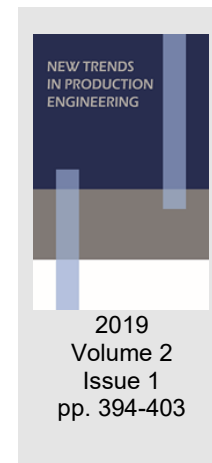


Effective utilization of man shift through sustainable workload testing for underground mining machine operators. An ergonomic based man-machine interface approach

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INTRODUCTION

The Indian mining industries are considered to be the key economic pillars as it contributes to 2.2% to 2.5% of the gross domestic product (GDP) with a share of around 10% to 11% of total Indian industrial sector (Wikipedia 2018). In Indian mining industries, be it metal or coal, underground machineries plays an important role in excavation of mineral products. With different kind of job structures, Indian mining sector has the huge base of underground employees (Statista 2018), who undertake immense role in production of coal. It is the fact that there is multiple numbers of unit operations including different face loading and other machine operation like side discharge loading (SDL), load haul dumper (LHD), universal drill machine (UDM) and continuous miner (CM). Out of the all underground machineries, SDL and LHD machine operation is important as these machines are installed in maximum underground mines and provides useful contribution in terms of evacuation of blasted coal dispatch towards surface. However, most of the continuous mine unit operation along with appropriate stretch of job and adequacy of suitable workload is still unknown. In Indian mining, currently several machineries in use and there is inevitable evidence of muscle fatigue during machine operation (Dey et al., 2018). Different physical hazards like traumatic injury is making a potent and significant problem ranges from the trivial to fatal in mines all over the world (Groves et al., 2007). There are several repetitive work processes in a single work spell of an underground machine operator which makes these operation (SDL and LHD) more miserable under hectic mine environment (Dey et al., 2015a, Donoghue, 2004). Moreover, effect of different kind of nonliving stressors also known as abiotic stressors (AS) i.e. high temperature, humidity in mines are also posing some potent significant effect on miner's health especially, comfort and work efficiency (Dey et al., 2015b, Dey et al., 2017). Subsequently, mining operator and working environment interface is the most underrated but prime factor which depicts the pattern of discomfort of a miner under a given set

of environment. In Indian perspective two main environmental abiotic stress factors i.e. humidity and high temperature are important and currently under research prerogative of many scientists. Meanwhile, different research studies have been documented some adverse effect of working environment on miner's cardiac and physiological stress (Dey et al., 2006, Dey et al., 2014). Not in India only, the same is also found in abroad countries (Hull et al., 1996), where high temperature and excessive humidity is found important thermal stress factors in underground mines.

Work related stresses are very common in every work field so does in Indian mining and its' responses have potent synergic effects on loss of effective man hour shift (EMS) of a particular operator. There is insignificant engineering solution exists to fix those problems in underground mines. Fixation of suitable rest break in between spells and fixation of scientific workload is the effective possible solution. It is pertinent to mention here that most underground operation runs with unscientific workload distribution which may often create extra burden and onset of quick fatigue (Sharma et al., 2016). The current study is aimed with following objectives: (1) to identify dose-response relationship between underground mine environment and work stress factors. (2) to test suitable workload for better fatigue sustainability (FS) and muscle force (MF) during operation.

MATERIALS AND METHODS

Selection of participants

Total 12 (N = 12) machine operator, 6 side discharge loader operators and 6 load haul dumper operators are selected from single mines so that geo mining condition does not have any effect on participants. SDL and LHD operators are selected as because they devote at least 3-4 working spells (as per the availability of blasted coal it may increase) each of around 33-40 minute (33 minute for SDL and 40 minute for LHD). Participants are selected on the basis of measured physical fitness (basal metabolic index, body surface area, and resting electrocardiogram etc.) where rejection criteria is decided taking views of all concerned occupational health and safety (OHS) supervisors including information as received from the mine databases. Only those participants having BMI range of 18.5-25 kg/m² (WHO, 2000), BSA up to 1.9 m² (Medicinenet.Com 2016) and normal resting electrocardiograph (RECG) before work (Dale, 2000, Ganong, 2001) with no past illness record are asked to take part in the study.

