ERGONOMIC ASSESSMENT OF WORK POSTURE AND EVALUATION OF HAND-ARM VIBRATIONS IN UNDERGROUND MINES

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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DECLARATION

by the Ph. D Scholar

I hereby declare that the Research Thesis entitled **"Ergonomic assessment of work posture and evaluation of hand-arm vibrations in underground mines"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mining Engineering** is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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C E R T I F I C A T E

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DEDICATED
TO
MY FAMILY,
MY TEACHERS AND
MY FRIENDS

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ABSTRACT

The Indian mining industry is transforming highly mechanized operations by deploying Mobile Mining Equipment (MME) to increase production. The regular usage of MMEs comes up with a cost to the health of the operators in the form of increased risk for musculoskeletal disorders (MSDs). Several factors contribute to MSDs, including physical and psychosocial factors as well as organisational, interpersonal, and individual factors. These physical risk factors include vibrations, repetitive actions, heavy lifting or transporting, awkward postures, and intense exertions. The Directorate General of Mine Safety (DGMS), in its 11th Conference on Safety of Mines, has recommended conducting an ergonomic assessment of all the latest machines as per ISO standards.

It is evident from the available literature that there is a significant research gap in this regard. Hence, there is an immediate need for ergonomic assessment of working postures and evaluation of hand-arm vibrations of miners working in Indian underground metal mines, along with the evaluation of acceptable workloads. This study was carried out in an underground metal mine in western India. Forty MMEs and their operators are used in underground mines for handling ore, and waste/overburden, such as Low Profile Dump Trucks (LPDTs) and Load haul Dumpers (LHDs), transporting personnel, explosive charging, scaling, breakdown rescue, and other multi-utility activities were involved in studying the workloads, working postures and the Hand Arm Vibration (HAV) exposure among the operators. Henceforth, the present study has five objectives.

The study's first objective was to find the Aerobic Strain among MME operators due to the fact that the maximum aerobic capacity and relative aerobic strain could be employed as indicators to establish a balance between work and individuals. Unfortunately, information about the physiological demands of Mobile Mine equipment operators working in underground mines is nearly nonexistent. The present research aimed to determine the Mobile Mine equipment operators' maximum aerobic capacity and relative aerobic strain and assess their relationship with their age and Body Mass Index. Forty

operators involved in transporting ore, overburden, mine personnel, explosives, repair material and etc., were examined. The maximum aerobic capacity was determined indirectly using the heart rate of the operators. The mean aerobic capacity of the operators was 38.75 mL/kg/min, and the lowest mean aerobic capacity was found in LHD operators, 37.98 ± 3.93 mL/kg/min. The maximum aerobic capacity was negatively correlated with age and Body Mass Index. 11 out of 40 operators had relative aerobic strain exceeding 50% of the maximum aerobic capacity. The mean relative aerobic strain was 46.9 ± 5.54, and the highest mean relative aerobic strain of 49.37 ± 5.55 was found among LHD operators. The relative aerobic strain had a positive correlation with age and BMI.

The study's second objective was to assess the work postures of the MME operators using the Rapid Upper Limb Assessment (RULA) method. The working posture of the operators was recorded with the aid of a digital camera. The frequently adapted posture by the operators was identified by analyzing the video graph and converted into a static image for the RULA. The RULA was performed using CREO-26 software by creating digital human models of the operators. The results from the study show that the MME operators frequently adapt postures that put them into the medium-risk category. Also, two operators adapted awkward postures with a RULA grand score of 7, representing the high-risk category. The statistical assessment carried out to find the association between awkward postures and MSDs of the upper extremities was significant, with a p-value of 0.06, implying that awkward posture was a significant factor in causing MSDs at the workplace.

The third objective of the study was to evaluate the Hand-Arm Vibrations (HAVs) of LHD and LPDT operators based on different components of a job cycle. The study involved 12 LPDTs and eight LHDs. HTV readings were measured at the interface between the hand and the steering device using the SV 105B triaxial hand accelerometer connected to the SV106 human vibration analyzer adhering to the guidelines set by ISO 5349:200. The results from the study show that the z-axis was the dominant axis of vibrations while performing hauling tasks. The empty hauling operations had the highest contribution towards total daily exposure A(8) in LPDTs. In the case of LHDs, high-vibration responses were recorded during the mucking operations with the x-axis as the dominant axis. The results also showed that six LPDTs and three LHDs were producing vibrations exceeding the stipulated Exposure Action Value (EAV) of 2.5m/s2.

The fourth objective of the study was to assess the risk of the MSDs of the upper extremities of MME operators exposed to HAVs with a case-control approach. The study was carried out involving 80 male workers at the same mine. The research enrolled MME operators, office employees, supervisors, engineers, mechanical engineering, and logistics personnel. The case group consisted of 40 MME operators exposed to HTVs regularly, and the control group consisted of the remaining participants without any exposure to vibrations. Twenty-eight out of the 40 MMEs generated HTVs exceeding the stipulated daily vibration limits, putting 70% of the operators at increased risk for developing MSDs. The case group was found to have an elevated risk of exposure with an odds ratio (OR) of 7.56 (95% confidence interval (CI), 1.159, 49.39) and OR 12.80 (95% CI, 2.436, 67.285) times more likely than the control group to suffer discomfort in the left shoulder and left wrist, respectively, indicating an increased risk of exposure to HTV.

Additionally, cases had elevated risk associated with exposure to tobacco, OR 9.35 (95% CI, 1.856, 47.129) compared to those who did not use tobacco. MSDs were more prevalent in the case group compared to the control group. The field investigations and the responses of MME operators to the questionnaires validated this observation.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
A(8)	Total daily vibration exposure for a reference duration of eight hours
ANOVA	Analysis of Variance
BBS	Bambach Saddle Seat
BMI	Body Mass Index
CMDQ	Carpel Tunnel Syndrome
CS	Conventional Seat
CTD	Cornell Musculoskeletal Disorder Questionnaire
DASH	Digital Human Modeling
DC	Direct Current
DGMS	Directorate General For Mine Safety
DHM	Disabilities of the Arm, Shoulder, and Hand
EAV	European Union
ELV	Exposure Action Value
EU	Exposure Limit Value
GDP	Gross Domestic Product
HAV	Hand Arm Vibrations
HAVS	Hand Arm Vibration Syndrome
HEMM	Heavy Earth Moving Machine
HGCZ	Health Guidance Caution Zone
HR	Heart Rate
HRR	Heart Rate Ratio

HTV	Hand Transmitted Vibration
ICP	Injection Control Pressure
IEA	Integrated Electronics Piezo-Electric
IEPE	International Ergonomics Association
ILO	International Labor Organization
ISO	International Organization For Standardization
LBP	Low Back Pain
LHD	Load Haul Dumpers
LPDT	Low Profile Dump Trucks
MEMS	Micro Electro-Mechanical System
MHR	Maximum Heart Rate
MME	Mobile Mining Equipment
MSD	Musculoskeletal Disorders
MT	metric tonnes
NIOSH	National Institute For Occupational Safety And Health
OWAS	Ovako Working Posture Assessment System
PATH	Posture, Activity; Tools And Handling
PLIBEL	Plan För Identifiering Av. Belastningsfaktorer
QEC	Quick Exposure Check
RAS	Relative Aerobic Strain
REBA	Rapid Entire Body Assessment
RHR	Resting Heart Rate
RMS	Root Mean Square
RPAC	Research Progress Assessment Committee
RPE	Rating of Perceived Exertion

RULA	Rapid Upper Limb Assessment
VDV	Vibration Dose Value
VO2	Oxygen Consumption
VO2max	Maximum Aerobic Capacity
VTC	Vocational training Centre
WBV	Whole Body Vibration
WERA	Workplace Ergonomic Risk Assessment
WHO	World Health Organization
WHR	Working Heart Rate
WRMSD	Work-Related Musculoskeletal Disorders
WUED	Work Related Upper Extremity Disorders

CHAPTER-1

INTRODUCTION

"If you cannot grow it, you must mine it" (Panchuk, 2015). This phrase tells the importance of the mining industry. The mining industry is the foundation for all downstream sectors to thrive and expand (McMahon and Moreira, 2014). Most supply chains operate because of the natural resources obtained through mining (Min and Kim, 2012). Minerals are essential to the growth of every country's economy, and nature has bestowed an exceptional amount of these natural resources upon India. India's mining industry significantly impacts the nation's economy (Bosworth et al., 2006). As stated in the Annual Report 2018 released by the Indian Ministry of Mines, "India produces as many as 95 minerals, which includes four fuels, ten metallic, 23 nonmetallic, three atomic and 55 minor minerals." Bauxite, Coal, Chromite, Titanium, Natural Gas, Petroleum, Diamonds, and Limestone are just a few of India's many mineral resources (Verma and Chaudhari 2016). According to a report on the mineral and mining industry in India published by the ministry of mines in January 2020, the mining industry's contribution to the GDP is from 2.2% to 2.5%.

In contrast, its contribution to the GDP of the entire industrial sector is between 10% and 11%. Even small-scale mining contributes 6 percent to the total cost of mineral production. The mining sector of India employs over 700,000 workers. Owing to factual inadequacies, the Directorate General for Mine Safety (DGMS) projected that one million people worked in the mining sector. (Kaku, L. C. 2004).

The mining industry has progressed from using human labor and hand shovels to advanced and intricate mechanized equipment (Peterson, D. J 2001). Over the years, mining companies have been under intense pressure to deliver high-quality goods on schedule and in the predetermined amount (Barve and Muduli 2013). Considering the depletion of resources and the need to satisfy ever-increasing product demand, the mining industry is moving towards innovative mining technologies (Keenan et al. 2019). The

Indian mining industry is being transformed into highly mechanized operations by deploying Mobile Mining Equipment (MME) to increase production. The MMEs are used in underground mines for handling ore and waste/overburden, such as Low Profile Dump Trucks (LPDTs) and Load haul Dumpers (LHDs), transporting personnel, explosive charging, scaling, break down rescue, and other multiutility activities. The regular usage of MMEs comes up with a cost to the health of the operators in the form of increased risk for musculoskeletal disorders (MSDs). Despite global concern and efforts to prevent work-related MSDs, they burden people and society significantly (Wells et al. 2007).

The current level of mechanization is not accompanied by the practices and laws necessary for the safe operation of the machines. For the proper selection of ergonomically built machines and the adoption of optimal work practices, it is essential to understand the potential health effects on workers in the mining Industry (Mandal et al., 2013). Underground mining is a physically demanding occupation where workers are prone to injuries and ailments, necessitating studies and assessments on noise-induced hearing loss, ergonomics, respiratory diseases, security system operation, and risk management (Donoghue 2004).

1.1 Risk Factors for Work-Related Musculo-Skeletal Disorders (WRMSDS)

Several factors contribute to MSDs, including physical and psychosocial factors as well as organizational, interpersonal, and individual factors. These physical risk factors include vibrations, repetitive actions, heavy lifting or transporting, awkward postures, and intense exertions (Da Costa and Vieira 2010; Punnett and Wegman 2004; Putz-Anderson et al. 1997).

1.1.1 Hand arm vibrations (HAVs)

Vibrations are generated by different sources, such as the running engines and interaction between the uneven and rough surfaces of the haul roads while operating automobiles (Akmar and Aziz 2017). The vibrations are transmitted to the operators' cabin and experienced in the steering devices, pedals, and seats (Nishiyama et al. 2000). Vibrations are transmitted to the hands of the driver through the steering device, which is an essential component in ensuring that the automobile retains its dynamic control. (Dewangan and Tewari 2009) (Goglia et al. 2003). HTV exposure is linked to musculoskeletal complications in the upper extremities (Hagberg 2002). Exposure to HAV is believed to cause pain, stiffness, and inflammation, resulting in reduced grip strength and a loss of movement of the musculoskeletal system in the affected employees (Nyantumbu et al., 2007).

1.1.2 Awkward work postures

The working posture can be defined as a "position adopted because it is appropriate for the task being performed" (Taylor and Haslegrave, 2007). Adapting to regular non-neutral work postures is one of the most significant physical risk factors for developing job-related MSDs (Da Costa and Vieira 2010). Work involving lifted arms is a significant risk factor for shoulders and neck disorders (Petit et al. 2014; Van Rijn et al. 2010). Also, It has been found that one of the most critical risk factors for low back pain is working with bent or twisted trunks (Coenen et al. 2016; Jansen et al. 2004). Similarly, working with outstretched arms has been linked to an increased risk of MSDs of the neck and shoulders (Viikari-Juntura et al. 2001; Coenen et al. 2017). Conversely, continuous sitting is associated with musculoskeletal disorders, cancer, cardiovascular diseases, and diabetes (Lis et al. 2007; Van Uffelen et al. 2010; Carson et al. 2014). In contrast, prolonged standing can cause leg and back pain, cardiac issues, exhaustion, and pregnancy complications (Leroux et al. 2005; Gallagher et al. 2014). Professional drivers are at increased risk for musculoskeletal problems affecting the spine (Hildebrandt 1995), knees, and shoulders (van der Beek and Frings-Dresen 1995). The driver's work environment, which includes ambient conditions within the cabin, exposure to noise and vibration, fluctuating climatic conditions, and driving postures, must be considered stress factors contributing to their ill health (Göbel et al. 1998).

1.2 Criteria for Risk Assessment

In 1977 the International Labor Organization (ILO) listed vibration as an occupational hazard and made recommendations as follows - "measures have to be taken to protect employees from vibration, the responsible authorities have to establish criteria to determine the danger; when necessary, the exposure limits must be defined employing these criteria. Supervision of employees exposed to occupational hazard as a result of vibration at their places of work must also include a medical examination before the beginning of a particular job, as well as regular check-ups later on"(ILO 1977).

Individuals in physically demanding jobs are more prone to take long-term sick leave and early retirement (Sundstrup et al. 2018) and claim disability pensions (Lund et al. 2005). The equilibrium between physical ability and workplace demands is significant in maintaining labor in physically demanding professions (de Zwart BC et al. 1995). "Relative Aerobic Strain" (RAS) is frequently used to define an appropriate workload level. It is determined as the ratio of oxygen consumed during a particular work (VO_2) to the maximum aerobic capacity (VO_{2max}) of a person (Yang et al. 2019). The International Labor Organization (ILO) established an acceptable workload limit of 33% RAS in dynamic work activities across an eight-hour shift. The limit set by the ILO is in accord with the findings of multiple investigations (Bink 1962) (Wu and Wang 2002). The acceptable limit for activities with rest breaks is 50% of the VO_{2max} (Ilmarinen 1984).

Several criteria have indeed been suggested for establishing ergonomic exposures and acceptable workloads. International Organization for Standardization (ISO) and European Union Directive are the common standards for analyzing human exposure to vibrations at the workplace. International Organization for Standardization (ISO) provides guidelines to measure and assess HAVs in a workplace through ISO 5349:2001.

The European Union directive evaluates HAV using the Exposure Limit Value (ELV) and the Exposure Action Value (EAV). The ELV is the A(8) of 5 m/s2 to which workers are not entitled to be subjected due to the substantial health risk involved. The EAV value is the upper limit A(8) up to 2.5 m/s2 for eight hours per day, over which vibration exposure reduction measures should be implemented.

1.3 Origin of the Work

Despite the size of the mining sector, there is a relative lack of research as far as the Indian Mining Industry is concerned on the extent and nature of Musculoskeletal Disorders (MSDs) caused due to awkward work postures and hand-arm vibrations. Significant knowledge gaps exist about the occurrence and risk factors for MSDs in the Indian mining industry, and it has been hypothesized that MSDs are more severe in developing nations. (Chopra and Abdel-Nasser 2008). Few studies were reported concerning Heavy Earth Moving Machine (HEMM) operators in the Indian mining industry. However, there is still a significant gap in the research regarding hand-arm vibrations related to different kinds of jobs performed in underground mines.

The Directorate General of Mine Safety (DGMS), in its 11th Conference on Safety of Mines, has recommended conducting vibration studies of mining machinery before they are put into operation. It also recommended performing an ergonomic assessment of all the latest machines as per ISO standards. This ergonomic assessment should include:

* Assessment of work process.

* Assessment of working Aids/tools

* Assessment of working posture

It is evident from the available literature that there is a significant research gap in this regard. Hence, there is an immediate need for ergonomic assessment of working postures and evaluation of hand-arm vibrations of miners working in Indian underground mines, along with the assessment of acceptable workloads.

The present study will help the mine authorities identify the ergonomic risk factors causing MSDs among the MME operators and formulate measures to mitigate them to protect operators' health and increase productivity. Also, the study will help assess the operators' workload in terms of Maximum Aerobic Capacity and Relative Aerobic Strain.

