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Ergonomics Evaluation of Manual Lifting Task on Biomechanical Stress in Symmetric Posture

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ABSTRACT

Introduction: Manual lifting operations continue to play a key role in the industrial and service sectors, inflicting physical strain on the musculoskeletal system, despite advances in automation. As a result, an experiment is carried out to assess the impact of two lifting task parameters; weight and height, based on the estimation of subjective responses and biomechanical loading, while lifting the weight symmetrically in the sagittal plane. Also to recommend the safe limit for manual lifting tasks.

Methods: Twelve volunteer male students in the age group of 21 to 26 years performed lifting tasks from floor to 5 different heights (below the knee to ear level), with 5 different weights (10 to 20 kg) using free-style lifting techniques. The load pan with no handle was used for lifting weight, which is typically adopted in the Indian building construction field. The subjective estimate was obtained using workload assessment by body discomfort chart. The biomechanical loading (loading rate) for each lifted weight and height was collected using a force platform.

Results: The results showed that heavier weights produced higher stresses than lower weights. The loading rate was found to be almost similar at waist or knee level. The loading rate was observed to be linearly increasing after waist level. The overall workload rating seems to be a good correlate with the mean loading rate to some extent.

Conclusion: It is proposed to keep the maximum acceptable lifting *weight* from floor to knee, up to ear level is 15 kg, to prevent any musculoskeletal or chronic injury.

Key words: Construction Worker, Loading Rate, Manual Material Handling, Workload Assessment.

INTRODUCTION

Construction workers (for example, brick masons and roofers) are constantly subjected to increased physical hazards due to monotonous motion (lifting/ lowering weights) and awkward postures, which are the leading causes of work-related musculoskeletal disorders (WMSDs).[1] WMSDs are one of the most common causes of occupational accidents in the building construction industry due to the types of work involved.[2] As compared with other industries, WMSDs are accountable for about 34% of nonfatal injuries[1]. According to the recent Labour Force Survey 2021, over 12 months, an estimated 1.7 million workers suffered from work-related ill-health, 0.8 million workers from work-related stress, depression, or anxiety, and 0.5 million workers from WMSD.[3]

Construction workers may sustain a variety of injuries as a result of repetitive lifting operations.[4] WMSDs have a wide range of symptoms, although complaints concerning the neck, upper limbs, and lower back region of the human torso are common among workers.[5,6] The studies[7,8] also appear that lifting and

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bending may be important risk factors. WMSDs, in particular, cause not just worker illness but also decreased productivity and financial loss.[3] As a result, to formulate appropriate ergonomic interventions to avoid WMSDs in construction workers, risk factors linked with WMSDs should be identified.

According to the experimental study[4] on effects of lifting load and postures on spine biomechanics, the result suggests that increased muscle activity and fatigue may elevate the risk of WMSDs. The study also found that lifting load and vertical heights are key drivers of the lumber load during manual handling tasks.[9] The study experimented effect of lifting three different loads 5 to 15 kg on four vertical lifting heights from knee to maximum reach level of the subjects, utilizing 10 female building construction workers.[8] To further precisely measure the influence of the work-stress factor, the study found that interaction effects of different lifting parameters must be considered.

The ground reaction forces (GRFs) reflect a general indicator of the intensity of stress on the musculoskeletal system during ground contact.[10] When GRFs are large, the musculoskeletal system is unable to disperse the stresses, resulting in an increased risk of injury.[11] These risks may be amplified if the magnitude of loading rate is significant due to shock absorption and force distribution occurring in the musculoskeletal system.[12] Many studies used vertical GRFs and loading rate (LR) as the key matrix to assess its impact on the human body, while performing various physical activities such as running, walking, hopping, etc., but only a few studies have looked at lifting and carrying jobs.[13-15] The vertical GRF represents the highest magnitude and is mainly produced by the acceleration of the body in the vertical direction during bending and stretching.[13,15]

The peak rate of vertical GRF (LR) indicates the possibility of repetitive injury as a result of these activities.[15,16] The studies[17,18] used the GRF as an indicator to determine musculoskeletal overload. Furthermore, the higher loading rate and peak forces may put an excessive amount of stress on the ankle joint.[19] The effect of seven independent manual lifting task parameters (i.e., lifting weight, frequency, coupling, asymmetric angle, and destination heights) on GRFs, LR, oxygen uptake, and heart rate were investigated.[20] The lifting weight, frequency, and destination heights were observed to be significant. It was also discovered that when weight and vertical distance rise, the instantaneous loading rate increases. It was proposed to keep the maximum acceptable limit for LR to be 380 Newtons per second.