Measurement of work stress and environment

Work stress

Physiological parameters i.e. heart rate and metabolic rate (MR) [Eq. No. 1] parameters are measured through direct measurement of heart rate with portable heart rate monitor (HRM) RS 400 (FS Finland) continuously during work exposure. Work stress parameter metabolic rate (MR) is well represented by following equation of Yokata et al (Yokata et al., 2008).

$$MR = [0.68 + 4.69 (\text{HRratio} - 1) - 0.052 (\text{HRratio} - 1) (\text{Ta} - 20)] 58.1 \text{AD} \quad (1)$$

where:

HR ratio = observed HR given at the time/resting HR of the individual,

T_a = ambient temperature in OC

AD = body surface area (m²).

Environmental stress measurement

Environmental stress measurement is done throughout the working shift of 8 hours for the period of 30 days with a measurement interval of 20 minute while mean value is taken for analysis. The environmental heat stress measurement as wet bulb globe temperature (WBGT) is widely used and considered here to measure and analyze the mine status of environmental heat stress. The analysis is done through analyzing formula (Dimiceli et al., 2011) of WBGT [Eq. No. 2]:

$$\text{WBGT} = 0.7 \text{NWB} + 0.3 T_g \quad (2)$$

T_g represents here black globe temperature which measures the heat generation including heat generation from radiation and all possible sources. As temperature in an underground mining comes from various kind of sources hereby, inclusion of black globe temperature in heat stress measurement is most suitable.

Workload testing

For workload testing a simulation approach has been undertaken. Similar workload type has been adopted which was measured earlier in the mines. Based on measured HR ratio and workload of mines, workload has been simulated on treadmill by following BRUCE protocol (Bruce, 1972, Akinpelu, 2017). Testing of total three workloads as per Astrand classification (Åstrand et al., 2003) i.e. low (HR ratio = 0-1.25), moderate (HR ratio = 1.25-1.53) and high (HR ratio = 1.53-1.81) have been planned. Working heart rate below 90 bpm⁻¹ for low category workload, working heart rate between 90-110 bpm⁻¹ for moderate category workload and heavy category of workload with heart rate 110-130 bpm⁻¹ have been adopted for workload testing respectively. Participants are carried to the level of peak HR which they have achieved down the mines. Total seven stages of workload testing are performed to reach the peak heart rate level on the case to case basis of the subject's ability and plan of the experiment. Seven stages are performed with an increase of 2% grade in each stage. A three-minute period for every stage is given to achieve a steady state before workload is increased for the next stage. The simulation approach is taken to get unbiased result of working environment and also for inability to take the whole set up to the underground. Muscle force and fatigue sustainability after each experiment has been recorded.

Muscle force and fatigue sustainability measurement

Muscle force or strength analysis is measured through hand grip dynamometry (HGD). This is applied to every participant for three consecutive times in operator's dominant hand. Mean HGD score of three measurements is taken as result. One HGD experiment is done before starting the machine operation and

one after the completion of working spell. The workers are seated in 60° flexion and the sidearm is rested at 90° angle with the floor. Angular measurement is done with the help of a goniometer. In every measurement, maximal grip strength (MGS) is taken for consideration. Alteration or decrease in % MGS is measured before and after performing each working spell. Same measurements are also performed after each workload testing.

As per Brouha's fatigue assessment technique (Biswas et al., 2011) resting pulse of recovery period i.e. from 30 second to 1 minute after completion of work is considered as recovery pulse 1 (RP1), from 1½ to 2 minute as recovery pulse 2 (RP2) and from 2½ to 3 minute as recovery pulse 3 (RP3). A difference of third pulse (RP3) and first pulse (RP1) is considered as fatigue sustainability.

Statistical analysis

The statistical design is planned to study the significance differences between the parameters. All sets of environmental, physiological, muscle force related data variables have been considered for the Pearson's student t-test and mean and standard deviation are noted for each set of data. Difference between mean values are tested by one tail paired 't' test with ' α ' = 0.05 as the significance level. Null hypothesis (H_0) is proposed in the study that there is no significant difference between the group means. Correlation test is also done between parameters to find out interrelationship between measured variables. Moreover, positive or negative correlation in the range of 0.7 to 1 is considered in the study as strong correlation while the range of 0.3-0.7 as medium strong correlation and below 0.3 score is considered in the study as weak correlation (Ratner, 2009).