1.4 Objectives

1. To find the Aerobic Strain among MME operators working in underground metal mines.
2. To analyze postural risk in operating MMEs in underground metal mines using RULA.
3. To evaluate the Hand-Arm Vibrations (HAVs) of LHD and LPDT operators based on different components of a job cycle.
4. To assess the risk of the MSDs of the upper extremities of MME operators exposed to HAVs with a case-control approach.
5. To suggest measures for the prevention/minimization of MSDs among MME operators in underground metal mines.

1.5 Contents of the Thesis

The thesis consists of eight chapters. Chapter one consists of a brief introduction followed by risk factors for work-related musculoskeletal disorders (wrmsds), risk assessment criteria, the work's origin, and the research objectives. Chapter two includes a literature review. Chapter three gives detailed information on instrumentation and methodology. Chapter four comprehends the assessment of aerobic strain among MME operators working in underground metal mines. Chapter five discusses the postural risk assessment in operating MMEs in underground metal mines using RULA. Chapter six discusses the Hand-Arm Vibration (HAVs) assessment of LHD and LPDT operators based on different components of a job cycle. Chapter seven includes the risk assessment of the MSDs of the upper extremities of MME operators exposed to HAVs with a case-control approach. Chapter eight consists of Conclusions, Measures for the prevention/minimization of MSDs among MME operators in underground metal mines, and scope for future work.

CHAPTER-2

LITERATURE REVIEW

Improving worker productivity and occupational health and safety (OHS) are key industry concerns, particularly in developing countries. The key issues in the industries are an improper design of the workplace, poorly structured tasks, an imbalance between job demands and worker capabilities, an unpleasant environment, inadequate human-machine system design, and inappropriate management programs (Shikdar and Sawaqed 2003). This causes workplace dangers, poor worker health, injuries, and disabilities, resulting in decreased productivity, job quality, and increased expenses. Work system design that incorporates ergonomics can establish a balance between worker characteristics and task requirements. This can increase worker productivity, promote worker safety, physical and emotional well-being, and increase job satisfaction (Hasselquist 1981; Schanauber 1986; Das 1987).

2.1 Ergonomics

The term "ergonomics," which translates to "the science of work," is derived from the Greek words ergon and nomos, meaning "work" and "law of nature," respectively. In 1857, a Polish scholar named Wojciech Jastrzbowski was credited with first using the term "ergonomics."

2.1.1 Work System Study

International Ergonomics Association (IEA) (2019) defined ergonomics as a scientific discipline focused on "…the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design to optimize human well-being and overall system performance." In workplaces, the terms "ergonomics" and "human factors" are considered synonymous. Both terms are used to describe the relationship that exists between an employee and the requirements of their job. Authors and researchers have defined ergonomics in the past from different perspectives as follows:

It is a scientific discipline that improves relationships between individuals and their working environments (Tayyari and Smith 1997).

It is a scientific area involved in designing a workplace, machine, tool, product, environment, or system to maximize the efficiency and output of those systems without compromising the workers' health, safety, or comfort (Fernandez 1995).

Ergonomics is an applied discipline that coordinates the design of equipment, systems, and physical working circumstances with the capabilities and needs of workers (Te-Hsin and Kleiner 2001).

Ergonomics is a field that concentrates on the characteristics of human-artifact interactions, as seen through the aspect of the engineering, science, technology, design, and control of human-friendly systems. These systems comprise various natural and manufactured goods, processes, and living situations (Karwowski 2005). Figure 2.1 depicts the many dimensions of the ergonomics discipline as described in this manner.

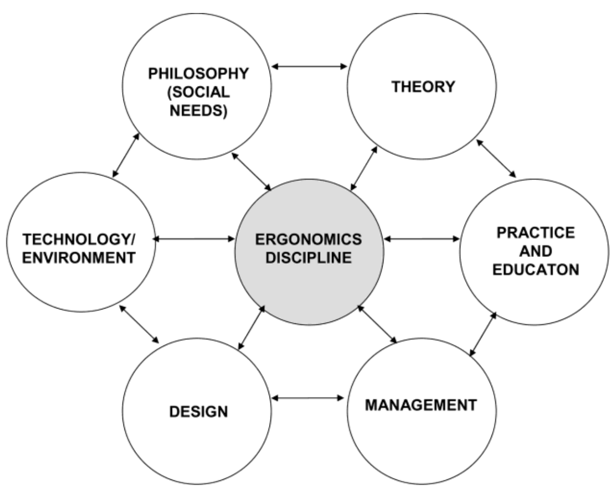


Figure 2.1: General dimensions of ergonomics discipline.

Source: (Karwowski 2005)

Ergonomics is an interdisciplinary branch of study that supports a comprehensive perspective. It can be regarded as comprising multiple domains, the most common physical, cognitive, and organizational. Enhancing productivity is one of the primary goals of ergonomics in the workplace. Any contradiction between these two essential elements in the workplace may lead to physical and/or mental strain for the employee, leading to poor performance and decreased production (Scott and Christie, 2004). When it comes to ergonomics, there are two different approaches. 'Fitting the task to the individual is a common technique that enhances work design to avoid ergonomic risks. It involves the design of equipment and workplaces to minimize physical strain (Kroemer and Grandjean, 1997). It also involves reorganizing and re-structuring jobs so that work activities and workloads are appropriate for maintaining or enhancing health (Holtermann et al. 2017). The alternative strategy is "matching the individual to the job." Employers adopt the method of selecting individuals based on their physical capabilities or training them to meet the work requirements for several professions that may need a high level of physical and mental capacity, such as fighter pilots, armed forces, police, and fire-fighters. This can be achieved through training to enhance working style and techniques (Feuerstein 2007; McGill 2009) for personalized strength training programs to improve fitness and capacity (Sjøgaard et al. 2014).

Objectives of ergonomics

Ex-president of the IEA, the late Professor Alphonse Chapanis (1996), proposed some of the objectives of the ergonomics discipline are to:

- Reduce errors, increase safety, and improve the system's overall performance.
- Increasing the reliability and improving the maintainability of the system.
- Reduce personnel and training requirements.
- Improve the work environment.

- Reduce fatigue and physical stress among the employees.
- Increase ease of use and user acceptance
- Increase aesthetic appearance
- Reduce losses of time and equipment
- Increase economy of production

2.2 Work-Related Musculoskeletal Disorders (WRMSDs)

An occupational disease is one for which there is a proven link between exposure to a hazardous environment and the development of the disease, as defined by the World Health Organization (WHO). Work-related illnesses are classified as multi-factorial when the work environment and job performance play a substantial role in disease pathogenesis. Hazardous working circumstances can exacerbate work-related diseases.

Musculoskeletal disorders (MSDs) are pathological entities in which the musculoskeletal system functions are disrupted or aberrant. Injuries to the upper and lower extremities, trunk, back, and neck that are not terminal and/or not caused by trauma are examples of musculoskeletal disorders. Musculoskeletal illnesses that can be directly or indirectly linked to employment are called Work-Related Musculoskeletal Disorders (WRMSDs) (Nunes and Bush, 2012). They are the most prevalent occupational hazard, resulting in poor health, decreased work efficiency, and absenteeism. It also makes engaging in family and recreational activities challenging, causing individual misery and financial costs to organizations and society. MSDs can be challenging to estimate since they consist of direct expenses, i.e., noticeable expenses due to medical costs, insurance, and compensation, and indirect costs due to labor turnover, decreased productivity, and diminished quality (Rose et al. 2013). Globally, an estimated 15% to 49% of all MSDs can be traced back to one's place of employment (Niu 2010; Punnett et al. 2005).

Numerous physical, organizational, individual, and psychosocial factors affect the correlation between physical work and its influence on health since work is defined by its activities, environment, equipment, and timeframes (Guérin et al., 2007). Every person is unique and performs the work tasks following their capacity. Personal factors, working methods, expertise and experience, and an individual's present mental state all play a significant role while performing work triggering physiological responses internally. The reactions, such as metabolic changes and activations of the body's muscular and nervous systems, depend on the individual's activity and personal capacity. This can further contribute to exhaustion and poor health, or it might lead to continued and enhanced health, depending on the work's frequency, duration, and intensity level (Sjøgaard and Søgaard, 2015). The characteristics of the specified job, individual work styles, and physical capabilities might be addressed through interventions aimed at lowering ergonomic risks by examining the work by assessing the vibrations, forces, working postures, and physiological demands of the job.

2.3 Risk Factors for WRMSDs

Risk factors are known to be associated with an individual's likelihood of getting an illness or ailment (Kleinbaum et al., 1982). Several factors contribute to MSDs, including physical/bio-mechanical and psychosocial factors as well as organizational and individual ones.

The physical risk factors include vibrations, repetitive actions, heavy lifting, awkward postures, and intense exertions (Da Costa and Vieira 2010; Punnett and Wegman 2004; Putz-Anderson et al. 1997). The angular flexion and extension of the wrist were also determined to be potential risk factors for Carpel Tunnel Syndrome (CTD) while performing dynamic industrial tasks (Marras and Schoenmarxlin 1993). Armstrong et al. (1986) identified several biomechanical risk factors for the development of Work Related Upper Extremity Disorders (WUEDs), which are listed below:

- Intense exertions and movements
- Persistent actions and exertions

- Extreme shoulder, forearm, wrist, and hand postures
- Mechanical stress concentrations at the palm's base, the surface of the fingers, and the sides of the fingers
- Exertion, posture, and motion duration
- Hand-arm vibrations
- Exposure to low temperatures
- Inadequate resting or leisure time
- Use of gloves

The term "psychosocial factors" refers to "the subjective components of organizational setting and the way employees and the management view them" (Hagberg et al., 1995). The psychosocial risk factors consist of workload (National Institute for Occupational Safety and Health 1997), job demands (Xu et al. 2012), job stress (Bongers et al. 2002), social relationships, and administrative concerns (Westgaard and Winkel 1997). In a study conducted by (Macdonald et al. 2001), significant relations were identified between psychosocial and physical work factors.

Work organization might even substantially impact the development of WUEDs (Sommerich et al. 2006). Work organization is described as "the objective nature of the work process. It concerns how work is organized, monitored, and processed" (Hagberg et al., 1995). The work organization specifies the expected level of work production, how the job is to be performed, work–rest schedules, the social order, and the monitoring method. Organizational factors can increase the risk for WUEDs by affecting the degree of exposure to physical and environmental risk factors and an individual's response to stress, consequently increasing the risk associated with a certain level of exposure. Several organizational factors, such as work duration (Balogun and Smith 2020), experience (Emkani et al. 2017), shift system, and job type, also play a significant role in developing MSDs in the workplace. The organizational framework in which work is performed affects employees' physical and mental strain and health significantly.

Along with the risk factors mentioned above, environmental factors such as varying temperatures (Yong et al. 2020) and personal characteristics such as age (Aghilinejad et al. 2016; Njaka et al. 2021), BMI (Ahmad and Alvi 2017), sex (Guo et al. 2004; Hooftman et al. 2004) and smoking (Sridhar et al. 2022) have been found to be associated with the occurrence of WRMSDs.

2.4 Physiological Demands and Workload

Relative aerobic strain (RAS) is commonly employed to establish a tolerable workload. It is measured as the ratio of an individual's oxygen consumption to maximum aerobic capacity. The ILO has set the acceptable workload limit for dynamic work tasks at 33 percent RAS during an eight-hour workday (Smolander and Louhevaara, 2011), which agrees with past studies (Waters et al., 1993; Wu and Wang, 2002).

Maximum aerobic capacity (VO_{2max}) is the maximum rate at which the body can absorb and use oxygen during intense workouts. It is one of the most critical variables in exercise physiology and is usually used to determine an individual's cardio-respiratory fitness.VO_{2max} is a measurement that can be used to determine an individual's aerobic capacity (Kaminsky et al. 2014). VO_{2max} is the most reliable and accurate indicator of aerobic capacity in young people (Armstrong and Welsman 1994). It refers to an individual's peak oxygen intake during aerobic exercise or work and is dependent on the efficiency with which their lungs, heart, and muscles take in, deliver, and use oxygen (Poole et al. 2008) and is employed to evaluate tolerance to physical activity and to recommend exercise (Salehi et al. 2014).

Additionally, it can be utilized to determine a person's risk of mortality (ACMS 2013). It depends on numerous parameters, including oxygen in the atmosphere, mitochondrial content, diffusion capacity of pulmonary arteries, cardiac output, vascular oxygen transfer capability, and muscle characteristics of an individual (Bassett and Howley 2000). It is also influenced by factors such as age (Betik and Hepple 2008), gender

(Wang et al. 2010), Body mass index (BMI) (Parikh et al. 2017), and physical activity (Bori et al. 2016).

In a study conducted by Oja et al. (1977), a total of 54 Finnish postal carriers from the genders, the full work-age spectrum, and both city and suburban delivery areas underwent an assessment of the relative aerobic strain (RAS) of non-motorized mail delivery. Regarding maximum oxygen intake (ml/kg/min), the mean RAS over the entire delivery period was 55 %. It was more significant for suburban delivery than downtown delivery and higher for women than men. After age 50, the RAS tended to rise progressively with age. It was determined that the workload of mail carriers over 50 was high, particularly women working in suburban areas, leading to severe strain on the workers.

Vogel and Eklund (2015) evaluated twenty-one beef and pig cutters to analyze physiological demands in meat cutting. They compared them with the recommendations for acceptable workload provided by the ILO and discovered the relationship between individual and work-related characteristics. The workload for 13 of the 21 meat cutters surpassed the ILO limits of RAS. Furthermore, the workload was more significant in cutting beef than pork, according to this study, and more years on the job correlated with a lower RAS. Also, individuals who were paid piece wages had a greater RAS than those who received payment hourly, implying that working for a piece wage needs more effort from the person than working for a remuneration based on the number of hours worked and that it was challenging to alter a long-established work pace.

Saha et al. (2007) conducted a study to evaluate the physiological stress experienced by 98 healthy coal miners working in deep mines between the ages of 23 and 58 during their active period. Workers' heart rates were continuously monitored to determine the level of physical strain they were under, and the results showed that it ranged from high to severe. Oxygen consumption was evaluated directly using an oxylog-2 machine, which related to metabolic expenditure ranging from 4.96 to 5.47 kcal/min for various activities. The mean RAS ranged from 47.4% to 56.8%, indicating that the permissible threshold of physical strain was substantially exceeded by the miners, who had poor recovery responses regardless of age or category.

Dey et al. (2006) conducted a study in underground mines in India to examine the physiological strain of trammers during regular operation, comprising 30 healthy volunteers from two distinct age groups. Heart rate (HR) varied between 101.6 and 104.7 beats/min, with a mean net cardiac cost of 33.06 and 34.06 beats/min for the younger and older groups, respectively. Younger adults had a lower average relative cardiac cost than older subjects. The VO_2 was measured using an Oxylog-II machine (UK), and the data were then approximated. VO_{2max} was assessed with an indirect method following a conventional step test protocol. The average VO_2 during the activity was 0.75 and 0.8 L/min, respectively, and the VO_{2max} was 38.13± 2.4 (33.0-41.6)ml/min/kg for the younger group and 36.04 ±2.27 (30.7-38.9) ml/min/kg for the older group. Regarding RAS, the younger group had a RAS of 36.2± 4.75% of their maximum aerobic capacity, whereas the older group had a RAS of 42.5±4.47%. The workload in terms of HR and Energy Expenditure (EE) was modest, but the aerobic strain experienced by elderly employees exceeded the tolerable limit.

Thirty-nine healthy carriers aged 23 to 57 years were studied by Saha et al. (2008) in underground coal mines in eastern India over two different work spells of a single work shift. Subjects were segregated into two groups based on their age. The first group consisted of carriers less than 40 years of age with a sample size of 21 and greater than or equal to 40, with 18 carriers coming under the second group. The mean heart rate for both groups was 124-133 beats/min, with a 50-66% relative cardiac cost. Following a typical step test methodology, maximum aerobic capacities were calculated indirectly. The average oxygen intake was 1.07-1.1 l/min, and the RAS for the first spell was 50.4 6.8% and 57.4 5.5% of the maximum aerobic capacity for the younger and older groups, respectively. In contrast, the RAS for the second spell was 51.4% and 59 5.5% of their respective maximum aerobic capacities. The distance traveled by the older age group and their work pace was relatively more significant than their counterparts considered in the study, which could account for the greater physiological strain experienced by, the older employees.

2.5 Awkward Postures

Posture is a condition of the body defined by two different relationships: the body to the surface and the parts to one another (Martin 1977). Work posture is a "position adopted because it is suitable for the task being executed" (Taylor and Haslegrave 2007). Awkward postures raise the likelihood of fatigue, pain, or injury when used repeatedly or for an extended period (Keyserling et al. 1992).