Ergonomics designed for normal manual handling duties are still insufficient for repetitive lifting tasks. Many construction industries desire to enhance their workplaces and task circumstances, but they are unaware of the acceptable limits and activities that should be taken to prevent occupational illnesses and injuries.[21] Therefore an experimental study was performed to determine the effect of biomechanical stresses on the musculoskeletal system while performing manual lifting tasks. The lifting task was considered similar to the task used in the building construction industry in India. The study aims to investigate the impact of two lifting task variables; lifting magnitude and lifting height based on subjective and biomechanical loading estimates while lifting weight pan symmetrically. The findings from the study can not only reduce the risk of WMSDs but are also helpful to improve the work performance and quality of construction workers.

METHODS

In the present study twelve male subjects, (mean age 23.5 ± 1.78 years, weight 70.67 ± 2.57 kg, and height 1.76 ± 0.027 m) mainly undergraduate and graduate students from within the institute have participated in the study. The participant's mean height and weight were found to be approximately the same due to the closed age group. Before the experiment, each participant reviewed and signed an informed consent form approved by the University's Institutional Review Board. The subjects were all in good health and had no prior medical history. Subjects were excluded from the study if they had: a back injury or complaint in the last six months; had undergone spinal surgery; had any cardiovascular or neurological condition; and had a musculoskeletal injury at the time of the study. Before the start of the real experimentation, all the subjects were trained for the task. The remuneration was given to the participants for their participation. During the lifting cycle, the subjects were instructed to lift a pan (dimension 30×30×25 cm) of the concrete-cement mixture in a designated area on the floor.

The lifting cycle began with the pan being lifted from the floor to a bench at the desired destination level, then resting for 3 seconds (without slipping from the pan's grip) before lowering the pan to the floor. Subjects performed a lifting task with 5 different weights, in which 10, 12.5, 15, 17.5, and 20 kg pans were lifted to 5 different vertical heights; below the knee, knee, wrist, shoulder, and ear level of the subjects. This manual lifting task was found to be consistent with the building construction industry for performing the concreting operations.

Experimental setup.

The experimental study was performed in the Biomechanics Lab of the National Institute of Technology Rourkela; NIT Rourkela.[22] The study was carried out using laboratory simulated experiments. Kistler's multiaxial force platform (500×590×50 mm) measures GRFs, which was used in this study (model AA9260). The analog output from the force platform passes through an internal amplifier and reaches Kistler's data acquisition system (type 5691A1), where data was collected with a sampling frequency of 1000 Hz to generate a digital signal. The Nyquist theorem is used to determine the sampling frequency. For smoothing data, the Butterworth filter was used, which attenuates frequencies over the set cut-off frequency while allowing frequencies below the cut-off to pass through. Finally, the data is reflected in Qualisys track manager software.

Biomechanical Evaluation

The manual lifting task was evaluated using a force plate and subjective workload assessment by body discomfort chart. The vertical (F_z), longitudinal (F_y), and latitudinal (F_x) GRF beneath feet produced during lifting were measured using force platforms. Fx is perpendicular to motion direction and Fy is parallel to motion direction and Fz is along the vertical direction. The setup arrangement is shown in Figure 1. During the lifting task, Fx and Fy are determined to be smaller in magnitude than Fz. Fz always uses his feet to propel himself upward. Loading rate (LR) is calculated by determining the time required for the vertical force to rise by lifting the weight from the floor to the destination height. The peak rate of vertical GRF (LR) indicates the possibility of chronic damage as a result of these activities.[6,23] The ratio of peak loading and time to peak loading during human activities is referred to as the loading rate (LR).

$$LR = \frac{F_{zmax} - F_{zmin}}{t_2 - t_1} \qquad \text{(Equation 1)}$$

F_{zmax} and F_{zmin} are the peaks and lower values of F_z of one lift and (t_2-t_1) is the period between these values. Finally, the magnitude of loading rate obtained from GRF was compared to subjectively evaluated physical discomfort and overall workload.

