3. *p*-Values for Two-Factor Interactions.

Task Characteristics	<i>p</i> -Value
Weight vs. Frequency	0.69
Weight vs. Duration	1.00
Weight vs. Distance	0.17
Weight vs. Angle	0.17
Frequency vs. Duration	0.29
Frequency vs. Distance	0.0351 *
Frequency vs. Angle	0.29
Duration vs. Distance	0.47
Duration vs. Angle	0.47
Distance vs. Angle	0.17

* *p*-Value < 0.05.

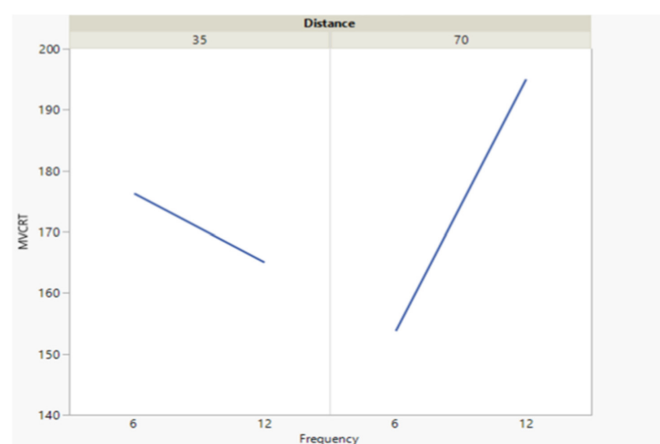


Figure 9. MVCRT vs. (Frequency vs. Distance). The line graph show the mean values at each level of the task characteristics.

An ANOVA test was performed on the means of the interactions. The *p*-values of the ANOVA test are presented in Table 4. None of the three-factor interactions was significant, with the interaction of weight, frequency, and duration having the closest value at 0.06.

Table 4. *p*-Value for Three-Factor Interactions.

Task Characteristics	<i>p</i> -Value
Weight vs. Frequency vs. Duration	0.06
Weight vs. Frequency vs. Distance	0.47
Weight vs. Frequency vs. Angle	0.47
Weight vs. Duration vs. Distance	0.29
Weight vs. Duration vs. Angle	0.29
Weight vs. Distance vs. Angle	0.29
Frequency vs. Duration vs. Distance	0.47
Frequency vs. Duration vs. Angle	0.47
Frequency vs. Distance vs. Angle	1.00
Duration vs. Distance vs. Angle	0.71

4.2. Mathematical Modeling of MVCRT

4.2.1. Backwards Selection Method

This method involved removing the least significant variables based on the *p*-value threshold of 0.05. The task characteristics and their interactions were initially included in the model, and non-significant variables were eliminated progressively. The final regression model achieved an R^2 value of 0.49. The R^2 value indicates that the backward selection model has only moderate to relatively weak predictive capability, as approximately half of the variability in MVCRT remains unexplained by the equation. Therefore, the model should be interpreted as a preliminary estimation framework rather than a highly accurate predictive model. Table 5 provides the final model for the backward selection of the equation. The present study was conducted using male university students without occupational manual material handling experience under controlled laboratory conditions. The study focused on male participants during the preliminary model development phase to reduce physiological variability and because the lifting standards applied in the experimental protocol were based on male participant characteristics. Future studies should evaluate potential sex-based differences in muscle fatigue and recovery behavior by developing comparative models involving both male and female participants. Industrial workers may differ substantially from student populations in terms of physical conditioning, task familiarity, muscle adaptation, and baseline fatigue tolerance. Therefore, the proposed MVCRT model should be interpreted as a preliminary estimation framework, and additional validation involving occupational worker populations is necessary before broader industrial application of the model. Accordingly, the proposed work-rest recommendations should not be generalized directly to female workers, older workers, or broader industrial populations without additional validation, because physiological characteristics, occupational experience, and recovery responses may differ across these groups. The model was not considered sufficiently predictive to establish safety protocols independently. Instead, the analytical objective was to identify general relationships between task characteristics and recovery time. Given the R^2 value of 0.49 and the substantial unexplained variability, the model should be used only as an initial estimation tool and should be supplemented by additional validation and ergonomic assessment before being considered for occupational decision-making.

Table 5. Backward Selection with R^2 Value.

Formula	R^2 Value
$MVCRT = 0.1 + 12.19 W + 6.75 D$	0.49

4.2.2. Simplified Model

A model having all the task characteristics was developed and given in Table 6. Standard errors for the simplified model coefficients are also reported in Table 6 to indicate the precision of the parameter estimates. The equation is evaluated in the next section.

Table 6. Simplified Model with R² Value and Standard Errors.