In a pilot study, Schneider et al. (2001) evaluated postural stress during excavation operations. They assessed the postural needs of operators performing trench-digging operations on two distinct types of construction machinery. For both pieces of equipment, at least a quarter of the cycle time was spent with the trunk flexed or rotated. Most of the cycle time was spent with the right shoulders elevated, and at least 22% was spent with the neck either twisted or rotated.

An ergonomic study was conducted by Courtney and Chan (1999) to assess the design of the workstation and workplace of operators' cabins in grab unloaders used for handling bulk material in cargo ships. Their findings revealed that the operators frequently adopted awkward postures, partly because the cabin's basic geometry restricted the use of the central lower front window only for downward vision and the location of the control boxes that obstructed their vision. All the operators complained about having to keep and perform their jobs in an awkward posture. The most affected body parts were the lower back (88%), neck (81%), shoulders (50%), and mid-back (50%). More than half (56%) of drivers sought medical attention for these issues. It was discovered that operators spent half of their cycle time looking down, leading to static loading of the back and neck with the trunk bent forward 30 to 40 degrees and the neck stretched ahead 60 to 70 degrees from the vertical to ensure proper monitoring of the work beneath the operators' cabin.

Torén and Öberg (2001) tried to find out if free-swiveling saddle chairs while driving an agricultural tractor in the field affected the time spent in a twisted trunk position. Ten tractor drivers volunteered to participate in this study. The findings of this study revealed that using the saddle chair instead of the conventional chair reduced exposure to extremely twisted trunk posture during harrowing. However, when ploughing, the exposure to highly twisted postures decreased by half compared to the traditional chair. As a result, it is possible to conclude that using a freely swiveling mechanism and adequate swivel space would be beneficial in reducing postural stress.

Gustafson-Söderman (1987) investigated the relationship between a seat with an adjustable sitting angle and presumed distress in the back, neck, and shoulder areas among crane operators. The crane operators stated that the discomfort was primarily caused by a forward flexed sitting position during lifts near the crane. One of the three cranes evaluated had an adjustable sitting angle (test seat), while the other two had a standard seat. The operators who used the conventional seat experienced the highest levels of discomfort, while those who utilized the test seat with an adjustable sitting angle reported the lowest pain levels.

Bovenzi et al. (2002) assessed the risk of LBP in 219 port machinery operators in a study. The operators were exposed to Whole Body Vibrations (WBV) and postural load, as well as 85 maintenance workers at the same company who served as a control group. Forklift truck drivers had a significantly higher one-year prevalence of low back symptoms than controls or the other two groups of port machinery operators. Port machinery operators with extensive driving experience also increased the risk of lumbar disc herniation.

Massaccesi et al. (2003) conducted a study involving 77 drivers of garbage collection vehicles who sit in a yardstick posture and road washing vehicles who drive with the neck and trunk flexed, bent, and twisted was conducted using RULA, a method for assessing risk factors affiliated with work-related upper-limb disorders. A statistically significant correlation was found between subjects' entire trunk and neck scores and any self-reported pain, ache, or discomfort in the trunk or neck regions. The neck score, in particular, was significant in both postures, indicating high neck loading. Furthermore, drivers whose seats were adjustable compared favorably to those whose seats were not flexible regarding posture scores.

Scutter et al. (1997) surveyed 179 male farmers to acquire preliminary knowledge of headaches and neck pain incidence. The survey findings revealed a high prevalence of headaches and neck pain, with 33.5% of respondents having neck pain at least once weekly. Tractor driving was the activity that caused the most neck pain and headaches. The particular issue with tractor driving was being subjected to vibrations and needing to gaze behind them while working, resulting in a twisted neck.

2.5.1 Health effects of awkward postures

MME operators spend most of their shift time in a sitting position. Sitting is characterized by a continuous upright trunk position with limited options to shift posture or position (Keyserling et al. 1988). According to a study conducted by A. Nachemson (1966), sitting raises intra-discal pressure (IDP) by 40% more than standing, leading to Low Back Pain (LBP). Andersson et al. (1975) conducted a similar experiment utilizing a subminiature pressure transducer and determined that the IDP in standing is approximately 35% of that in comfortable sitting without back support. Globally, LBP has become the primary cause of disability and absenteeism (Maher et al. 2017). Several researchers have studied awkward postures of different body parts and their associated health risks. The following are some of the literature reviewed and are presented in table 2.1:

Table 2.1: Awkward body postures and associated health risks

Body Part	**Posture**	**Health Risk**	**Author(s)**
Neck	Extension of the head or neck	Neck pain	Ariëns et al. 2000
	Flexion of 20 to 45°	Neck pain	Hüṅting et al. 1980; Jonsson et al. 1988
	Flexion greater than 45°	Severe neck pain	Keyserling et al. 1992
	Twisting and/or lateral bending > 20°	Neck and shoulder pain	Tola et al. 1988
Shoulders	Protracted extension exceeding 60°	Reduced blood supply to muscles and thereby limiting muscular performance	Jensen et al. 1995
	Long-term elevation greater than 90°	Pain in the shoulders	Leclerc et al. 2004; Lin et al. 2010
	Shoulder flexion 120°	Muscle fatigue	Murphy and Russo 2000
	Lifting heavy loads or using high force	Pain in the shoulders	Svendsen et al. 2004
Lower arms	Working with arms above shoulder level	Pain in the shoulders	Leclerc et al. 2004
	Working with elbows above shoulder height	Disorders of the shoulders	Punnett et al. 2000
	Overextended or Flexed	Pain in the arms and wrists	Murphy and Russo 2000
	Activities involving	Muscle disorders	Dennerlein and

Wrists	extension and flexion		Johnson 2006; Nordander et al. 2013
	Wrist extension of 30°	Muscle disorders	Keir and Wells 2002
	Awkward postures combined with vibrations, force, and repetition	Carpal tunnel syndrome and repetitive strain injury	Franzblau et al. 1999
Trunk	Bent 20 to 40° with a twisted back	LBP	Bovenzi et al. 2006
	Rapid flexion	Disorders of the lower back	Marras et al. 199)
	more than 20° flexion for one-third of work duration	Disorders of the lower back	Keyserling et al. 1988
	forward flexion greater than 45°	Increased discomfort and biomechanical loads	Andersson et al. 1977; Boussenna and Corlen 1982
	Fixed or periodic spinal flexion for thirty minutes	Up to 24 hours of ligament creep and accompanying impairment of the back muscles.	Solomonow et al. 1999
Legs	Standing for an extended period of time	LBP and pain in the lower extremities	Anthony Ryan 1989; Krause et al. 2000
	Walking excessively	Compression of the inter-	(Wilke et al. 1999)

		vertebral discs and vertebral endplates	
	Squatting	Pain and numbness	(Sandhu and Sandhey 1976)
	Kneeling	Pain, trauma, and numbness in the lower extremities	(Chung et al. 2003)

2.5.2 Postural assessment tools

There are two kinds of postural exposure measuring techniques: indirect and direct. A self-reported questionnaire or a subjective evaluation is used in the indirect approach, whereas trained observers or video recordings are used in the direct technique (Burdorf and Beek 1999). The direct methods can measure ergonomics risk factors on a vulnerable person using tools such as electromyography, goniometry, and an inclinometer. Since they are reliable and valid, direct measurements are used to assess biomechanical or physical exposures. However, its application is limited in areas where it involves people and is focused on equipment for the most part (Burdorf et al. 1997; Juul-Kristensen et al. 2001).

Researchers around the globe have developed several observational techniques. They include Rapid Upper Limb Assessment (RULA) (Mcatamney and Corlett 1993), Rapid Entire Body Assessment (REBA) (McAtamney and Hignett 2004), Quick Exposure Check (QEC), Workplace Ergonomic Risk Assessment (WERA) (Abd Rahman et al. 2011), Posture, Activity; Tools And Handling (PATH) (Buchholz et al. 1996), Ovako Working Posture Assessment System (OWAS) (Karhu et al. 1977), Plan för Identifiering av. Belastningsfaktorer (PLIBEL) (Method for the identification of musculoskeletal stress factors which may have injurious effects) (Kemmlert 1995). This study used RULA to evaluate the postural stress among the MME operators working in an underground metal mine.

Mcatamney and Corlett (1993) developed RULA in the year 1993. This survey-based method investigates the presence of WRMSDs in the upper limbs of a subject and evaluates the risk of those WMSDs at different workplaces. It is an observation - based technique that necessitates no special equipment for ergonomics evaluation, making it quick and straightforward. It evaluates factors such as posture, movement, exertion force, repetition, and work duration for several body parts, including the neck, lower and upper arms, and trunk.

Gandavadi et al. (2007) used the RULA assessment to evaluate the posture of dentistry students during tooth extraction in two seating conditions. Sixty students were randomly chosen and offered two types of seats: conventional seats (CS) and Bambach Saddle Seat (BBS). The RULA results show that BBS scores are lower than CS students while performing teeth operations. It demonstrates that BBS reduces posture risk and improves dental students' ergonomics.

Singh (2010) has done a study to assess the risk of MSDs in individuals working in a small-scale forging unit using the RULA method. One hundred thirty workers involved in processes like forging, punching, broaching, and grinding participated in the study. The RULA results revealed that approximately 30% of the workers were at high risk and actually needed instant change. Nearly 33% and 37% of the workers were at medium and low-risk levels, respectively.

A study was conducted by Sharan and Ajeesh (2012) to find the relationship between musculoskeletal discomfort and RULA postural score in IT professionals. The case study included 620 IT employees with a mean age of 28.45±10.4 years, height of 1.63±0.935 m, and weight of 61.45±7.44 kg. The postures of the employees were evaluated while they were using computers. According to the findings, 65% of workers were at a lower risk level, 30% were at medium risk, and 15% were at high risk. The most common workstation risk factors were incorrect chair height (12%), keyboard and monitor height (27%), and mouse tray height (32%). The results show room for improvement in the ergonomics of IT employees in terms of sitting posture, working environment, and work duration.

Mohamad et al. (2013) assessed the WRMSDs of an employee in the packaging industry by using Digital Human Modeling (DHM) and RULA method. The posture adopted by the worker for the repeated lifting of a product that weighed 39.4kg was analyzed. The entire load-lifting operation was videotaped and separated into five different postures. The postures were recreated using DHM, which rendered the worker's position in a 3D graphical interface. The RULA assessment on DHM of the worker in all of the different postures was carried out with the help of the CATIA P3 V5R14 software. The investigation found that the individual suffered from high-load lifting and the accompanying posture.

2.6 Mechanical Vibrations

Vibration is defined as a relative oscillation around a fixed point. It functions as a mechanical wave and, as a distinctive feature, only transfers energy instead of matter. A wide range of processes and operations in manufacturing, construction, mining and quarrying, agriculture and forestry and utility services causes mechanical vibration. Human vibration is typically divided into two types; whole-body vibration (WBV) and hand-transmitted vibration (HTV) (Griffin and Erdreich 1991). WBV occurs when the human body is supported on a vibrating surface like a seat or a vibrating floor. This can lead to discomfort, tamper with activities, and impair one's health (Van Niekerk et al. 2000). The vibration that is transferred from the vibrating tool or surface to the hand-arm system, is referred to as hand-transmitted vibration, abbreviated as HTV (Griffin and Bhattacharya 1996).

A. Whole Body Vibrations (WBV)

In a study by Wolfgang and Burgess-Limerick (2014), the authors predicted that haul truck operators would be exposed to WBV during their working hours in various road conditions. The different road conditions in a surface coal mine in New South Wales were primarily dirt roads of a new production area with a damp climate, graded surface, and a combination of jagged and maintained surfaces. Measurements taken from 32 different haul truck capacities (136 t to 290 t) in uneven terrain confirmed that the magnitude of acceleration for dump trucks fell within the HGCZ for an 8-hour work duration. It was also found that the vibration magnitude varied with load-carrying capacity for the same haul road condition, with the magnitude being greater for small-sized dumpers.

Chaudhary et al. (2015) examined the impact of rock parameters on operators of large blast-hole drill machines. The frequency-weighted rms acceleration (m/s2) was measured during the investigation and compared to ISO recommendations. The parameters considered were the machine's manufacturer, age, height, seat thickness, and rest height. Similarly, rock hardness, uniaxial compressive strength, and density were taken into account to monitor the magnitude of vibration. After conducting a study on 28 operators working in various iron ore mines, the researchers concluded that the extent of vibration increased as rock strength, age, and seat height increased. In light of the preceding research, the authors felt that the mechanics of vibration transmission should be better understood and design modifications should be implemented to achieve lower vibration magnitudes.

Smets et al. (2010) monitored WBV at the interface of operator and seat for eight haul trucks of three different capacities (35, 100, and 150 t) throughout various operations, such as loading, loaded hauling, unloading, and empty hauling, during routine procedures. The magnitudes for equivalent daily exposure A(8) varied from 0.44 to 0.82 ms^2 for frequency-weighted RMS and between 8.7 and 16.4 ms^2 for the vibration dose value (VDV) technique. The majority of vehicle operators experienced physical discomfort while driving. The maximum rms acceleration was found along the z-axis (vertical), and the maximum A(8) was found during loaded and unloaded travel.

B. Hand Arm Vibrations

Mechanical vibrations that harm workers' health and safety when transmitted to the hand-arm system are known as hand-arm vibrations (EU Directive, 2002). Hand-Arm vibration is caused by the vibrations transmitted into the hand and arms through the palm and fingers. The handle of the machine or the surface of a work piece vibrates rapidly, and this motion is sent to the hand holding the equipment.

Van Niekerk et al. (2000) conducted an in-depth analysis of over 700 vibration data sets collected from 70 equipment spread across 15 mines. Rock drills (hydraulic and pneumatic), jackhammers and pavement breakers, pneumatic wrenches, hand-held compactors, and electric hammer drills had the highest vibration levels in the study's hand-arm category. The rock drills were the only ones with measured vibration bandwidths of more than 20 m/s^2.

Su et al. (2011) conducted a cross-sectional study on a Kuala Lumpur construction site to determine the prevalence of hand-transmitted vibration exposure problems among Malaysian construction workers. The vibration magnitudes of concrete breakers, drills, and grinders were measured using a three-axis accelerometer. The total vibration values for concrete breakers, impact drills, and grinders were 10.02 m/s^2, 7.72 m/s^2, and 5.29 m/s^2, respectively. 18% of the workforce was subjected to intense vibrations. Among a group of construction workers exposed to hand-transmitted vibrations, the study has identified clinical symptoms and signs consistent with a diagnosis of HAVS.

Akmar and Aziz (2017) conducted a study using a Bruel & Kjær Type 4447 human vibration analyzer to monitor the HAV levels from the steering wheels of three-ton trucks of the Malaysian army. The study was conducted for different vehicle speeds and idling conditions. The total daily vibration for an eight-hour shift A(8) values for the speeds of 20, 40, and 60 km/hour were found to be 1.66, 2.13, and 2.73 $m/s^{2,}$ respectively. The A(8) value during the idling condition was 0.82 m/s^2. The highest A(8) values up to 4.39 m/s^2 were recorded while driving at 80 km/hour speeds. The results showed that the HAV levels increased with the increasing speed of the vehicles. Also, the major contribution towards A(8) was coming from the z-axis, i.e., the longitudinal direction.

Yoo et al. (2011) conducted a study to assess the HAVs from the steering wheels involving two cars of Korean manufacture for different speeds and road conditions at the Korea Automotive Technology Institute. The results from the study showed that the x-axis was the major contributor toward A(8) while driving on uneven and asphalt roads. The rms acceleration was more dominant in the y-axis for Belgian, cobblestone, and block roads. Furthermore, regardless of the kind of road, the vibration values increased with increasing vehicle speed.

Dewangan and Tewari (2009) conducted a study to evaluate and quantify HAV in a small hand tractor during forward transit on tarmacadam road, rotary tilling in the dry land, and rotary puddling in wet land circumstances as per the ISO 5349-2 guidelines at the Indian Institute of Technology Kharagpur, India. The investigation results showed that the x-axis had the highest rms acceleration, followed by the z-axis, and the least rms acceleration values were in the y-axis. The peak rms acceleration of 8.07 m/s^2 was found during rotary tilling, followed by transportation and rotary puddling, with rms acceleration values of 5.52 and 5.27 $m/s^{2,}$ respectively. The highest vibration total values (a_{hv}) occurred during transport, followed by rotary tilling and rotary puddling.