The Subjective evaluation was performed by giving a questionnaire[24] to each participant as shown in figure 2. The questionnaire includes a chart for measuring physical discomfort as well as a rating scale for the total workload. After executing the lifting task for each test condition, the participants were asked to rate the level of discomfort in each of the body parts. The degree of discomfort is measured on a five-point scale that ranges from no sensation or soreness (zero) to extreme pain or soreness (4). Following the discomfort assessment, the participants were asked to rate the overall workload for the task under consideration. The overall workload scale is also a five-point scale, with '1' being very light and '5' being very hard. The physiological workload was thought to be a major risk factor for WMSD.[4]

Test procedure

The weight was lifted using an open circular-shaped plastic pan with no handles. To make lifting easier, a weight of concrete mixture (cement, sand, and grit) was placed in the pan. The pan is similar to that used in construction fieldwork. Before the lifting task, the subjects were given thorough instructions and requested to complete two to three trials while standing on a force plate. Each participant lifted a weight in 25 different combinations of lifting parameters (5 weights and 5 destinations) in symmetrical freestyle lifting. The order of the lifts for each participant was randomized to prevent *order* effects. After each lifting task, a sufficient rest period was given to allow the muscles to recuperate. During the lifting cycle, the participants were instructed to maintain a fixed, symmetrical foot position. The Fz was measured for each test condition for all the subjects against a time scale (in seconds).

Response Data Analysis

A full factorial analysis of variance (ANOVA) was performed using the statistical package for social sciences (SPSS Inc., Chicago, USA, version 16) to evaluate the subject's response. The result from statistical analysis is presented in terms of probability value (p-value) and data R^2. For the ANOVA of both the independent variables; five lifting weights and five lifting heights, a within-subjects design was adopted. Because each subject's assessments were collected repeatedly for all of the test situations, the repeated-measures design was well suited. Wilcoxon signed ranks test was also carried out on all the data to determine whether the independent variables had a significant effect on dependent variables. Further, the two-tailed test was employed at a 5% level of significance ($p<0.05$). All of the data was manually coded and analyzed using the statistical program SPSS.

For interpreting the ANOVA, two further statistical measures were used: partial eta squared and the observed power. Partial eta squared is a way to measure the effect size of different variables and to understand the major effects or interactions. The observed power was computed to increase the likelihood of detecting an effect correctly. An observed power of 0.95 in the range of 0 to 1 indicates a 5% possibility of detecting a false-positive result.

RESULTS

Vertical Reaction Force (Fz) was measured for all the 12 subjects for all trials over an experimental period. One such plot of one participant lifting the weight of 17.5 Kg at shoulder height for one minute has been shown in Figure 3.

The value of the mean loading rate and overall workload of all the 12 subjects are plotted as shown in figures 4 & 5. The plot indicates that, with the increasing weight lifted, the loading rate significantly increases. Also, the loading rate increases with increased destination heights. The loading rate shows no significant change between knee level and waist height for all the lifting weight magnitudes ($p>0.05$). However, there is a remarkable increase in loading rate when the destination heights increase beyond this level to ear level ($p<0.05$). Moreover, no significant effect was observed, if participants lifted varying weights from the floor to below knee level ($p>0.05$). It has also been seen from the plot that the least loading rate was observed for lifting the smallest (10 kg) weight and there has been no significant difference in loading rate for lifting 10 kg weight for all vertical distances ($p>0.05$). This was also confirmed by the least overall workload from the overall workload rating plot, figure 5.