RESULTS

Results are obtained in respect to the objectives of the study. In the first part the analysis result of dose response relationship between underground environmental heat stress and exposure time period (ETP) of operators have been established. In the second part simulation result of workload experiment is discussed.

Environment-operator dose-response relationship

Total 6 hours working time out of 8 hours shift has been analyzed. As two of the operation is near about similar, overall analysis of all the operators [N = 12] has been done. Environmental stress parameter WBGT has been taken as the indicator for the assessment of environmental stress while MR has been taken for physiological stress indicator against the environmental response.

It is found that during operation in underground mines, metabolic rate highly depends on alteration of environmental heat stress variables and exposure time period (ETP). A strong positive correlation ($R^2 = 0.69$, $r = 0.84$) is found (Figure 1) between environmental stress and metabolic rate during operation while interrelationship between exposure time period and metabolic rate has been established (Figure 2) also as a strong positive correlation ($R^2 = 0.81$, $r = 0.90$).

High mean value of humidity of 96% and low air current of 0.1 m/s has been also recorded.

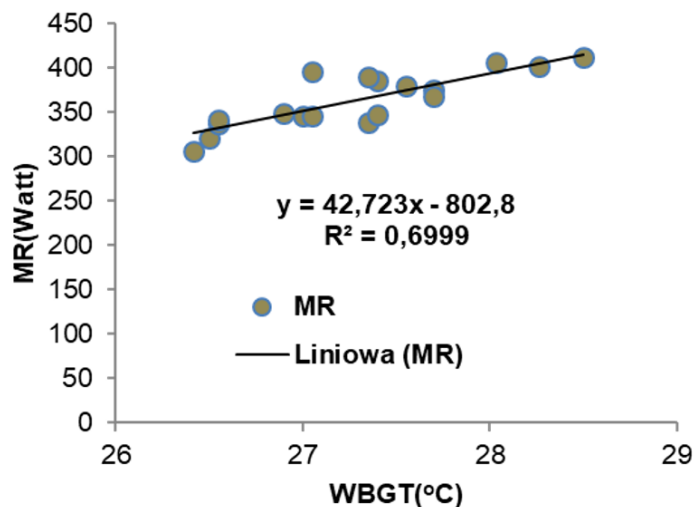


Fig. 1 MR vs. WBGT relationship

The result shows continuous exposure throughout the whole working shift may increase metabolic rate. From the Figure 2 it can be concluded that in between spells the adequacy of proper scientific rest break was inappropriate.

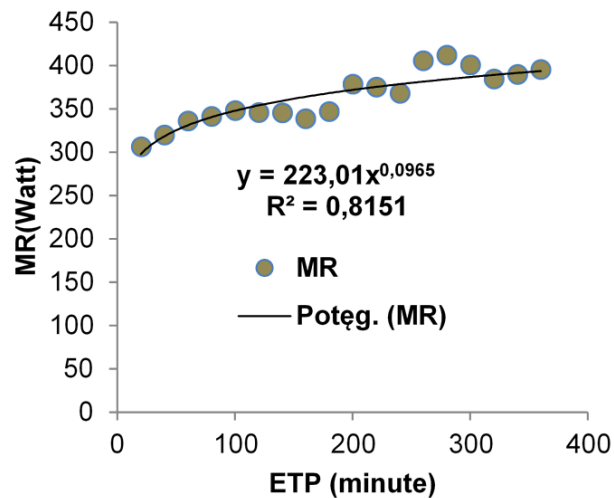


Fig. 2 MR status with ETP

In underground mines there are plenty of heat generating sources including heat generation from rock movement, machine operation which may lead to increase of WBGT values with increasing time of operation.

ETP vs. muscle force

Muscle force alteration is recorded with increasing ETP. Significant differences ($p < 0.05$) have been observed between muscle force measured prior to start of the operation and end of the operation. Total 4 spells for SDL and LHD have been analyzed and result is shown with Figure 3.