A study was conducted by Goglia et al. ((2003) to evaluate the vibration transmitted from the steering wheel of a small four-wheel drive tractor to the operator's hands. The tractor was selected randomly from the company's store, and the steering wheel vibration level was recorded and analyzed for idling and movement with a full load. The results from the study showed that the vibration levels at idling and full load were 4.26 and 17.91 m/s^2, respectively, well beyond the limits of 2.5 m/s^2. The highest vibration readings were recorded in the z-axis for both conditions, followed by x and y-axes for idling and y and x-axes for traveling with a full load. The authors also concluded that 10% of individuals exposed to these vibration levels would develop finger blanching within two years or less.

2.6.1 Health effects of Hand Arm Vibrations

Generally, several millions of employees in industries such as vehicle operating are occasionally subjected to hand–arm vibrations every year, which exerts a large amount of stress on their musculoskeletal system (Haber 1971). A survey in the United Kingdom reported that a frequency range between 2 to 1500 Hz potentially damages the arm and fingers (Health and Safety Executive 2012). In addition, research has shown that frequencies between 20 and 50 Hz cause substantial damage to the hand and arm system, and frequencies beyond 80 Hz are considered significantly harmful to the fingers. (Dong et al. 2004, 2010).

Hand-Arm Vibration Syndrome (HAVS), a chronic, progressive condition affecting the vascular, neurological, and musculoskeletal systems, is linked to higher risk when prolonged occupational vibration exposure. Blanching of the fingers, tingling, loss of sensitivity, numbness, and discomfort in the fingers are signs of the early stages. In its latter phases, this condition may result in diminished hand functionality and necrosis of the fingers (Van Niekerk et al. 2000). HAVS was identified for the first time in the limestone quarries of Bedford, Indiana, between the years 1890 and 1900 (Taylor et al. 1984). The development of HAVS depends on various factors, including the vibration magnitude of the tool, the volume of cumulative exposure, and the ergonomics (grip, posture, adjustability) of the instrument in use (Lin et al. 2005). Vibration dose, the product of vibration level, and exposure times are critical for developing HAVS. A strong relationship was found between the severity of HAVS and the exposure time (Bovenzi, 1998).

Employees may develop vascular, neurological, or musculoskeletal complications individually or in combination with one or more of the above conditions (Nilsson et al., 2018). Neurological and vascular problems have been researched more often than musculoskeletal ones (Hagberg 2002). Even the Stockholm Workshop Scale, a widely used screening approach for HAVS, has only categorizations for vascular and neurological problems (Thompson et al. 2007) amidst recorded concerns from employees regarding aches and discomforts in the upper extremities as a result of exposure to HAV (Ahmad Nasaruddin et al. 2014). Although a higher incidence of upper limb pain has been reported among HAV-exposed workers, few studies have examined the severity of the impairment or the relationship between musculoskeletal symptoms and vibration exposure (Charles et al., 2018).

Human exposure to HAV is associated with musculoskeletal problems in the hands, wrists, elbows, shoulders, and neck (Hagberg 2002). Tools like drills, saws, and impact wrenches generate high-frequency vibrations that are primarily absorbed by the fingers. Vibrations, particularly at lower frequencies, are transmitted into the shoulders, arms, and even the neck, thus linked to musculoskeletal disorders in these areas (House et al. 2009). Exposure to HAV is believed to cause pain, swelling, and stiffness, resulting in reduced grip strength and a loss of motion of the musculoskeletal system among affected workers (Nyantumbu et al., 2007).

Exposure to HAV has been linked to various pathologies, including cysts, osteoarthritis, and tendonitis/synovitis inflammation (Gemne and Saraste 1987). High rates of upper limb disability were found in people exposed to HTVs, according to research conducted in Norway using the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire (Buhaug et al. 2014). Long-term exposure to HAV has been shown to result in vascular, neurological, and osteoarticular symptoms such as white fingers, cold intolerance, numbness, stiff fingers, decreased touch sensation, and reduced grip strength (Hol and Yu 1986; Ld et al. 2001; Widia 2010).

Nyantumbu et al. (2007) studied HAVS in South African gold miners. The study has identified the first instances of HAVS in the mining industry of South Africa. A smaller-than-anticipated occurrence of HAVS can be attributed to several factors, including a larger-than-anticipated number of survivors and fewer reports of vascular symptoms caused by the warm-ambient temperatures.

Hill et al. (2001) conducted a study to enlighten, guide, and offer suggestions on mitigating hand-arm vibration syndrome (HAVS) among the 617 workers at a base metal mine in northern Ontario. Half of the participants were identified as having HAVS, while the remaining 26% had other diagnoses. Some participants had multiple conditions, such as HAVS and carpal tunnel syndrome.

Widia (2010) measured muscle activation at the arm and shoulder and grip strength before and after seven participants used electric and bench drills to drill through the wood for five and 15-minute periods, respectively. Results showed a decrease in grip strength for all trials, with more significant reductions in grip strength associated with higher vibration levels and more prolonged exposure durations.

Ho and Yu (1986) examined the effect of HAV exposure on the median and ulnar nerves. They found a significant dose/effect correlation between the direction, duration, and nerve conduction velocity. Longer exposure times were associated with reduced nerve conduction velocities.

Reducing the median or ulnar nerve conduction velocities would decrease a person's ability to detect touch, known as touch sensation threshold, and reduce their grip strength. Changes in finger touch sensation threshold are found among dentists and dental technicians who commonly use tools with HAV levels exceeding 1000 Hz (Hjortsberg et al. 1989).

Touch sensation threshold and grip strength decrease with age and decline in motor nerve function (Metter et al. 1998). The reduction in grip strength associated with HAV exposure has been shown in short-term studies where participants use vibrating hand tools and epidemiological studies of more long-term effects (Widia and Dawal 2010; 2011).

2.6.2. Standards for HAV measurement and assessing the associated health risks

International Organization for Standardization (ISO) and European Union Directive are the specific standards for assessing workplace human vibration exposure. ISO offers various guidelines for evaluating human vibrations, including ISO 2631-1, 2, 3, 4, and 5 for assessing whole-body vibrations (WBVs), ISO-5008 for measuring WBVs in agricultural field machinery and tractors, ISO-7096 in HEMMs and ISO 5349:2001 for measuring HAVs. Directive 2002/44/EC of the European Union offers guidelines for HAV exposure. In this study, ISO 5349:2001 and European Union Directive 2002/44/EC are the two standards studied for evaluating HAV.

2.6.2.1 ISO 5349:2001

The ISO 5349 standard has two components. Part-I, ISO 5349-1, outlines the general criteria for measuring HAV, whereas part-II provides practical recommendations for measuring and evaluating HAV in the workplace. According to ISO 5349-1 root mean square (rms), the magnitude of HAV is determined using frequency-weighted acceleration given in m/s2. Since HAV will have contributions from all three axes of measurement, vibrations will be measured along all three axes: x, y, and z. However, the evaluation of HAV is based on the sum of all vibration values in the three measuring directions a_{hwx}, a_{hwy}, and a_{hwz}. The total vibration a_{hv} value is determined by equation 2.1.

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \text{ m/s}^2 \qquad (2.1)$$

Where a_{hwx}, $a_{hwy,}$ and a_{hwz} are the frequency-weighted acceleration (wrms) values for x, y, and z-axis, respectively, and a_{hv} is the total vibration value.

The magnitude of vibrations and the exposure duration during the work session influence HAV exposure. The daily vibration exposure duration is normalized to an eight-hour reference period and is given by equation 2.2:

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \text{ m/s}^2 \qquad (2.2)$$

Where,

A(8) is the total daily vibration value normalized to an 8-hr reference shift period.

T is the total daily exposure duration for each shift, and T0 is the 8-hour duration taken as a reference

In the case of different durations of exposure and magnitudes due to several work components, then A(8) is calculated by equation 2.3:

$$A(8) = \sqrt{\frac{1}{T_o}\sum_{i=1}^{n} a_{hvi}^2 T_i} \text{ m/s}^2 \qquad (2.3)$$

Where,

a_{hv} is the vibration total value for the i^{th} operation;

n is the number of individual vibration exposures;

T_i is the duration of the i^{th} operation.

Furthermore, the ISO 5349:2001 standard does not set specific safety limits for exposure to HAV; instead, it merely provides a reference for determining the degree to which one has been exposed to HAV. In light of this, the primary purpose that ISO 5349:2001 serves in this investigation is to measure the HAV. In contrast, the European Union (EU) Directive 2002 is utilized to assess the dangers posed by the obtained HAV results.

2.6.2.2 European Union (EU) Directive 2002

The EU Physical Agents Directive establishes an 8-h equivalent exposure action value (EAV) of 2.5 m/s^2 and an 8-h equivalent exposure limit value (ELV) of 5 m/s^2 for HAV. Workers must not be exposed above the exposure limit number, according to the Directive. If the EAV is surpassed, the employer must design and execute technical and/or organizational measures to decrease exposure to mechanical vibration and the associated risks to a minimum level. The Directive requires employees susceptible to mechanical vibration exceeding the EAV to receive proper health surveillance. However, health surveillance is not limited to instances in which the EAV has been surpassed: monitoring is required if there is any reason to worry that individuals may be affected by the vibration, even though the action value has not been exceeded.

CHAPTER-3

INSTRUMENTATION AND METHODOLOGY

3.1 Selection of Mine Site

This research study was conducted in an underground metal mine in western India. Zinc is the principal mineral extracted from the mine, followed by lead and traces of silver. The mine has a total reserve and resource of 5.5 million metric tonnes (MT) with a zinc-lead reserve grade of 6.1%. The mine is accessed via a decline, and the blast hole open stoping method is employed for mining. Backfilling of the mined-out stopes is carried out using cemented rock and cemented tailing in paste form.

3.2 Ethical Clearance

The study was approved by the Research Progress Assessment Committee (RPAC) of the institute and the respective mine management based on the recommendations of the Director General of Mines Safety (DGMS), the regulatory body of mines in India, in its 11th conference on Safety of Mines to carry out the vibration and work posture studies of the mining equipment operators. A detailed explanation of the study was given to the participants involved in the study in both Hindi and English languages.

3.3 Methodology

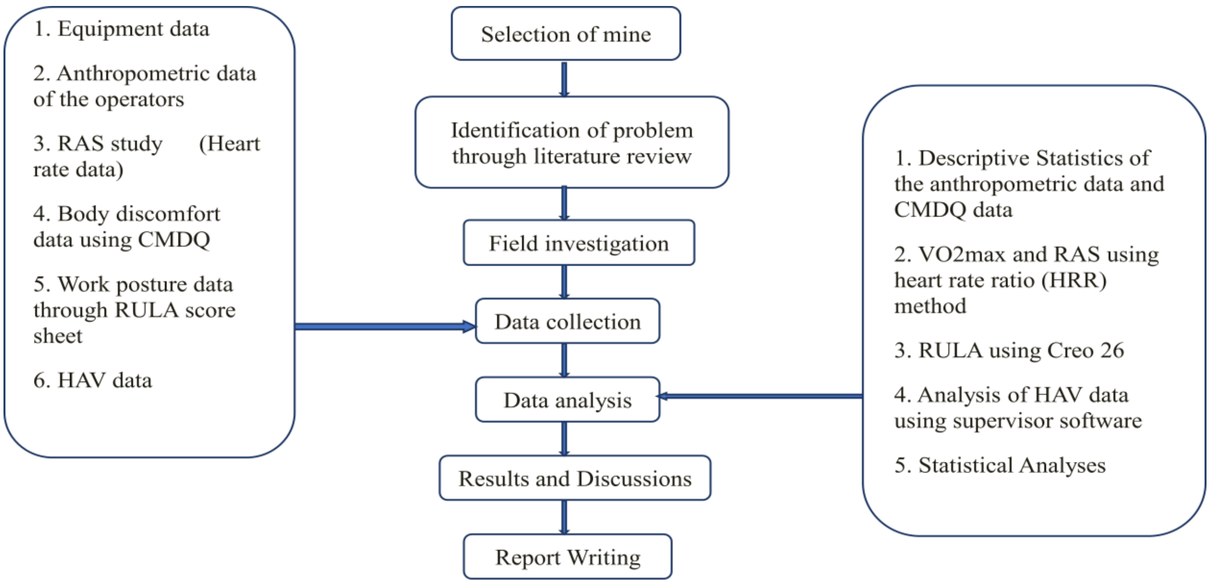


Figure 3.1: Flowchart of methodology

3.3.1 Relative Aerobic Strain (RAS) study

3.3.1.1 Selection of Participants

Forty MME operators aged between 26 and 45 involved in transporting ore, overburden, mine personnel, explosives, repair material, etc., were examined. Physically fit and healthy operators with no illness or medical history participated in the study. The operators worked in shifts of 8 hrs per day for six days a week. The average operating time of each piece of machinery was 6.5 hrs per shift.

The operators were divided into three groups based on the machine they operated. The first and second groups consisted of Low Profile Dump Truck (LPDT) and Load Haul Dumper (LHD) operators. The operators from both these groups were directly involved in production. The third group consisted of auxiliary equipment operators such as scalers, roof bolters, personnel carriers, explosive carriers, water tankers, breakdown rescue vehicles, etc.

The operators were encouraged to sleep for 7-8 hours and to refrain from using tobacco the day before the study. The study was conducted in the general shift, i.e., 9:00 AM to 5:00 PM. The operators who participated in the study had no physical exercises or training except for routine household chores.

3.3.1.2 Data collection

There are two methods to determine VO_{2max} - Direct and Indirect. The direct methods include cycle ergometry, step test, and treadmill test, which are precise, time-consuming, costly, and require qualified professionals (Howley 1995). The indirect approaches utilize Astrand charts and formulas, physiological (e.g., Heart Rate [HR]), and subjective (e.g., Rating of Perceived Exertion [RPE]) factors (Pooja M A, Aryaa B 2018). Direct methods are helpful when assessing a small number of individuals, whereas indirect methods are advantageous and helpful for evaluating VO_{2max} on an industrial scale (Habibi et al. 2014). The heart Rate Ratio (HRR) method was utilized to indirectly estimate the VO_{2max} and RAS.

Operators were informed and made to rest in their comfortable position for 30 minutes before the start of the measurement. The mine's safety officer collected participants' anthropometric Heart Rate (HR) data at the vocational training facility. The HR data collection was initiated by measuring the participants' Resting Heart Rate (RHR) using a portable Heart Rate Monitor. The next measurement step was to collect the participants' Working Heart Rate (WHR). The WHR data collection of the participants was carried out after one hour after the start of the shift and in regular intervals of 5 minutes for three trials every hour till the end of the shift. The mean WHR was considered for further calculations.

The Relative Aerobic Strain (RAS) was calculated by the Heart Rate Ratio (HRR) method using the below empirical relationships:

Relative Aerobic Strain (RAS) is the ratio of oxygen consumption (VO_2) during a task to the maximum aerobic capacity (VO_{2max}) of a person and can be denoted as:

$$RAS = VO_2 / VO_{2max} \quad (3.1)$$

The maximum aerobic capacity (VO_{2max}) of an individual can be estimated indirectly using the ratio of Maximum Heart Rate (MHR) to the RHR and is expressed as (Uth et al. 2004):

$$VO_{2max} = 15(MHR/RHR) \text{ mililitre/ kilogram/minute (mL/kg/min)} \quad (3.2)$$

The MHR of an individual can be theoretically found using the empirical relationship (Tanaka et al. 2001):

$$MHR = 208 - (0.7 * age) \quad (3.3)$$

The working VO_2 of an individual is estimated using the expression (Habibi et al. 2014):

$$VO_{2max} = \frac{VO_2 * (220\text{-}age\text{-}73\text{-}(Sex*10))}{(WHR\text{-}73\text{-}(Sex*10))} \text{ mL/kg/min} \quad (3.4)$$

*Sex= 1 for male and 0 for female

$$VO_2 = \frac{VO_{2max}(WHR - 73 - (Sex * 10))}{(220 - age - 73 - (Sex * 10))} \text{ mL/kg/min} \quad (3.5)$$

The BMI of the operators was determined using the equation (Fuchs-Buder et al. 2007):

$$BMI = Weight/Height^2 \quad (3.6)$$

The BMI of the operators is categorized into two groups - Normal for a range of 18.5-24.9 and overweight for a range of $\geq$25-29.9.

3.3.1.3 Statistical analysis

A descriptive statistical analysis was performed to summarize the anthropometric and field data of the participants, along with the results obtained through calculations. The

Pearson product-moment correlation coefficient (r) was used to investigate the association between anthropometric variables (age and BMI) and relative VO_{2max} and RAS. Regression models with an independent variable, relative VO_{2max}, and RAS as the dependent variables. The r^2 value was used to determine the correlation between the two variables.