The overall workload yields a similar rating between knee level and waist height for all the lifting weight magnitudes ($p>0.05$). The rating of overall workload shows a significant rise while lifting more than 15 kg weight ($p<0.05$). The mean value of the degree of discomfort for each body part of all 12 subjects was also computed. The result showed that lifting 20 kg weight at shoulder level causes mild pain (rating 2) in both thighs. An increase in height to ear level for the same 20 kg weight, brings slight pain in the mid to lower back in addition to mild pain in both thighs.

Within-participants when statistical analyses were performed to determine the general effects on the loading rate and overall workload for both independent variables; weight and destination height (Table 1-2). The table 1 and 2 interpret *significant main* effects and *interaction effects* for the judgment of responses. In general, the observed power takes high values for both these variables. The results show that the highest contribution comes from both the independent variables, followed by the contribution of the interaction variable.

Table 1: Within-subjects effect of test parameters on Loading Rate

Sources	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial eta Squared	Observed Power
Weight (W)	1540285.72	1.38	1114554.43	430.14	.00	.975	1.0
Height (H)	1029168.98	2.15	478481.93	513.79	.00	.979	1.0
W * H	363187.94	3.10	117106.94	73.54	.00	.87	1.0

Table 2: Within-subjects effect of test parameters on Overall Workload

Sources	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial eta Squared	Observed Power
Weight (W)	183.52	1.638	112.05	208.54	.00	.95	1.0
Height (H)	149.68	1.67	89.42	260.80	.00	.96	1.0
W * H	42.34	4.21	10.05	30.53	.00	.735	1.0

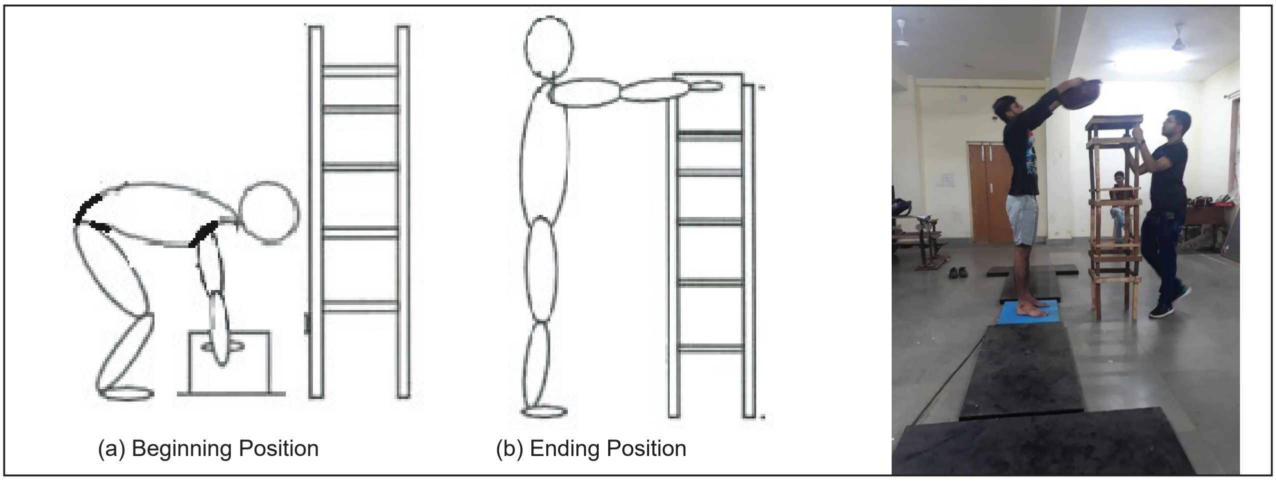
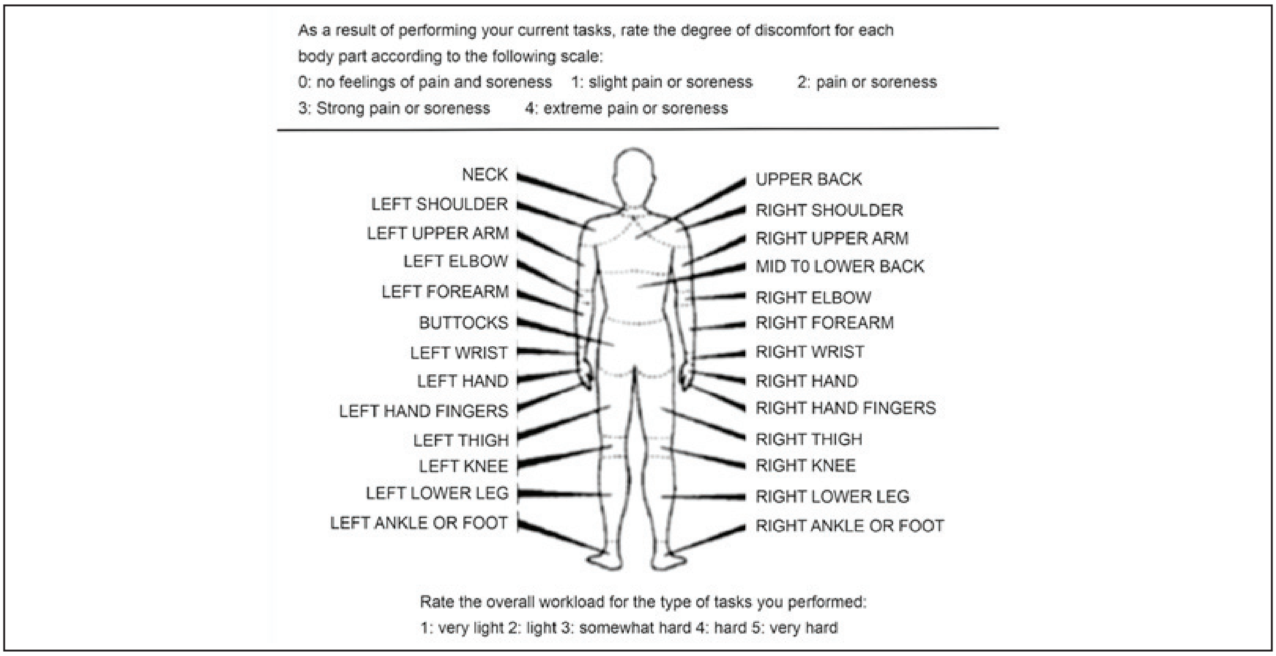