Variable/Model	Coefficient/R ²	Standard Error
Intercept	−30.00	42.21
Weight (W)	12.19	2.87
Frequency (F)	2.50	1.91
Duration (D)	6.75	2.30
Distance (H)	0.11	0.33
Angle (A)	0.04	0.13
MVCRT = −30 + 12.19 W + 2.5 F + 6.75 D + 0.11 H + 0.04 A	0.52	

5. Evaluation

The power analysis determined that data from 10 participants were needed to evaluate the models. Five participants' data were selected randomly from the model, while five other participants were tested, and experimental data were collected. Thus, the model evaluation considered 10 observations in total, including five observations from the original experimental dataset and five additional experimental observations collected separately. Table 7 shows the difference between the values obtained from the model and the actual results. The first five combinations were derived from modeling data, while the last five were obtained from experimental data. The most significant difference in the values was for treatment 3 in the table, with an increase of 33%. The second highest difference was a decrease of 23% for treatment 9, where the recovery time decreased by 41 s. The most significant difference in time was for treatment 2, with a decrease of 45 s. The closest value to the actual results was treatment 8, with a 4 percent or 7 s reduction. Overall, although the model produced an average MVCRT value close to the observed mean, the individual prediction differences indicate that the model should be interpreted as a preliminary estimation framework rather than a high-precision prediction tool for direct practical application. An ANOVA test showed no significant difference between the actual and model-generated data, with a *p*-value of 0.89. However, the absence of a statistically significant difference should not be interpreted as evidence of high predictive precision, since some individual treatment combinations still showed noticeable prediction variability. These larger discrepancies indicate that the simplified model did not perform equally well across all treatment combinations. Specifically, the model overestimated MVCRT for Treatment 3 and underestimated MVCRT for Treatment 9, suggesting that individual prediction errors may remain substantial even when the overall mean difference appears small. Therefore, the model should be interpreted cautiously as a preliminary estimation framework rather than a reliable treatment-specific prediction tool.

Table 7. Evaluation of MVCRT.

Treatment No.	Weight	Frequency	Duration	Distance	Angle	MVCRT Actual	MVCRT Model	Percentage Change
1	12	6	5	35	90	210	172.48	−18%
2	12	12	10	70	90	270	225.08	−17%
3	8	6	5	35	0	90	120.12	33%
4	8	12	5	35	90	120	138.72	16%
5	12	6	10	35	0	180	202.63	13%
6	8	12	5	35	90	150	138.72	−8%
7	12	6	5	70	0	150	172.73	15%
8	12	6	10	35	0	210	202.63	−4%
9	8	12	5	70	0	180	138.97	−23%
10	8	12	10	35	90	150	172.47	15%
Mean						171	168.50	−1%
S.D.						51.09	34.27	−33%

It should be noted that the comparison between the model-generated values and the additional experimental data was intended as a preliminary evaluation of model behavior rather than a complete statistical validation of the five-variable regression model. Because of the limited number of additional experimental observations, the model should be interpreted as an initial work-rest estimation framework. Broader validation using a larger independent sample and additional treatment combinations is needed before the model can be generalized for wider industrial applications. The small validation sample, including only five newly collected experimental observations, limits the ability to fully assess model generalizability and predictive stability across broader populations and task conditions. The authors acknowledge that the out-of-sample evaluation included only five newly collected observations and therefore does not provide sufficient statistical power for a rigorous external validation of the model. Consequently, the evaluation should be interpreted as a preliminary assessment of model behavior rather than conclusive evidence of predictive performance, and larger independent validation datasets are needed in future studies.

6. Discussion

The MVCRT increased for all the task characteristics from the lower to the higher levels. The highest increase was found in weight and duration, while the lowest was in distance and angle of symmetry. The recovery time for the weight increased by 32.5% from lower to higher levels. The weight results are consistent with the study by Nimbarte [48], which showed that EMG activity increased with the increase in weight. The recovery time increased by 21% for the duration and 9% from a lower frequency to a higher frequency. The study by Kroon and Naeije [40] found that the duration of the activity had a significant impact on the EMG signal, thus significantly affecting the recovery time. A study by Banks and Aghazadeh [42] also found that the progression of muscle fatigue is based on the duration. These findings are consistent with prior MMH and EMG fatigue studies showing that increased loading demands and longer task exposure contribute to greater muscle fatigue accumulation and longer recovery periods. The recovery time increased by 2% for both distance and angle of symmetry from a lower level to a higher level, and the recovery times also increased from a lower level to a higher level for the two-factor interactions. However, the recovery time decreased for frequency and distance from 6 lifts per minute

for 35 cm to 12 lifts per minute. Similarly, the recovery times also decreased for 90 degrees from 35 cm to 70 cm. For three-factor interactions, the trend continues with recovery times increasing from lower combinations to higher combinations. However, there were three instances where the recovery time decreased from a lower combination to a higher one. There was a decrease in recovery time for the combination of five minutes and 35 cm from 6 to 12 lifts per minute. The recovery time also decreases for five minutes and zero-degree combination from 6 lifts per minute to 12 lifts per minute, and for the combination of 35 cm and zero degrees, from 6 to 12 lifts per minute.