3.3.2 Work posture assessment

3.3.2.1 RULA analysis

Rapid Upper Limb Assessment (RULA) is an observational postural analysis method designed to analyze and evaluate upper body postures while addressing any MSD issues. The technique enables a swift evaluation of the upper limbs, neck, and trunk postures. It also considers the muscular functioning and loads on the operator's body. RULA consists of three tables: Table A, Table B, and Table C. Table A assesses the upper and lower arms, the wrist, and the wrist flexion based on the location of the lower and upper arms and the degree of twisting and flexion of the wrist. Table B assesses trunk and neck posture based on the position of the trunk and neck from the center of the legs and body, considering whether they are supported or not. The final RULA score is generated from Table C using Tables A and B scores. The RULA assessment generates a list of action categories with a code indicating the degree of necessary intervention needed to lessen the risk of worker discomfort. The instrument delivers a single score for the complete assignment that evaluates the requisite posture, force, and movement. The scores are then divided into four action categories, determining when a risk mitigation step should be taken.

Figure 3.2: RULA Posture Assessment Worksheet. (Image Source: ergoplus.com)

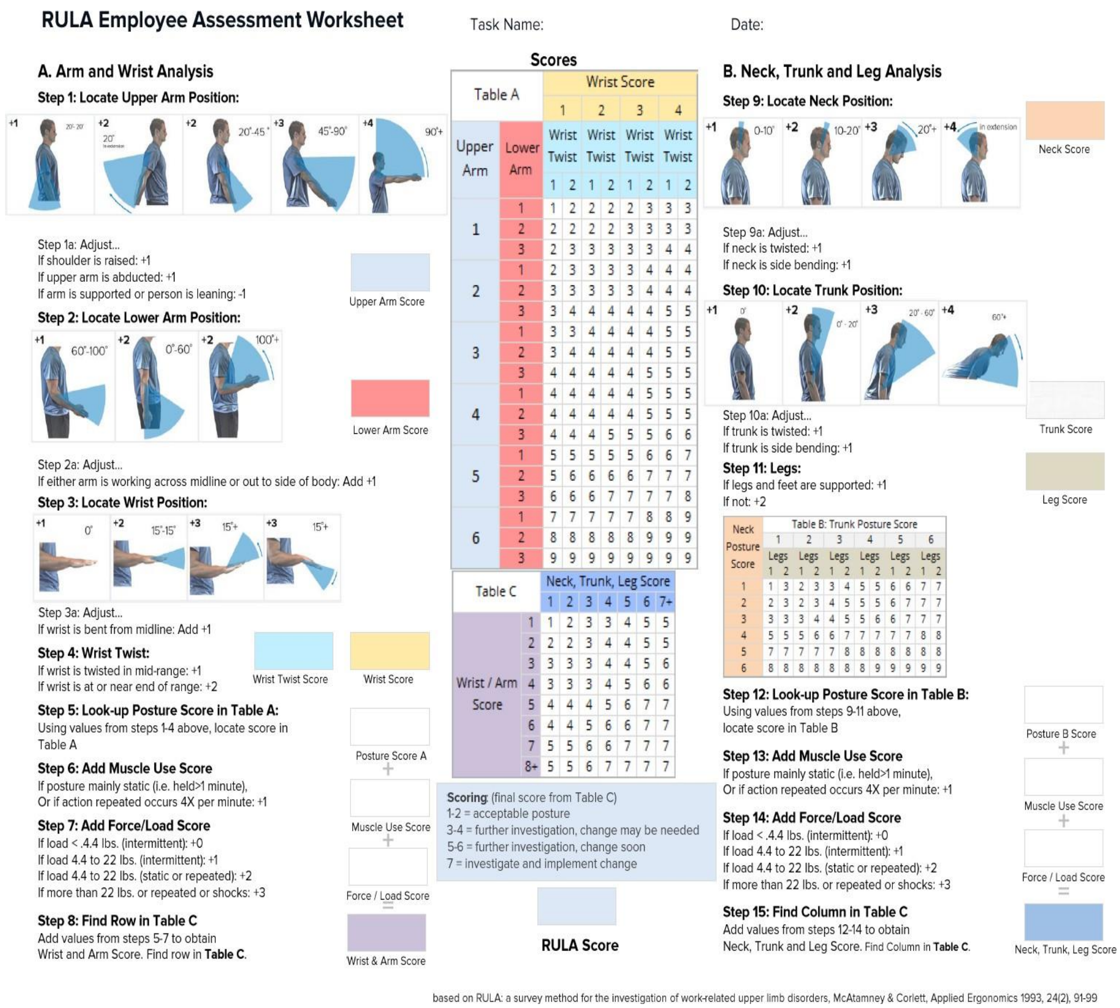


Table 3.1: RULA Action Scores

RULA Total Score	MSD Risk Level
1-2	Acceptable posture if not prolonged or sustained for extended durations
3-4	Additional investigation is warranted, and a modification in posture may be needed.
5-6	Assess and adopt posture corrections as quickly and efficiently as possible to avoid continued exposure to the risk of MSDs.
7+	Necessitates immediate attention and posture modifications

3.3.2.2 Data collection and analysis

The working posture of the operators was recorded with the aid of a digital camera. The frequently adapted posture by the operators was identified by analyzing the video graph and converted into a static image for the RULA analysis. In this study, the RULA analysis was carried out for 40 personnel involved in operating three different types of mobile mine equipment. The equipment considered in the study included Low Profile Dump Trucks (LPDTs), Load Haul Dumpers (LHDs), and Auxilliary machines. The analysis was performed using CREO-26 software (previously known as PRO-E) by creating digital human models of the operators.

3.3.3 Hand Arm Vibration (HAV) study

3.3.3.1 Instrumentation

ISO 8041 completely specifies the instrumentation to be used for ISO 5349 hand-arm vibration evaluation. ISO 5349, in particular, establishes the general requirements for measuring and evaluating employees exposed to hand-transmitted vibration. It is supported by material from ISO 5349-2, which provides practical recommendations for implementing proper measurement and evaluation methodologies in the workplace. The HAV measurements were carried out using SV 105B Triaxial Hand-Arm Accelerometer connected to an SV106 human vibration analyzer for data logging.

Fig 3.3: SV 105B Tri-axial Hand-Arm Accelerometer

The SV 105B Triaxial Hand-Arm Accelerometer is designed for Human Vibration measurements conducted following ISO 5349-2 using the SV 106 six-channel analyzer. The accelerometer has three adapters to fit the grip of various vibrating surfaces. Each adapter features an adjustable rubber strap for securely and comfortably attaching the accelerometer to the operator's hand, reducing disruptions while performing his task. The accelerometer has an internal memory containing sensitivity information sent to the SV 106 instrument automatically. The accelerometer has an excellent resistance to shock, no Direct Current (DC)-shift effect, and uses significantly less power than Integrated Electronics Piezo-Electric (IEPE) or Injection control pressure (ICP) sensors.

Fig 3.4: SV 106 Six-channel Human Vibration Analyzer

The SV 106 Six-channel Human Vibration Analyzer meets the criteria of ISO 8041-1:2017 and is an appropriate device for measuring human vibrations according to ISO 2631, ISO 5349, and European Parliament Directive 2002/44/EC. The SV 106 has two 3-axial inputs for IEPE or Micro-Electro-Mechanical System (MEMS) sensors. The Root Mean Square (RMS), Peak, Peak-Peak, or dose results such as A(8) and Vector with all required weighting filters for human vibration measurements are stored on a microSD card.

3.3.3.2 Data Collection and analysis

Prior permission from the mine management was obtained to conduct a session involving the machine operators at the Mine's Vocational training Centre (VTC). The operators were informed about the purpose of the study and the procedures involved in HAV measurement. The details of the equipment considered in the study were accessed through the mechanical engineering department of the mine.

The job cycle and time-motion studies of the LPDTs and LHDs were carried out before taking the vibration readings. The event sampling technique was utilized for collecting the vibration data based on different components of a job cycle. Whereas the time sampling technique was used in the context of the case-control approach to capture the vibration readings from the MME operators, the vibration data was captured for 15 minutes. All the measurements were taken for three trials, and the mean values were taken for the data analysis. The instruments were calibrated before the data collection procedure per the manufacturer's guidelines.

The data collection procedure was initiated by tightly fixing the SV 105B Triaxial Hand-Arm Accelerometer to the operator's hand in touch with the steering device of the vehicle. Special care was taken to ensure that the hand wielding the accelerometer was in constant contact with the steering device during the measurement period. The accelerometer was connected to SV 106 Six-channel Human Vibration Analyzer for data capturing. The vibration data was captured along the three orthogonal directions, namely, the x-axis (longitudinal-front to back), y-axis lateral-side to side) and z-axis (vertical) based on the ISO 5349 guidelines.

The collected field data was analyzed using the Supervisor software package provided with the instrument. The supervisor application facilitates data transfer and equipment setting and offers comprehensive tools for determining hand-arm vibration exposure. The readings were recorded in m/s2 and are directly comparable to the European Directive 2002/44/EC-established limits.

3.3.3.3 Statistical analysis

Multiple regression analysis and Analysis of Variance (ANOVA) was performed to examine the effect of machine parameters on total daily HAV exposure A(8). The predictor variables considered for the study include haulage capacity, machine working hours, and machine load condition (loaded vs. empty).

3.3.4 Case-control study

Case-control studies are used to compare two groups of individuals with an outcome disease or a condition subject to exposure to a particular factor, substance, and/or a working state. The study explains the impact of exposure on the occurrence of disease. The exposed group is considered the case group, and the other is the control group.

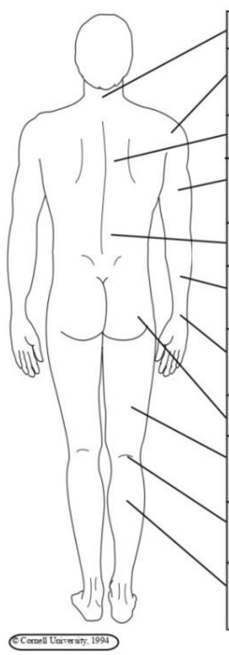
3.3.4.1 Selection of Participants

The case-control study was carried out involving 80 male workers at the same mine. The research enrolled MME operators, office employees, supervisors, engineers, mechanical engineering, and logistics personnel. The case group consisted of 40 MME operators exposed to HTVs regularly, and the control group consisted of the remaining participants without any exposure to vibrations.

3.3.4.2 Data collection

The participants' anthropometric and body discomfort data was collected in the presence of the mine's safety officer at the vocational training facility. The body discomfort data was collected using the Cornell Musculoskeletal Disorder Questionnaire (CMDQ) (male version) for sitting positions. The questionnaire comprises 54 items to be completed by study subjects, including a body map diagram and questions on the prevalence of musculoskeletal discomfort in 18 different body areas. However, the study concentrated on the upper extremities; only ten body regions were selected. The participants were asked to rate their level of discomfort on an ordinal (visual analog) scale ranging from 0 (never) to 10 (many times per day) and the intensity of their discomfort on a scale ranging from 1 (mildly uncomfortable) to 3 (very uncomfortable). A pain level of at least "moderately uncomfortable" was used as a severity criterion for assessing prevalence and frequency. The degree to which the discomfort interfered with work was graded on a scale of 1 (no interference) to 3 (substantial interference). The total pain score was determined using the following formula: Discomfort Score = Frequency of discomfort *Intensity of discomfort* Interference level.

The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.



		During the last work week how often did you experience ache, pain, discomfort in:					If you experienced ache, pain, discomfort, how uncomfortable was this?			If you experienced ache, pain, discomfort, did this interfere with your ability to work?		
		Never	1-2 times last week	3-4 times last week	Once every day	Several times every day	Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable	Not at all	Slightly interfered	Substantially interfered
Neck		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shoulder	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Arm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Forearm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrist	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hip/Buttocks		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Thigh	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Knee	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Leg	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Fig 3.5: Cornell musculoskeletal discomfort questionnaire (sedentary worker, male version) **(**Source of instrument: Human Factors and Ergonomics Laboratory at Cornell University)

The vibration data were collected from the mine involving 40 participants from the case group operating different MMEs using a tri-axial hand accelerometer coupled with a human vibration analyzer. The detailed procedure of the same is explained in section 3.3.3.

3.3.4.3 Statistical analysis

The statistical tool IBM-SPSS version 26 was used to evaluate the acquired field data to make statistical conclusions to calculate the relative risk of MSDs in the upper extremities of the MME operators. Binary logistic regression was used to determine the factors significantly affecting the dependent variable since the relationship between predictor and response variables is usually categorical. Binary logistic regression models are employed when the dependent variable is binary, expecting only one of two different and incompatible values. Typically, the binary response variables are coded as '1' for the existence of a disorder and '0' for its absence. A general form of a binary logistic regression model is given in equation 3.7 to calculate the OR of exposure to a risk factor if you have the disease by evaluating the 14 independent variables (risk factors) against the health endpoint of interest.

$$\ln(p\backslash 1\text{-}p)=B+B_1x_1+B_2x_2+\ldots\ldots\ldots\ldots\ldots B_{14}x_{14} \qquad (3.7)$$

Where p is the probability of MSD risk in the upper extremities; B is the constant; $B_{1,}$ B_2,..…..B_{14} are the coefficients corresponding to the predictor variables x_1, x_2,..., x_{14}.

The 14 independent variables considered to analyze the overall MSD risk of the operators are the Neck, Right Shoulder, Left Shoulder, Upper Back, Upper Right Arm, Upper left Arm, Right Fore Arm, Left Fore Arm, Right Wrist, Left Wrist, Body Mass Index, Age, Experience and Tobacco usage.

CHAPTER-4

ASSESSMENT OF RELATIVE AEROBIC STRAIN AMONG MOBILE MINE EQUIPMENT OPERATORS

There have been various criteria offered for determining appropriate workload and ergonomic risks. Based on actual measurement data and quantitative exposure-response relationships, some recent research recommended threshold limit values. The acceptable workload is often defined using Relative Aerobic Strain (RAS). It is calculated as the ratio of oxygen consumption (VO_2) to maximum aerobic capacity (VO_{2max}) for an individual. The International Labor Organization established a limit of tolerable workload in dynamic job tasks of 33 percent RAS for an 8-hour working day.

4.1 Methodology

The participants' Relative Aerobic Strain (RAS) was assessed using an indirect approach of the Heart Rate Ratio (HRR) method explained in Chapter 3.

4.1.1 Selection of Participants

Forty Mobile Mine Equipment (MME) operators involved in transporting ore, overburden, mine personnel, explosives, repair material, etc., were examined. Physically fit and healthy operators with no illness or medical history participated in the study. The operators were encouraged to sleep for 7-8 hours and to refrain from using tobacco the day before the study. The study was conducted in the general shift, i.e., 9:00 AM to 5:00 PM. The operators who participated in the study had no physical exercises or training except for routine household chores.

4.1.2 Data collection

The anthropometric and personal data of the operators was collected in the Vocational Training Centre (VTC) of the mine. The anthropometric data collection included the measurement of the height and weight of the operators. The personal data such as age, experience, and tobacco usage of the operators, were recorded through personal interviews. The operators were divided into three groups based on the machine they operated. The first and second groups consisted of Low Profile Dump Truck (LPDT) and Load Haul Dumper (LHD) operators. The operators from both these groups were directly involved in production. The third group consisted of auxiliary equipment operators such as scalers, roof bolters, personnel carriers, explosive carriers, water tankers, breakdown rescue vehicles, etc.

Operators were informed and made to rest in their comfortable position for 30 minutes before the start of the measurement. The HR data collection was initiated by measuring the participants' Resting Heart Rate (RHR) using a portable Heart Rate Monitor. The next measurement step was to collect the participants' Working Heart Rate (WHR). The WHR data collection of the participants was carried out after one hour after the start of the shift and in regular intervals of 5 minutes for three trials every hour till the end of the shift. The mean WHR was considered for further calculations. The anthropometric, RHR, and MHR data collected from the field investigation are presented in Table 4.1.