Figure 1: Laboratory set-up of force plate at NIT Rourkela



As a result of performing your current tasks, rate the degree of discomfort for each body part according to the following scale:

0: no feelings of pain and soreness 1: slight pain or soreness 2: pain or soreness

3: Strong pain or soreness 4: extreme pain or soreness

NECK
LEFT SHOULDER
LEFT UPPER ARM
LEFT ELBOW
LEFT FOREARM
BUTTOCKS
LEFT WRIST
LEFT HAND
LEFT HAND FINGERS
LEFT THIGH
LEFT KNEE
LEFT LOWER LEG
LEFT ANKLE OR FOOT
UPPER BACK
RIGHT SHOULDER
RIGHT UPPER ARM
MID TO LOWER BACK
RIGHT ELBOW
RIGHT FOREARM
RIGHT WRIST
RIGHT HAND
RIGHT HAND FINGERS
RIGHT THIGH
RIGHT KNEE
RIGHT LOWER LEG
RIGHT ANKLE OR FOOT

Rate the overall workload for the type of tasks you performed:

1: very light 2: light 3: somewhat hard 4: hard 5: very hard

Figure 2: The body discomfort and overall workload questionnaire[24]

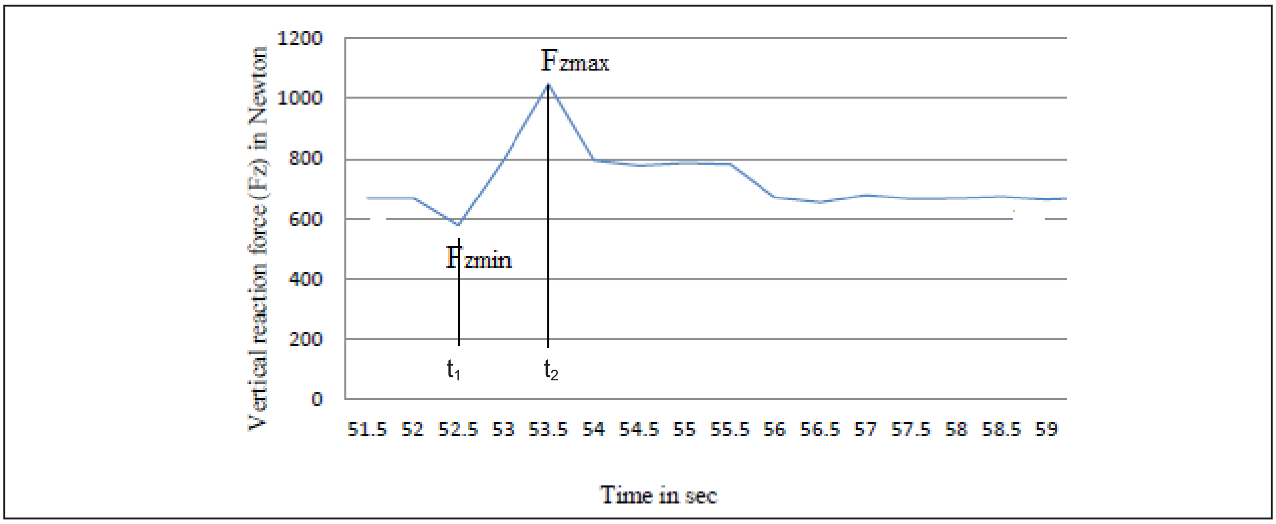


Figure 3: Vertical force-time graph for participants lifting load of 17.5 kg at shoulder height

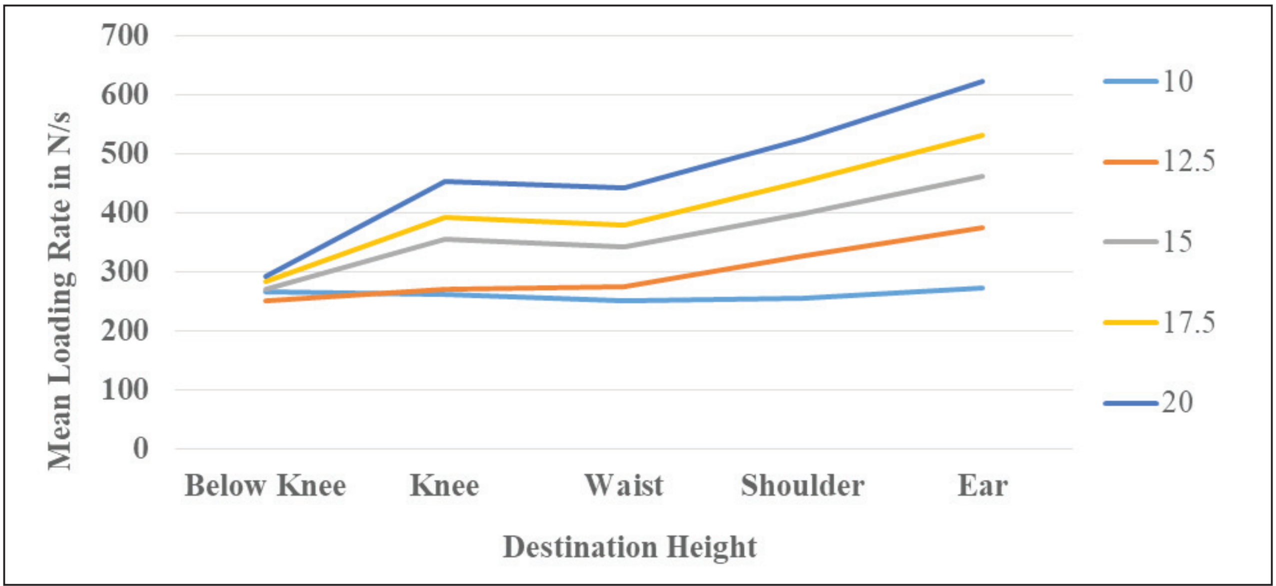


Figure 4: Mean loading rate plot with variation in weight and destination height.