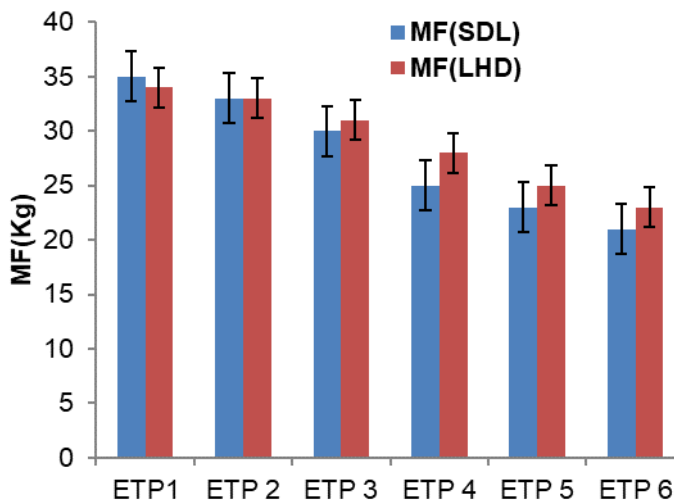


Fig. 3 Muscle force with exposure time

Muscle force degradation is noticed in both SDL and LHD operation. Muscle force is negatively correlated with exposure time period. For SDL operator’s muscle force it is $r = -0.99$ while for LHD operation it is found almost same i.e. $r = -0.99$. However, mean muscle force degradation is found 43.2% less in ETP 6 compared to the muscle force prior to the operation. Moreover, 5.4% muscle force degradation is seen after 33 min of SDL operation after one single spell. Similarly, for LHD operation muscle force degradation is found 32.4% less in ETP 6 compared to prior to the operation. Meanwhile, 5.6% muscle force degradation is found after 40 minute of LHD operation. However, muscle force degradation of LHD operation at the end of the operation is 10.8% less as compared to SDL operation.

Results on workload testing

Muscle force ($p < 0.05$) and fatigue sustainability ($p < 0.05$) results measured at mines and treadmill have shown significant differences (Figure 4 and Table 1).

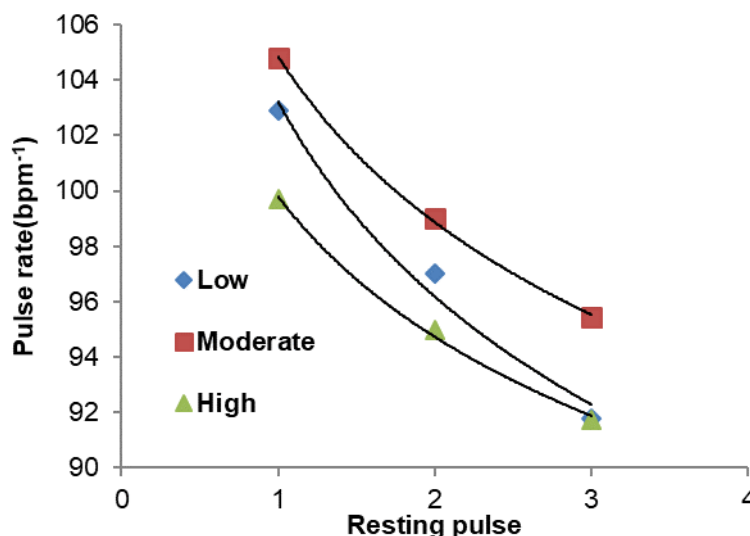


Fig. 4 Fatigue sustainability in different tested workload

Table 1 Fatigue sustainability under different workload testing

HR _{Rec} at resting condition	Operator at mines (bpm ¹), Mean±SD(Range)	Workload	Operator at surface (bpm ¹); Mean±SD(Range)	P value (one tail, homoscedastic)	Remarks
RP3-RP1	-6.95±0.9 (-6- -8)	Low	-11.08±2.27 (-8- -14)	P = 0.000001	60% FS increase
RP3-RP1	-6.95±0.9 (-6- -8)	Moderate	-9.36±1.16 (-8- -12)	P = 0.000001	35% FS increase
RP3-RP1	-6.95±0.9 (-6- -8)	High	-7.98±0.603 (-7- -9)	P = 0.012	15% FS increase

Analysis of workload testing result shows that low type of workload is suitable for maintaining higher rate of fatigue sustainability during continuous machine operation compared to moderate and high workload. In comparison to fatigue sustainability of mine, treadmill fatigue sustainability is found significantly higher in case of low ($p = 0.000001$), moderate ($p = 0.000001$) and high workload ($p = 0.012$). Muscle force after workload testing also differs in low (45% higher), moderate (42% higher) and high workload (25% higher). Differences in muscle force may occur from differences in working environment and comparatively better air velocity.