Table 4.1: Anthropometric, RHR, and MHR data of the operators from three groups

MME operator	Machine Type	Group	Age in years	Experience in years	Height in m	Weight in Kgs	Tobacco usage	RHR in beats/ min	WHR in beats/ min
1	LPDT	G1	33	12	1.75	68	y	73	107
2			34	13	1.68	72	y	80	122
3			32	10	1.87	81	y	60	110
4			45	23	1.73	70	n	77	128
5			29	8	1.68	68	n	63	113
6			33	12	1.77	76	y	65	118
7			35	14	1.68	65	n	67	121
8			42	22	1.83	80	y	73	116

9			36	15	1.8	78	n	71	120
10			34	13	1.76	75	y	66	118
11			32	11	1.74	78	n	77	125
12			36	14	1.83	82	y	73	120
13	LHD	G2	42	21	1.76	76	y	76	126
14			36	12	1.72	74	n	77	123
15			36	15	1.78	73	n	64	120
16			38	18	1.81	85	n	71	126
17			36	15	1.85	92	y	80	128
18			35	14	1.74	85	y	83	126
19			34	12	1.69	70	n	66	109
20			38	16	1.89	75	n	64	120
21	Auxiliary machines	G3	28	7	1.76	72	y	60	118
22			32	11	1.85	85	y	61	121
23			34	13	1.76	83	y	78	124
24			26	5	1.79	81	n	73	124
25			28	9	1.81	85	n	76	123
26			29	9	1.83	90	y	79	127
27			31	11	1.71	75	n	74	122
28			30	10	1.84	95	y	79	129
29			26	5	1.79	70	n	57	106
30			28	7	1.82	75	n	66	111
31			28	6	1.69	78	n	78	126
32			29	8	1.87	96	y	80	129
33			32	11	1.82	88	n	80	127
34			27	6	1.79	92	y	83	124
35			32	10	1.68	75	y	73	128
36			32	10	1.83	80	n	69	117

37			28	7	1.78	82	n	73	121
38			36	14	1.81	85	y	76	125
39			32	11	1.75	75	n	70	117
40			38	16	1.84	92	y	80	126

4.1.3 Statistical analysis

IBM-SPSS version 26 assessed the gathered field data and derived statistical inferences. A descriptive statistical analysis was performed to summarize the anthropometric and field data of the participants, along with the results obtained through calculations. The Pearson product-moment correlation coefficient (r) was used to investigate the association between anthropometric variables (age and BMI) and VO_{2max} and RAS. Regression models with an independent variable and VO_{2max} and RAS as the dependent variables. The R^2 value was used to determine the correlation between the two variables.

4.2 Results and Discussions

A detailed descriptive statistical analysis of the anthropometric, RHR, MHR data of the MME operators collected from the field investigation and is presented in Table 4.2.

Table 4.2: Descriptive Statistics of the anthropometric, Personal, RHR, and MHR data of the operators

Field Data	G1 n=12	G2 n=8	G3 n=20	Total n=40
Age in years				
Mean	35.08	36.87	30.30	33.05
Standard Deviation	4.42	2.47	3.23	4.45
Range	29-45	34-42	26-38	26-45
Experience in years				

Mean	13.91	15.37	9.30	11.90
Standard Deviation	4.44	3.02	2.99	4.33
Range	8-23	12-21	26-38	5-23
RHR in beats/minute				
Mean	70.41	72.62	73.25	72.27
Standard Deviation	6.20	7.44	7.36	6.98
Range	60-80	64-83	57-83	57-83
WHR in beats/minute				
Mean	118.16	122.25	122.25	121.02
Standard Deviation	5.99	6.11	5.99	6.15
Range	107-128	109-128	106-129	106-129
BMI				
Mean	24.00	24.87	25.75	25.05
Standard Deviation	1.00	2.20	1.81	1.83
Range	22.20-25.76	21-28	21.85-28.71	21.00-28.71
Tobacco Usage				
Yes	7	3	10	20
No	3	5	10	20

This exploratory study enrolled 40 MME operators. The operators' mean age and experience were 33.05 and 11.90 years, respectively, with standard deviations of 4.45 and 4.33. The mean BMI of the operators was 25.05, with a standard deviation of 1.83. The mean RHR and WHR of the participants were 72.27 and 121.02, with standard deviations of 6.98 and 6.15, respectively.

4.2.1 Maximum Aerobic Capacity (VO_{2max})

The RHR data was collected from the field, and the MHRs of the operators were calculated using equation 3.3. The mean MHR for the operators was 184.95 beats/min.

The operators' Maximum Aerobic Capacity (VO2max) was determined using equation 3.2 and summarized in Table 4.3. The mean VO_{2max} of the operators was 38.75 mL/kg/min with a standard deviation of 4.14. The mean VO_{2max} was also calculated for all three groups; the findings are reported in Table 4.3. LPDT operators (G1) had the highest mean VO_{2max} of 39.40 mL/kg/min, followed by auxiliary machine operators (G3) at 38.66 mL/kg/min with standard deviations of 3.92 and 4.47, respectively. LHD operators (G2) had the lowest mean VO_{2max} of 37.98 $\pm$ 3.93 mL/kg/min. The variation in the mean VO_{2max} values among the three groups and the total mean VO_{2max} across all the groups, along with standard deviations, are depicted in Figure 4.1 using error plots.

Table 4.3: Descriptive Statistics of the physiological parameters of the operators

	G1 (LPDT) n=12	G2 (LHD) n=8	G3 (Auxiliary machines) n=20	Total n=40
MHR in beats/minute				
Mean	183.66	182.25	186.80	184.95
Standard Deviation	3.02	1.75	2.23	3.05
Range	177-188	179-184	181.00-190.00	177.00-190.00
VO_2 in ml/kg/min				
Mean	17.73	18.63	17.93	18.01
Standard Deviation	1.67	1.71	1.28	1.49
Range	13.50-20.0	15.70-20.40	15.90-21.20	13.50-21.20
Relative VO_{2max} in ml/kg/min				
Mean	39.40	37.98	38.66	38.75
Standard Deviation	3.92	3.93	4.47	4.14
Range	34.40-46.40	33.20-42.80	34.00-49.90	33.20-49.90
RAS %				

Mean	45.39	49.37	46.82	46.90
Standard Deviation	5.98	5.55	5.18	5.54
Range	35.50-58.00	37.40-54.80	32.80-52.90	32.80-58.00

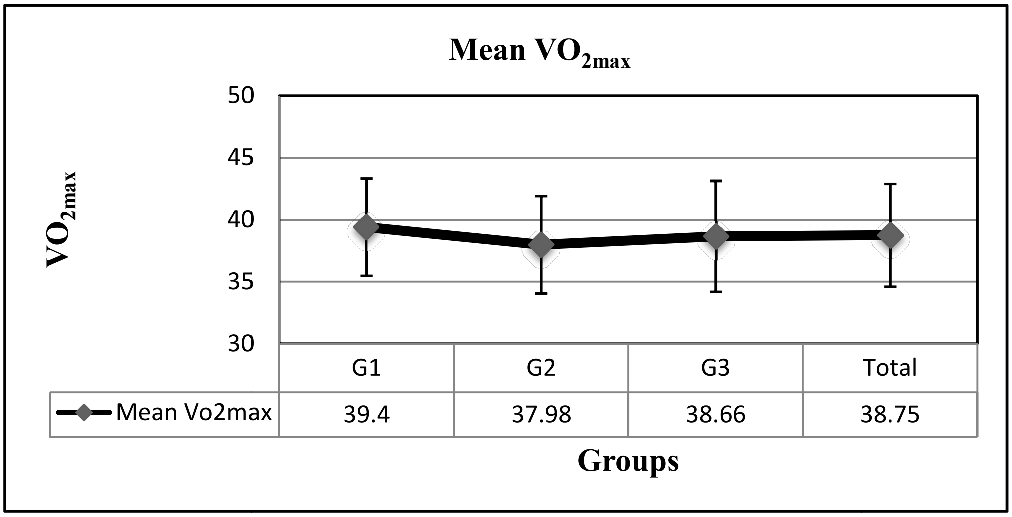


Figure 4.1: Mean VO_{2max} in mL/kg/min among the MME operators

The mean VO_{2max} recorded while considering the entire group of MME operators was 38.75 mL/kg/min. The lowest VO_{2max} of 37.98 mL/kg/min was found in G2 (LHD operators). This can be attributed to LHD operators working underground mines for their entire shift period. The findings of this study are comparable with the VO_{2max} of miners working in different underground coal mines in West Bengal (Dey et al. 2006) and miners working in a deep underground coal mine in India (Pal and Sinha 1994). The findings of this study are in accord with several studies conducted abroad involving miners in Poland, who recorded least VO_{2max} of 38 ± 7 mL/kg/min (Zahorska-Markiewicz 1991), and coal face miners from four collieries in Spain reported the least VO_{2max} of 38.10 mL/kg/min (Palenciano 1996).

4.2.1.1 VO_{2max} and age

The association between VO_{2max} and age is illustrated in Figure 4.2 for both the groups and all the MME operators considered simultaneously. Regression equations were also generated to predict the VO_{2max} using age in the three groups and overall MME operators. The results of the regression analysis are presented in Table 4.4.

The results in Table 4.4 suggest a statistically significant negative association between VO_{2max} and age in G1 and all the MME operators considered together with p values of 0.036 and 0.046, respectively. The relationship was statistically insignificant in G2 and G3.

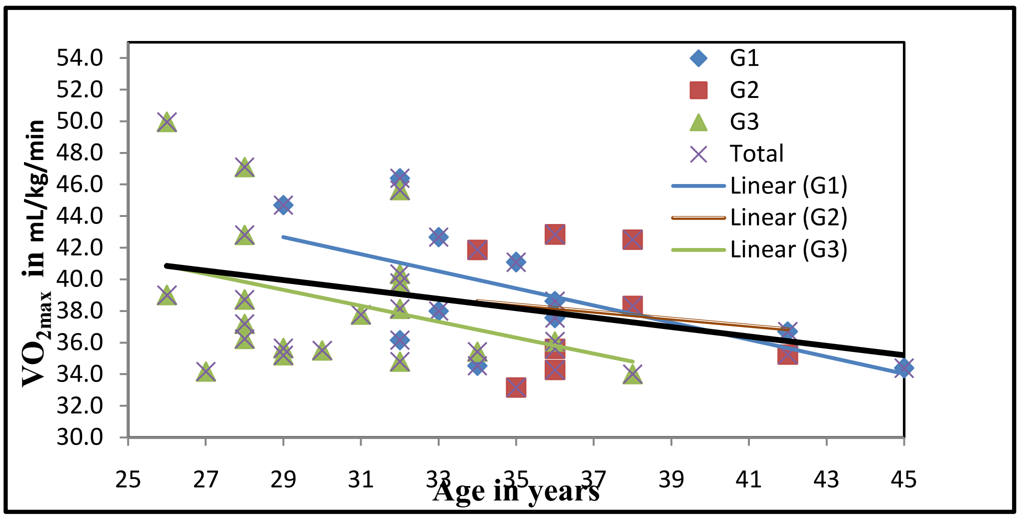


Figure 4.2: Association between VO_{2max} and age

Table 4.4: Association between VO_{2max} and age

Groups	Regression Equation	f	t	p	SE	Comments
G1	Y=-0.539x+58.32	5.874	-2.424	**0.036**	0.223	***Significant***
G2	Y=-0.223x+46.21	0.119	-0.345	0.742	0.643	*Insignificant*
G3	Y=-0.503x+53.94	2.732	-1.653	0.116	0.305	*Insignificant*
Total	Y=-0.296x+48.54	4.250	-2.062	**0.046**	0.143	***Significant***

After the age of 20-25 years, when the highest level of maximum oxygen intake (VO_{2max}) is attained, the rate of decline is approximately 1–2 % each year (Astrand et al.

1973). The maximum aerobic capacity of Indian males was found to be impacted by age, but a considerable drop occurred after 30 years of age (Malhotra et al. 1966). Similar observations of a reduction in VO_{2max} with an increase in age were made in a study involving dockworkers in Bombay (Saha 1975), and the mean VO_{2max} of the operators had a statistically negative relationship with age. A similar study involving mineworkers also showed a decrease in VO_{2max} with advancement in age (Mincheva and Nguyen 1986). The VO_{2max} of the MME operators who participated in this study declined with increasing age. The statistical analysis also showed a significant negative association between VO_{2max} and age, with a p-value of 0.046, when all the operators were considered together, thus falling in accord with the previous studies.

4.2.1.2 VO_{2max} and BMI

The association between VO_{2max} and BMI is illustrated in Figure 4.3 for both the groups and all the MME operators considered simultaneously. Additionally, regression models were built to estimate VO_{2max} using BMI in the three groups and when all the MME operators were taken into account together, which are presented in Table 4.5.

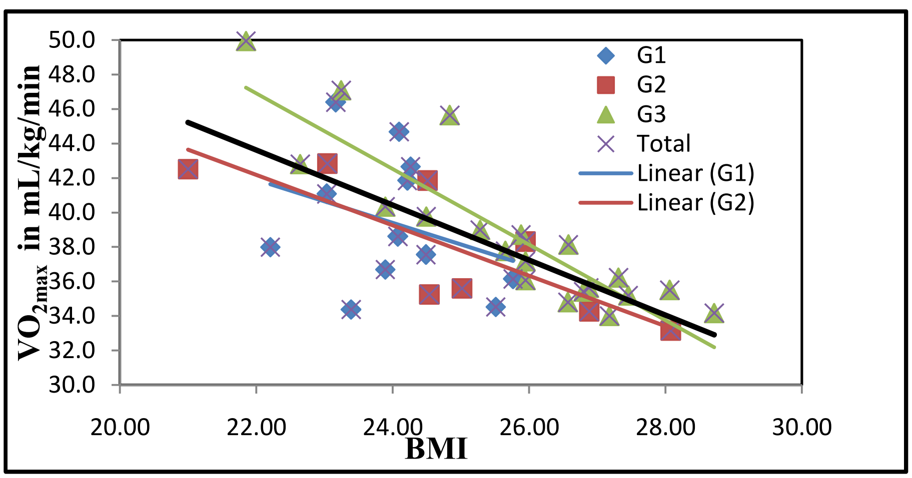


Figure 4.3: Association between VO_{2max} and BMI

Table 4.5: Association between VO_{2max} and BMI

Groups	Regression Equation	f	t	p	SE	Comments
G1	Y=-1.249x+69.37	1.131	-1.063	0.313	1.176	*Insignificant*
G2	Y=-1.461x+74.33	11.911	-3.451	**0.014**	0.421	***Significant***
G3	Y=-2.192x+95.14	66.11	-8.131	**0.000**	0.269	***Significant***
Total	Y=-1.593x+78.66	37.41	-6.116	**0.000**	0.260	***Significant***

The findings in Table 4.5 indicate a statistically significant negative correlation between relative $VO_{2max}$and BMI in G2, G3, and the group of MME operators, respectively, with p values of 0.014, 0.000, and 0.000. In G1, the correlation was statistically insignificant.

A considerable drop in VO_{2max} in overweight people was observed, indicating the likelihood of deconditioning and/or abnormalities in cardiovascular and respiratory performance (Setty et al. 2013). A similar study showed that obesity aggravates intolerance to exercise and decreases aerobic capacity. A decrease in VO_{2max} with increased BMI was also shown in similar studies (Ozcelik et al. 2004). The results of this study are corroborated by previous studies wherein there was a decrease in VO_{2max} with an increase in the BMI of the operators. The VO_{2max} of the MME operators was in a statistically negative relationship with BMI, with a p-value of 0.00.

4.2.2 Relative Aerobic Strain (RAS)

The RAS of the operators was calculated using Equation 3.1.Working VO_2 had to be computed to determine the RAS, which was done using Equation 3.5. The variation of RAS among the MME operators is depicted in Figure 4.4. The RAS values were above 50% in 11 of the 40 operators. The mean RAS of all the operators and in the groups was determined using descriptive statistics and summarized in Table 4.3, and the same is depicted in Figure 4.5 using error bars.

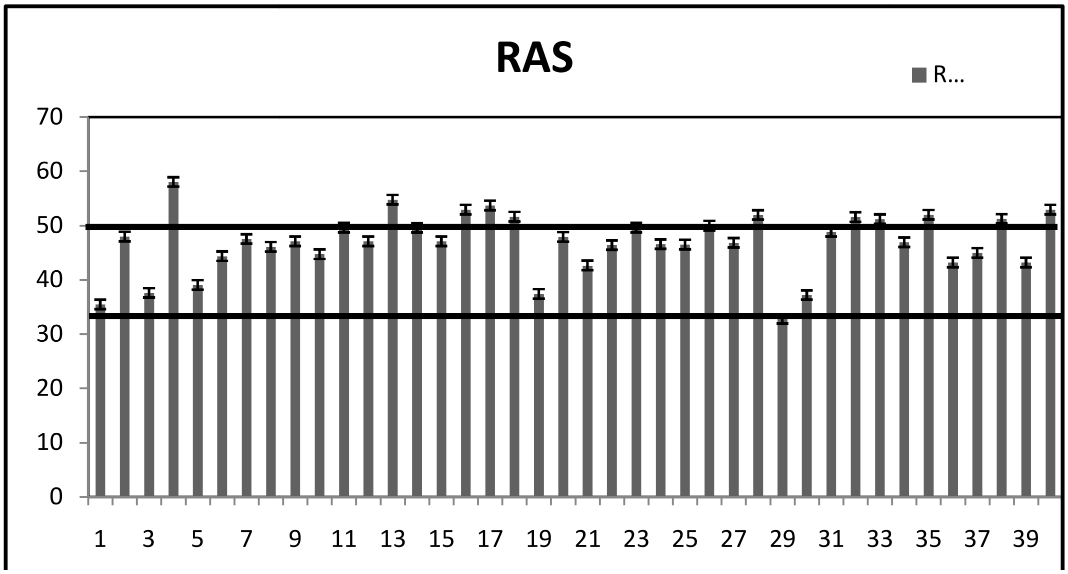


Figure 4.4: Variation of RAS among the MME operators

The mean RAS was 46.9% of the VO_{2max}, with a standard deviation of 5.54 when all MME operators were considered at once. The highest mean RAS value of 49.37% was found among LHD operators with a standard deviation of 5.55, followed by the operators of auxiliary machine and LPDTs with RAS values of 46.82%, and 45.39%, with standard deviations of 5.55, 5.18, and 5.98 respectively.