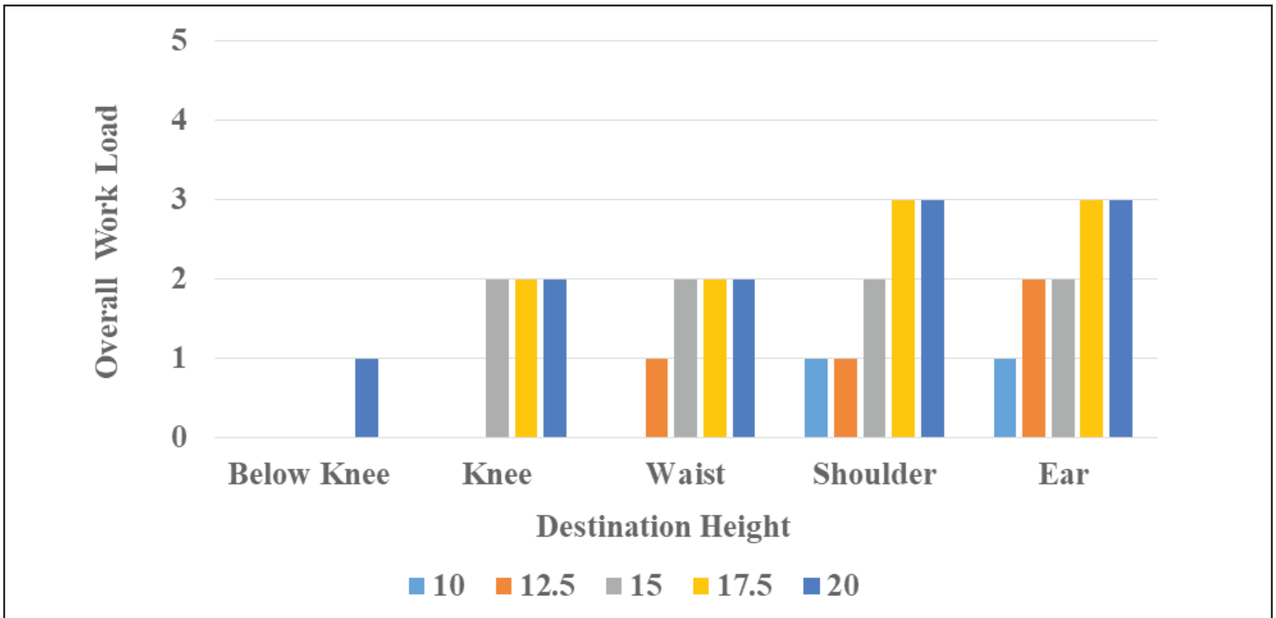


Figure 5: Mean workload rating plot with variation in weight and destination height.

DISCUSSIONS

Lifting heavy loads is one of the leading causes of injury in the workplace. Bending while lifting causes several problems for the back. It adds the weight of the upper body to the weight of the object being lifted. Bending and/or reaching moves the load away from the body and allows leverage to significantly increase the effective load on the back, leading to stress on the lower spine and muscle fatigue.

In the present study, weight and destination heights had a major impact on loading rate, therefore various combinations of these factors were explored to determine the least and the most exerting task conditions. For example, the average loading rate increased by about 38 to 40% when weight was increased from 12.5 to 20 kg, without changing the destination height. Similarly, when weight was kept constant and the destination height was increased from the floor to the ear level, the loading rate increased by around 26 to 29 percent.

Few studies[7,18] reported that the body could assume an upright stance while lifting to waist height. As a result, a sequential change in posture occurs. Even if overall stress is higher, the subjects were able to handle more physical load with less discomfort due to the dynamic change in posture.[21] Since the present study focuses on inexperienced Indian college students who are not accustomed to continuous heavy load lifting at various height levels as construction workers. As a result, the contribution of postural dynamic alterations was not found in evidence in the outcome of the present study.