DISCUSSION

In mining, underground machinery operations are mostly continuous type of job. Therefore; maintaining right pace of work and working efficiency is most important thing. In most of the underground mining, working environment is hectic for continuous type of job. In the present study, mean value of heat stress indicator WBGT is found to be in the range of 27.3°C which is not very hectic in nature, but humidity and air vapor pressure are found in the range of 96% and 3.4 kpa. Excessive humidity and air vapor pressure may contribute high rate of sweat loss which can reduce muscle force and fatigue sustainability during operation. As this study aims to measure the environmental stress and its' response, it showed that physiological stress parameter like MR is highly interrelated with exposure time during operation. Strong positive correlation is found between environmental stress vs. metabolic rate ($R^2 = 0.69$, $r = 0.84$) during operation and exposure time period vs. metabolic rate ($R^2 = 0.81$, $r = 0.90$). A strong negative correlation ($r = -0.99$) has been found with MF and exposure time if there is no scientific rest break. It indicates not only heat stress; there are other factors in continuous mining operation which impacts in muscle force degradation and fatigue sustainability alteration.

Workload testing result shows significant difference with performing same workload in underground mines. Workload simulation of SDL and LHD operator shows significant differences ($p < 0.05$) in muscle force and fatigue sustainability parameters. In comparison to underground operation, muscle force after low, moderate and high workload is found 45%, 42% and 25% higher respectively. With same workload, fatigue sustainability increased 60%, 35% and 25% respectively with low, moderate and high workload. Therefore; for better fatigue sustainability and muscle force and effective utilization of man shift it is better to adopt low workload instead of adopting moderate and high workload.

CONCLUSION

SDL and LHD operation deals with high skeletal muscle engagement during operation therefore; concern of muscle force and fatigue sustainability is very much significant to get desired efficiency. Meanwhile, working environmental stress parameters like air temperature, humidity, air velocity and air vapor pressure plays an important role in quick onset of fatigue during operation. Muscle force and fatigue sustainability is dependent on type of workload and exposure time. Increased fatigue sustainability up to 60% while increased muscle force up to 45% can be achieved with implementation of low continuous workload along with implementation of suitable rest break in-between spells. Better efficiency for industry could be gained with preferably implementing low type of workload rather than moderate and high type of workload.

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Abstract.

Insight of man-machine interfaces during mining machine operations, better co-ordination with human efficiencies and suitable workload selection in underground mining machine operation are the main viewpoints of the study. Total 12 side discharge loader (SDL) and load haul dumper (LHD) operators [N = 12] have been taken as participants of the study. The methodology is divided into two parts first part is devoted to measuring and analyzing workload response of machine operation with polar heart rate monitor. Machine operator's heart rate ratio (HR ratio) for the whole shift is recorded and metabolic rate (MR) has been analyzed. Additionally, fatigue sustainability (FS) and degradation of muscle force (MF) are recorded for each work cycles up to exposure time period (ETP) of 360 minutes. In the second part of the methodology, based on the HR ratio recorded during the mining operation, a workload simulation study is undertaken on a treadmill at the surface following BRUCE protocol. At treadmill, based on HR ratio, workload achieved from mines along with three different workloads i.e. low, moderate and high has been tested. Differences in FS and degradation rate of MF after each workload experiment have been recorded. A result from the underground operational study shows that there is about 43.2% and 32.4% of decreasing MF for SDL and LHD operators after end of spells at mines. Additionally, a negative correlation ($r = -0.99$) is found between ETP and MF. The workload simulation study shows that there are significant differences between FS ($p < 0.05$) and MF ($p < 0.05$) data of mining and treadmill experiment with the same workload. In comparison to an underground operation, FS rate of low, moderate and high workload is recorded 60%, 35%, and 15% higher respectively than of mine workload. Higher FS rate may achieve due to availability of good environment. Among the tested workload only low kind of workload is found suitable for mining machinery job as degradation of MF is found significantly ($p < 0.05$) low and FS is found significantly ($p < 0.01$) high in this kind of workload. Therefore, it can be concluded that in mining machinery operation better to adopt low workload for effective utilization of man shift (EUMS) as it gives comparatively low MF degradation and better FS during continuous work.

Keywords: Fatigue sustainability (FS), Muscle force (MF), Heart rate ratio (HR ratio), Exposure time period (ETP), Effective utilization of man shift (EUMS), Workload simulation