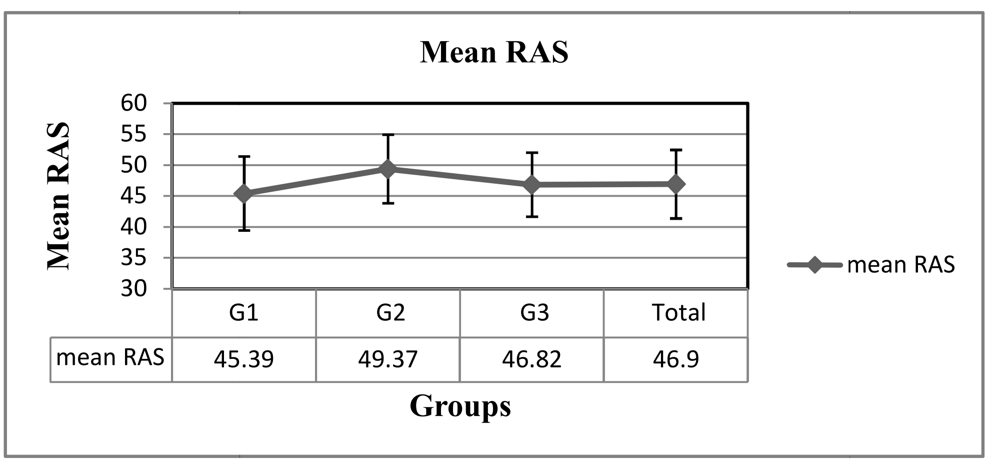


Figure 4.5: Mean RAS among the MME operators

Physical work levels ranging from 33 to 50% of RAS have been frequently cited in the literature as the general allowable range. The top limit of RAS at work should be 30% of VO_{2max} for dynamic work without particular rest breaks and 50% for combined dynamic and static work or dynamic work with rest breaks. The RAS was higher than the stipulated limits of 50% of the VO_{2max} in 11 (1-LPDT, 4-LHD, and 6-Auxillary machines) out of the 40 operators involved in the study. It was observed from the results that out of 11 operators, two were above the age of 40 years, and 9 had a BMI greater than 25.

4.2.2.1 RAS and age

Figure 4.6 illustrates the relationship between RAS and age for both the groups and for all MME operators taken into consideration at the same time. Regression models were also developed to forecast the RAS in the three groups and for all the MME operators. The primary findings of the regression study are summarized in Table 4.6.

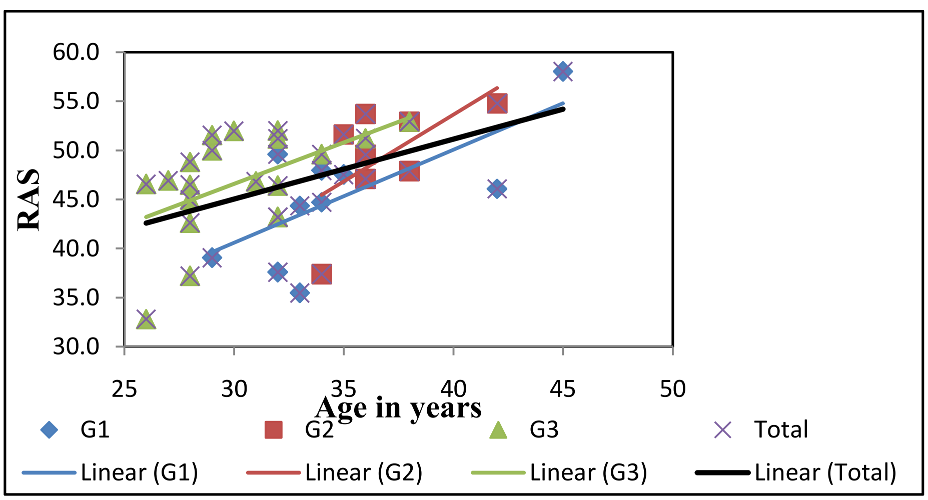


Figure 4.6: Association between RAS and age

The findings in Table 4.6 revealed a statistically significant positive correlation between RAS and age in G1, G3, and when all of the MME operators are considered collectively. The correlation was insignificant in G2.

Table 4.6: Association between RAS and age

Groups	Regression Equation	f	t	p	SE	Comments
G1	Y=0.946x+12.17	9.452	3.074	**0.012**	0.307	***Significant***
G2	Y=1.358x-0.714	3.485	1.867	0.111	0.729	*Insignificant*
G3	Y=0.842x+21.30	6.801	2.608	**0.018**	0.322	***Significant***
Total	Y=0.609x+26.76	11.95	3.457	**0.010**	0.176	***Significant***

According to a study of industrial workers, the RAS increases with age for heavy muscular effort, and this trend is much more robust in works involving both sensory and motor functions (Ilmarinen 1984). RAS also increased with age in non-motorized postal delivery jobs (Oja et al. 1977). A study conducted involving face trammers of two age groups in underground coal mines showed that the RAS of the older age group was on the higher side compared to their younger counterparts (Dey et al. 2006). The RAS of the MME operators who participated in the study increased with age. A p-value of 0.010 showed a significant positive correlation between the RAS and advancing age, consequently aligning with earlier research.

4.2.2.2 RAS and BMI

Figure 4.7 depicts the association between RAS and age for both groups and all MME operators taken into account simultaneously. In addition, regression models were created to forecast the RAS in each of the three groups for all MME operators considered together. The key findings of the regression investigation are summarised in Table 4.7.

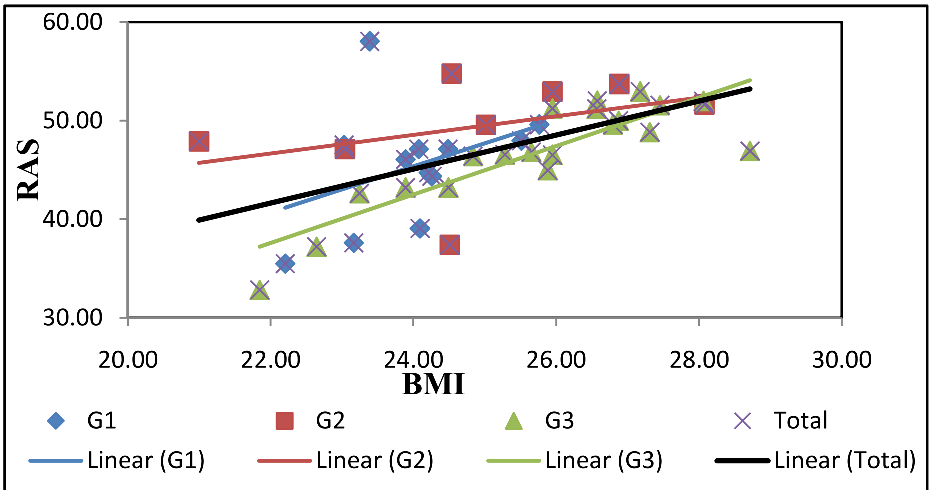


Figure 4.7: Association between RAS and BMI

Table 4.7: Association between RAS and BMI

Groups	Regression Equation	f	t	p	SE	Comments
G1	Y=2.334x-10.66	1.824	1.351	0.207	1.739	*Insignificant*
G2	Y=0.945x+25.86	1.099	1.048	0.343	1.439	*Insignificant*
G3	Y=2.458x-16.48	51.86	7.202	**0.000**	0.342	***Significant***
Total	Y=1.726x+3.655	18.41	4.292	**0.000**	0.402	***Significant***

The findings in Table 4.7 demonstrated a statistically significant positive association between RAS and BMI in G3 and when all MME operators are considered together. In both G1 and G2, the correlation was statistically insignificant.

In 11 of the 40, MME operators examined, the RAS was greater than 50% of VO_{2max}. Out of 11, 9 (81.81%) of the operators with a RAS greater than 50% had BMIs greater than 25, placing them in the overweight category. Additionally, statistical analysis revealed a positive correlation between RAS and BMI with a p-value of 0.00. The increase in RAS with BMI can be attributed to the negative correlation between BMI and VO_{2max}.

Low *R* Squared Values in Regression Analysis and Insignificant *p* Value Among the Groups

VO_{2max} and RAS of an individual are dependent on several factors such as age, BMI, sex, oxygen in the atmosphere, contents of the mitochondria, diffusion capacity of the pulmonary arteries, heart output, oxygen transfer capability by blood vessels, and muscle characteristics. The results in the regression table show relatively small R^2 values. The R^2 values explain the variation observed in the dependent variable due to the changes in the predictor variables. In this study, the participant's age and BMI were considered separately to analyze their effect on the variance of dependent variables, i.e., VO_{2max} and RAS. The predictor variables in this study had their influence on the dependent variables but did not explain the majority of the variance when considered independently. This holds good for any other regression analysis wherein several predictor variables influence the dependent variable, but only one predictor variable is considered for the analysis. Also, the value of R^2 increases as the number of predictor variables increases in the model and vice versa.

The fundamental regression thumb rule is high p values implying that the evidence is insufficient to demonstrate the existence of an effect in the group. An effect may exist, but it is too little, the sample size is too small, or there is too much variability to identify it. In this study, the sample size of the groups G1, G2, and G3 was 12, 8, and 20, respectively, less than half of the total when all the participants were considered simultaneously. Hence, the p-value was insignificant in some groups, while the p-value was significant when all the participants were considered together.

4.3 Summary

In any industry, optimizing workload in terms of acceptable work limits is critical for employee health preservation. The current exploratory study demonstrates that operating MMEs in underground mines imposes a significant physiological strain on the operators. According to the study, MME operators' maximum aerobic capacity was lower than their colleagues in other industries. The LHD operators' VO_{2max} was the lowest, as they spenttheir whole shift underground. Also, the maximum aerobic capacity was significantly affected with increased age and BMI. 11 out of 40, i.e., 27.5% of MME operators had RAS above 50% of their VO_{2max}. The RAS positively correlated with the operators' age and BMI. Thus, understanding the maximum capabilities of the MME operators while performing their work could be critical in determining the physical requirements for individuals operating in underground mines regarding acceptable work limitations.

CHAPTER-5

WORK POSTURE ASSESSMENT OF MOBILE MINE EQUIPMENT OPERATORS USING RAPID UPPER LIMB ASSESSMENT

MSDs are triggered by a wide range of physical and psychological factors, as well as institutional, social, and personal factors. Vibrations, repetitive motions, heavy lifting or hauling, awkward postures, and extreme activity are physical risk factors for MSDs. Several studies have been conducted in the past to investigate the role of awkward posture in the development of lower back and neck MSDs associated with mobile equipment operations such as tractors (Bovenzi and Betta 1994; Scutter et al. 1997; Torén and Öberg 2001), construction equipment (Schneider et al. 2001), port machinery (Bovenzi et al. 2002), grab unloaders (Courtney and Chan 1999), trucks (Massaccesi et al. 2003).

This cross-sectional study aims to find the relationship between work posture and with MSDs of the upper extremities among MME operators working in an underground metal mine in India with an analytical survey approach. Rapid Upper Limb Assessment (RULA) method was employed to collect the work posture data of the MME operators.

5.1 Methodology

5.1.1 Data Collection

5.1.1.1 Cornell Musculoskeletal Disorder Questionnaire (CMDQ) data

The physical discomfort and anthropometric data of participants were collected at the vocational training facility in the presence of the mine's safety officer. The physical discomfort data for sitting positions were gathered using the Cornell Musculoskeletal Disorder Questionnaire (CMDQ) (male version) (Hedge et al. 1999). The questionnaire consists of 54 items, including a body map diagram and questions regarding the prevalence of musculoskeletal discomfort in 18 different body sites, to be completed by the study participants.

5.1.1.2 Work posture data

In this study, the Rapid Upper Limb Assessment (RULA) was used to assess the work posture of 40 personnel operating three different types of mobile mine equipment. The equipment considered in the study included Low Profile Dump Trucks (LPDTs), Load Haul Dumpers (LHDs), and Auxiliary machines. The working posture of the operators was recorded with the aid of a digital camera. The frequently adapted posture by the operators was identified by analyzing the video graph and converted into a static image for the RULA. It is an observational postural analysis method designed to analyze and evaluate the upper body's working postures while addressing any MSD issues (Lynn and Corlett 1993). The method enables a swift evaluation of the upper limbs, neck, and trunk postures. It also considers the muscular functioning and loads on the operator's body. RULA consists of three tables: Table A, Table B, and Table C. Table A assesses the upper and lower arms, the wrist, and the wrist flexion based on the location of the upper and lower arms and the degree of bending and twisting of the wrist. Table B assesses trunk and neck posture based on the position of the neck and trunk from the center of the body and legs, taking into account whether they are supported or hanging in the air. The final RULA score is generated from Table C using Tables A and B scores. The RULA generates a list of action categories with a code indicating the level of intervention required to lessen the risk of worker discomfort. The instrument delivers a single score for the complete assignment that evaluates the requisite posture, movement, and force (refer Figure 3.2). The scores are then classified into four action categories that indicate when a risk management action should be initiated.

The RULA was performed using CREO-26 software (previously known as PRO-E) by creating digital human models of the operators.

5.1.2 Statistical analysis

The association between the independent factors, tobacco use and awkward posture, and the dependent variable, MSD of the upper extremities, was determined using the Chi-square test and binary logistic regression. When the dependent variable is binary, and only one of two alternative and incompatible values are expected, binary logistic regression models are used. In general, the binary output variables are coded as "1" for the existence of a disorder and "0" for the absence of that disorder. A linear solution of a binary logistic regression model is presented in equation 1 to calculate the odds ratio of exposure to risk factors, tobacco use, and awkward posture against the disease outcome of concern, i.e., MSD of the upper extremities.

$$\ln(p\backslash 1\text{-}p)=B+B_1x_1+B_2x_2 \qquad (5.1)$$

5.2 Results

5.2.1 CMDQ survey

The CMDQ was used to obtain data on the level of musculoskeletal discomfort experienced by the subjects. Those participants who reported a level of musculoskeletal discomfort greater than 10 in any body part were categorized as having discomfort or pain. In contrast, those whose scores were ten or lower were classified as not having discomfort or pain. The details of the body parts affected in the study subjects are tabulated in Table 5.1.

The results from the table show that 31 out of the 40 participants, i.e., 77.5%, experienced pain or discomfort in one or more body parts, whereas 9 participants i.e., 22.5% reported no pain or discomfort in any body part.

Table 5.1: Body discomfort data of the operators

Body Part	No. of affected	% of affected	No. of not affected	% of not affected
Neck	24	60	16	40
R Shoulder(rs)	27	67.5	13	32.5
L Shoulder(ls)	19	47.5	21	52.5
Upper Back(ub)	19	47.5	21	52.5
Upper R Arm(ura)	07	17.5	33	82.5
Upper L Arm(ula)	00	00	40	100
R Fore Arm(rfa)	00	00	40	100
L Fore Arm(lfa)	00	00	40	100
R Wrist(rw)	28	70	12	30
L Wrist(lw)	29	72.5	11	27.5

The data regarding tobacco usage among the participants was collected by conducting personal interviews in the presence of the mine's safety manager at the vocational training center of the mine. 22 (55%) of the participants used tobacco either in chewable form or through smoke inhalation. 18 (45%) of the participants responded that they were not using tobacco.

5.2.2 RULA

The participants were classified into three groups based on the equipment they operated. The first group comprised operators of LPDTs with steering wheels perpendicular to the operator's line of sight. The second group operated LHDs with a steering device in the left door. The third group was the drivers of auxiliary equipment with the steering wheel placed at the center of the dashboard and operated with the right hand away from the midline of the operator's body.

The RULA was carried out in the field through video graphing of the participants driving posture to identify the frequently adapted posture. The frequently adapted posture by the operators was converted into a static image for the RULA. The assessment was done by creating digital human models of static images in Creo 26 software. The risk scores for different body parts and the grand RULA score of the MME operators are tabulated in Tables 5.2, 5.3, and 5.4.