The result revealed that there is no significant difference in loading rate for lifting the smallest (10 kg) weight irrespective of destination heights. Thus lifting 10 kg weight from the floor to the ear level is safe, as the spinal force generated was less than the recommended limit according to the NIOSH lifting criterion.[25] From observed data, it is interesting to find that the mean loading rate and the overall workload rating are well correlated to some extent. Both are predicated on the idea of subjects exerting more effort when performing dynamic lifting tasks.

From the subjective rating of discomfort for each body part, it was observed that lifting 20 kg weight at shoulder level causes mild pain (rating 2) in both thighs. An increase in height till ear level for the same 20 kg weight, brings slight pain in the mid to lower back in addition to mild pain in both thighs. This could be due to the lifting of weight by participants in a confined posture, without moving both feet. Such confined workspaces increase the amount of stress on the subjects' bodies[6]. When lifting the weight from the floor, trunk flexion was rare, and lifting was primarily accomplished through knee flexion. This lifting becomes more stressful, at the shoulder or ear level, due to the dynamic trunk motion.

Several studies[4-9,20,21] observed that workers may get injuries while performing their daily jobs when handling objects and equipment by hand. Therefore, the safe limit for manual lifting in symmetric posture needs to be established to prevent/reduce injuries in construction fields. The safe limit has been proposed based on results obtained from loading rate and subjective rating, assuming alarming levels for perceived difficulty and workload as rating '2'. For example, if the weight is to be lifted from the floor to shoulder level and beyond, then the weight should not exceed 15 kg. Below shoulder level, the weight under study (10 to 20 kg) is permitted to lift the weight safely without any chronic injuries.

Based on the biomechanical and physiological experimental study by Singh et al. (2014), the safe upper limit of loading rate was recommended as 380 Newton/sec, while lifting different weights from 0-60 degree asymmetric angles.[20] From figure 5, assuming the overall workload rating '2' as less stressful for the worker indulged in the construction field, the present paper recommended the safe limit for loading rate as 480 N/s for lifting weight in symmetric posture. This variation in the established safe limit by an earlier study by Singh et al. (2014) could be due to the nature of responses measured, type, and level of input parameters investigated in the study. The present study's unique feature is the simultaneous collection and presentation of biomechanical loading and subjective estimate data for manual weight lifting tasks, both of which corroborate each other by demonstrating an almost similar trend in responses.

The laboratory-based nature of this study limits the extrapolation of findings to the working environment. While only male subjects took part in the study, the high predominance of male employees in heavy manual jobs makes the study relevant to a working population. Recruiting subjects without prior lifting experience also seems pertinent as novice workers are considered at high risk of musculoskeletal injury.[26] This study was conducted only on students whose ages ranged from 21 to 26 because they were easily available. The small sample size of young, fit, inexperienced male participants of narrow anthropometry age limits the applicability of the results. The limited range of task conditions also limits the predictive capacity. Although no restrictions were placed on the lifting technique adopted, aspects of the lifting task were constrained to control for potential confounders. The foot positions have been also considered important posture parameters for reducing the lumbar load during manual lifting[27]. Thus, future studies should consider a combination of both foot position and workers with a wider age range for more effective intervention.

CONCLUSION

The building construction industry is an occupationally hazardous sector. Evaluation and quantification of physiological stress associated with manual material handling were done in this study and determined the safe limits of significant parameters to reduce/prevent any musculoskeletal or chronic injury.

Although both responses are distinct, the study found that they followed a consistent pattern in predicting physical stress as a result of lifting tasks. The physiological demands were shown to be increased while lifting loads with a greater vertical distance. When the heavy load (20 kg) is lifted above the shoulder level, the tasks become considerably more stressful. Therefore, it is proposed to keep the maximum acceptable lifting *weight* from floor to knee, up to ear level is 15 kg, to prevent any musculoskeletal or chronic injury. Similarly, the study also recommends the safe limit for loading rate as 480 N/s for lifting weight in symmetric posture.

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