The backward selection method was used to select the best model. Although the model was less complex, a more straightforward model having all the task characteristics was developed, without their interaction. The accuracy of the simplified model was tested, and statistical testing showed no significant difference between the actual and model-generated values. The simplified model is proposed to include all the task characteristics, and it may provide a practical preliminary tool for ergonomic assessment in the field, although additional validation is still required before broader industrial application. The predictive capability of the simplified regression model should be interpreted with caution. Although the model identified general recovery time trends associated with task characteristics, the R^2 value of 0.52 indicates that a substantial portion of the variability in MVCRT remains unexplained. In addition, some treatment combinations showed prediction differences of up to 33% between the model-generated and experimental values. Therefore, the model is more appropriately considered an approximate estimation framework for ergonomic assessment rather than a highly precise predictive tool for individual recovery times. The relatively large standard deviations observed for some treatment conditions indicate inter-subject variability in physiological responses to repetitive lifting tasks. Differences in individual muscle strength, physical conditioning, fatigue tolerance, lifting technique, and recovery capacity may have contributed to the variability in MVCRT among participants. Furthermore, because each participant was assigned to only one treatment combination to eliminate carry-over fatigue effects, between-subject differences were not averaged across repeated trials. Future studies using larger sample sizes and repeated observations for each treatment combination may help reduce variability and improve model stability. However, the R^2 value of approximately 0.49 indicates moderate predictive capability with substantial unexplained variability, and therefore, the model should be interpreted as a preliminary estimation framework rather than a highly precise predictive tool. Because nearly half of the variability in MVCRT remains unexplained, direct application of the model for worker-specific work-rest scheduling may result in underestimation or overestimation of recovery requirements, and, therefore, the model should be used cautiously until additional validation is performed using larger and more diverse populations.

7. Limitations

Another source of limitation was the relatively high inter-subject variability observed in the recovery times. The relatively large standard deviations observed for some treatment combinations are expected in physiological recovery studies involving human participants performing manual material handling tasks. Variability in recovery time may arise from normal differences in muscle strength, fatigue tolerance, conditioning level, lifting technique, and recovery characteristics among individuals. Despite this variability, the effects of the task characteristics on MVCRT remained consistent across the experimental conditions, particularly for weight and duration, which demonstrated statistically significant effects on recovery time.

8. Conclusions

This study aimed to evaluate the impact of task characteristics on the MVCRT and develop a predictive model for recovery time. Five task characteristics were tested at two levels using a two-factorial block experimental design. The results were analyzed, and a backward selection method was applied to develop the model. However, without interactions, a model was developed and evaluated based solely on the task characteristics. The weight ($p = 0.0024$) and duration ($p = 0.0101$) significantly impacted the recovery time of the MVC, with percentage increases of 32% and 21%, respectively. The frequency and distance interaction was the only significant two-factor interaction. None of the three-factor interactions was significant. The ANOVA conducted on the simplified model showed no significant difference between the actual recovery time and the model recovery time. The findings can be used to redesign lifting tasks in industrial settings. By considering factors such as weight, duration, frequency, distance, and angle of symmetry, the work environment can be optimized to reduce the risk of overexertion and musculoskeletal disorders. The work-rest cycle model developed in the study can aid in determining appropriate rest periods between MMH tasks. This information can be utilized to create efficient job rotation schedules, ensuring that workers have sufficient recovery time between physically demanding tasks. The results of the study can contribute to the development of ergonomic guidelines for MMH tasks. Although the simplified model demonstrated reasonable agreement with the experimental means, the predictive accuracy remains moderate because the model explained 52% of the variance, and some individual prediction differences were relatively large. Therefore, the proposed equation should be considered a preliminary estimation tool that requires additional refinement and validation using larger and more diverse datasets before broad industrial application. Although these percentage increases indicate meaningful effects of the task characteristics on recovery time, the relatively large standard deviations observed across several treatment conditions suggest substantial inter-subject variability. Therefore, the reported percentage changes should be interpreted as overall trends within the study population rather than precise estimates applicable to every individual worker.

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Abbreviations

EMG	Electromyography
MVC	Maximum Voluntary Contraction
MVCRT	Muscle Voluntary Contraction Recovery Time
MAV	Mean Absolute Value
MMH	Manual Material Handling
WMSD	Work-Related Musculoskeletal Disorder

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