Table 5.2: Risk scores for different body parts and grand RULA score among LPDT operators

	Upper arm		Lower arm		Wrist posture		Wrist twist		Neck	Trunk	Legs	Grand Score	
	L	R	L	R	L	R	L	R				L	R
LPDT 1	3	3	2	2	3	3	2	1	2	2	1	4	4
LPDT 2	3	3	3	3	4	4	2	1	3	2	1	6	5
LPDT 3	3	3	2	2	3	3	2	1	2	2	1	4	4
LPDT 4	4	3	3	3	3	3	2	1	2	2	1	5	4
LPDT 5	4	3	3	3	4	4	2	1	3	2	2	7	6
LPDT 6	3	3	2	2	3	3	2	1	2	2	1	4	4
LPDT 7	3	3	3	3	3	3	2	1	3	2	1	6	5
LPDT 8	4	3	3	3	3	3	2	1	2	2	1	5	4
LPDT 9	3	3	2	2	3	3	2	1	3	2	2	4	6
LPDT 10	3	3	3	3	3	3	2	1	3	2	1	6	5
LPDT 11	3	3	3	3	3	3	2	1	3	2	1	6	5
LPDT 12	3	3	2	2	3	3	2	1	2	2	1	4	4

Table 5.3: Risk scores for different body parts and grand RULA score among LHD operators

	Upper arm		Lower arm		Wrist posture		Wrist twist		Neck	Trunk	Legs	Grand Score	
	L	R	L	R	L	R	L	R				L	R
LHD 1	3	3	2	2	3	3	2	1	3	3	1	6	6
LHD 2	3	3	2	2	3	3	2	1	3	2	1	5	5
LHD 3	3	3	2	2	3	3	2	1	2	2	1	4	4
LHD 4	3	3	2	2	3	3	2	1	2	2	1	4	4
LHD 5	3	3	2	2	3	3	2	1	3	3	1	6	6
LHD 6	3	3	2	2	3	3	2	1	3	3	1	6	6
LHD 7	3	3	2	2	3	3	2	1	3	3	1	6	6
LHD 8	3	3	2	2	3	3	2	1	2	2	1	4	4

Table 5.4: Risk scores for different body parts and grand RULA score among Auxiliary machine operators

	Upper arm		Lower arm		Wrist posture		Wrist twist		Neck	Trunk	Legs	Grand Score	
	L	R	L	R	L	R	L	R				L	R
A 1	5	4	2	3	3	3	1	2	2	2	1	6	5
A 2	5	4	2	3	3	3	1	2	2	2	1	6	5
A 3	5	4	2	3	3	3	2	2	3	2	1	7	6
A 4	5	4	2	3	3	3	1	2	2	2	1	6	5
A 5	5	4	2	3	3	3	1	2	2	2	1	6	5
A 6	4	3	2	3	2	2	1	2	2	2	1	4	4
A 7	4	4	2	3	3	3	1	2	3	2	1	6	6
A 8	5	4	2	3	3	3	1	2	2	2	1	6	5

A 9	4	3	2	3	2	2	1	2	2	2	1	4	4
A 10	4	3	2	3	2	2	1	2	2	2	1	4	4
A 11	4	3	2	3	2	2	1	2	2	2	1	4	4
A 12	4	3	2	3	2	2	1	2	2	2	1	4	4
A 13	5	4	2	3	3	3	1	2	2	2	1	6	5
A 14	5	4	2	3	3	3	1	2	2	2	1	6	5
A 15	4	4	2	3	3	3	1	2	3	2	1	6	6
A 16	4	3	2	3	2	2	1	2	2	2	1	4	4
A 17	5	4	2	3	3	3	1	2	2	2	1	6	5
A 18	4	3	2	3	2	2	1	2	2	2	1	4	4
A 19	5	4	2	3	3	3	1	2	2	2	1	6	5
A 20	4	3	2	3	2	2	1	2	2	2	1	4	4

Table 5.5: Distribution of RULA score among operators

Posture Risk	Risk Score Range	No. of operators	Percentage (%)
No Risk	1-2	00	00
Low Risk	3-4	15	37.5
Medium Risk	5-6	23	57.5
High Risk	7+	02	5.0

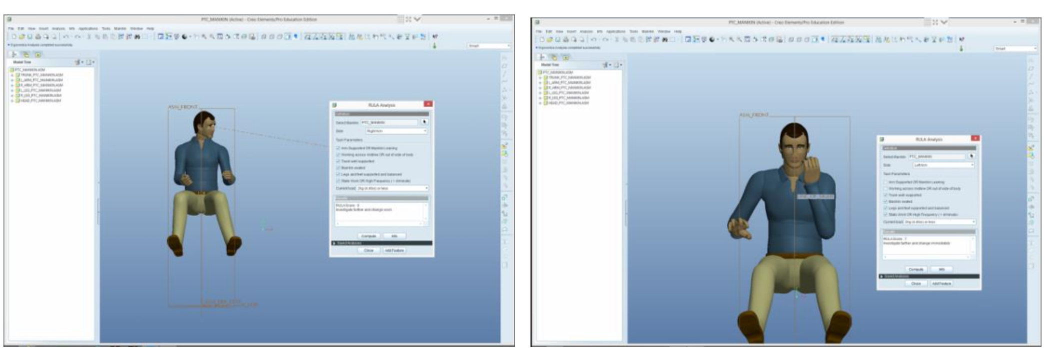


Fig 5.1(a) and (b): RULA using Creo

The results from the RULA clearly show that 02 (5%) of the operators were in the high-risk category with a grand score of 7, needing immediate intervention to change the awkward posture. However, most of the operators, i.e., 23 out of 40 (57.5%), were in the medium risk category necessitating further investigation to make changes soon. Also, 15 (37.5%) of the operators were in the low-risk category.

5.2.3 Relationship between awkward posture and MSDs

The work postures of the MME operators were assessed using the RULA method. The grand scores of the RULA assessment ranged from 4-7. The body discomfort data of the operators were collected using CMDQ. A chi-square test investigated the statistical relationship between awkward posture and MSDs**.** RULA scores less than or equal to four were coded "0," and the scores ranging from 5-7 were coded "1" to find the relationship between the two variables. Similarly, the presence of MSDs was coded "1" and the absence as "0". The results from the Chi-square test are presented in Table 5.6.

Table 5.6: Crosstab-MSD*RULA score

			RULA score		
			.00	1.00	Total
msd	0	Count	8	1	9
		% within msd	88.9%	11.1%	100.0%
		% within RULA score	53.3%	4.0%	22.5%
		% of Total	20.0%	2.5%	22.5%
	1	Count	7	24	31
		% within msd	22.6%	77.4%	100.0%
		% within RULA score	46.7%	96.0%	77.5%
		% of Total	17.5%	60.0%	77.5%
Total		Count	15	25	40
		% within msd	37.5%	62.5%	100.0%
		% within RULA score	100.0%	100.0%	100.0%
		% of Total	37.5%	62.5%	100.0%

The results from table 5.6 clearly show that the eight operators (88.9%) whose RULA scores were less than four had no MSD issues, and one operator (11.1%) with a RULA score more than four had experienced body discomfort. Whereas, among the operators having body discomfort, 7 MME operators (22.6%) had RULA scores less than or equal to four. but majority of the operators who experienced pain in one or more body parts had scores of 5 and above.

5.2.4 Relationship between tobacco usage and MSDs

Table 5.7: Crosstab- MSD* tobacco use

			tob		Total
			0	1	
msd	0	Count	8	1	9
		% within msd	88.9%	11.1%	100.0%
		% within tob	44.4%	4.5%	22.5%
		% of Total	20.0%	2.5%	22.5%
	1	Count	10	21	31
		% within msd	32.3%	67.7%	100.0%
		% within tob	55.6%	95.5%	77.5%
		% of Total	25.0%	52.5%	77.5%
Total		Count	18	22	40
		% within msd	45.0%	55.0%	100.0%
		% within tob	100.0%	100.0%	100.0%
		% of Total	45.0%	55.0%	100.0%

The results from table 5.7 clearly show that the eight operators (88.9%) who did not use tobacco had no MSD issues, and one operator (11.1%) with a history of tobacco usage had no body discomfort. Ten out of the 31 (32.3%) operators who experienced body discomfort did not use any form of tobacco. Whereas the majority of the operators

(67.7%) with pains in different body parts were consuming tobacco in one or the other form.

5.2.5 Binary Logistic Regression

The statistical significance between the examined independent variables (tobacco usage and RULA scores) and the response variable, i.e., MSD risk of the MME operators, was determined using binary logistic regression with a constant and a confidence interval threshold of 95 percent. The results of the binary logistic regression are presented in Table 5.8.

Table 5.8: Binary logistic regression model summary

		B	S.E.	Wald	df	Sig.(p)	Cox & Snell R Square	Nagelkerke R Square	Comments
Step 1[a]	tob(1)	-3.027	1.302	5.404	1	.020	.412	.628	***Significant***
	RULA score(1)	-3.491	1.281	7.421	1	.006			***Significant***
	Constant	5.209	1.578	10.894	1	.001			***Significant***

The results from the binary logistic regression reveal a statistically significant association between MSD risk and tobacco use, and awkward postures with p-values of 0.020 and .006, respectively.

5.3 Discussions

MSDs are caused by various physical factors such as vibrations (Atal et al. 2020) (Chaudhary et al. 2022) (Sridhar et al. 2022), awkward postures (Eger et al. 2010) (Eger et al. 2008) (Upadhyay et al. 2021), repetitive motions (Bandyopadhyay et al. 2012) (Yong et al. 2020), heavy lifting (Dube and Chiluba 2021) (Okello et al. 2020), working duration (Balogun and Smith 2020), etc. The condition of the MSDs is aggravated by some personal factors such as age (Ahmad and Alvi 2017) (Njaka et al. 2021), Body Mass Index (BMI) (Bio et al. 2007) (Smith et al. 2020), smoking (Emkani et al. 2017), etc. In this study, an attempt has been made to assess the working postures of the MME operators working in an underground metal mine in India. The study also examines the association of awkward work postures and tobacco use with MSDs of the upper extremity among the MME operators.

The working posture of the MME operators was assessed using the RULA method. RULA makes it possible to quickly assess the work-related loads to which individuals' musculoskeletal systems are subjected as a result of posture, muscle use, and the force exerted while performing their duties (Lynn and Corlett 1993). The RULA method's reliability and repeatability have already been demonstrated in studies involving workers in underground coal mines (Ijaz et al. 2020), dumper operators (Upadhyay et al. 2021), truck drivers (Massaccesi et al. 2003) and excavator operators (Koushik Balaji and Alphin 2016). The results from the study show that the MME operators frequently adapt postures that put them into the medium-risk category. Also, two operators were found to be adapting awkward postures with a RULA grand score of 7 which represents the high-risk category.

The statistical assessment carried out to find the association between awkward postures and MSDs of the upper extremities was significant with a p-value of 0.06, implying that awkward postures were a significant factor in causing MSDs at the workplace. The findings of the study suggest that professional drivers are at risk of developing MSDs due to awkward postures and are in line with studies involving excavator operators (Schneider et al. 2001) (Koushik Balaji and Alphin 2016), tractor drivers (Bottoms and Barber 1978; Bovenzi and Betta 1994) (Torén and Öberg 2001), Load Haul Dumper (LHD) operators (Eger et al. 2008) and dumper operators (Upadhyay et al. 2021).

The other objective of the study was to find the relationship between tobacco usage and the occurrence of MSDs. The results from the study indicate a strong statistical correlation between the two variables with a p-value of 0.020. The results show that tobacco usage aggravated the MSD concern in MME operators when consumed in any form. This study's findings corroborate with findings from past research involving drivers of heavy mining equipment (Emkani et al. 2017), Workers in stone and gravel mines (Smith et al. 2020). The findings agree with the results from a survey involving a population in Sweden (Jakobsson 2008).

5.4 Summary

The study involved forty MME operators working in an underground metal mine. The body discomfort data and the personal data of the operators were collected using CMDQ through one on one interviews. The work posture data was collected in the field, and the RULA was conducted using Creo software by creating digital human models of the operators. The study concludes that most MME operators adopt awkward postures, frequently increasing the risk of MSDs. The operators who used tobacco were more likely to fall prey to MSDs than those who did not.

CHAPTER-6

ASSESSMENT OF HAND-ARM VIBRATIONS OF LOW PROFILE DUMP TRUCK AND LOAD HAUL DUMPER OPERATORS BASED ON JOB CYCLE

Occupational exposure to Hand-Transmitted Vibrations (HTVs) is one of the hazards in the workplace which can cause several musculoskeletal, neurological, and vascular disorders in the human body, collectively called Hand Arm Vibration Syndrome (HAVS) (Pyykko 1986; Harada and Griffin 1991). Hand-transmitted vibrations are transmitted from the work surface to the operators' hands (Health and Safety Executive, 2012; Edwards and Holt, 2006).

In the case of moving vehicles, vibrations are generated from the engines and the interaction of the vehicles with the ground surface and transferred into the body of the operators through the surface of the seat, steering system, and the vehicle floor (Aziz SAA, Nuawi MZ, Nor MJM 2014). Numerous previous studies have established that operators of All-Terrain Vehicles (ATVs) (Anttonen and Virokannas, 1995; Rehn et al. 2004), motorcycles (Tominaga Y, 1994; Mirbod et al. 1997), snowmobiles (Anttonen H 1994), three-ton trucks used by Malaysian military (Akmar et al. 2015), and tractors (Goglia et al. 2003; Dewangan and Tewari 2009) were at risk of exposure to HTVs transmitted via steering devices.

6.1 Methodology

The vibration readings were measured using an SV 105B Triaxial Hand-Arm Accelerometer under ISO 5349-2:2001 criteria. The accelerometer was coupled to an SV106 human vibration analyzer for data logging. Extra efforts ensured the accelerometer was securely strapped to the operators' hands. During the measurement duration, the accelerometer-wielding hand was also kept in continual contact with the steering lever.

The measurements were carried out per the guidelines provided by ISO 5349:2001. As per the guidelines provided in the standard, the measurement of the frequency weighted root mean square (r.m.s.) acceleration has to be carried out in three mutually perpendicular directions, namely x (back to front), y (side to side), and z (up and down) represented as $a_{wx,}$ $a_{wy,}$ and a_{wz} respectively and expressed in terms of m/s^2. The measured HAV readings were analyzed using Supervisor Software provided in the instrument package.

When jobs are cyclic, measuring the rms acceleration during one cycle is feasible and can be used to anticipate a specific machine's daily vibration exposure A(8). To carry out the HAV assessment, the LPDTs and LHDs' entire job cycle was divided into four components each and discussed in the following sections.

Multiple regression analysis and analysis of variance were used to assess the impact of machine parameters on daily total HAV exposure A(8). The study considers independent variables of machine operating hours, hauling capacity, and load conditions (loaded vs. empty).

6.1.1 Data collection

LPDTs are used in conjugation with LHDs in underground mines to haul ore and overburden. The chosen mine utilizes 12 LPDTs powered by diesel engines of two distinct manufacturers and four dump box capacities of 30, 50, 60, and 65 tons. In addition, the mine utilized six LHDs with a 17-ton capacity and two LHDs with a 21-ton capacity of a single manufacturer.

The details of the LPDTs and LHDs are presented in Tables 6.1 and 6.2, respectively.

Table 6.1: Specifications of the LPDTs considered in the study

Sl.No	Local code	Manufacturer	Model	Dump box capacity (tons)	Total Working Hours
1	T5	Epiroc	MT5020	50	23226
2	T6		MT5020	50	20575
3	T7	Sandvik	TH550	50	21245
4	T8		TH550	50	19880
5	T16	Epiroc	MT6020	60	18067
6	T17		MT6020	60	20672
7	T19		MT65	65	8943
8	T21		MT65	65	9209
9	T22		MT65	65	8579
10	T101	Sandvik	TH430	30	7391
11	T102		TH430	30	7341
12	T104		TH430	30	5906

Table 6.2: Specifications of the LHDs considered in the study

Sl.No	Local code	Manufacturer	Model	Bucket capacity (tons)	Total Working Hours
1	L-5		LH-517	17	21335
2	L-6			17	22960
3	L-8			17	17927
4	L-11			17	14498

5	L-12	Sandvik		17	10229
6	L-15			17	6613
7	L-14		LH-621	21	6825
8	L-16			21	3598

6.1.2 Job component analysis

1. LPDTs

The complete LPDT work cycle was divided into four components to evaluate the vibration levels in every phase. The classification is as detailed below:

Loading is the initial phase of the LPDT operation in which ore/waste is transferred into the vehicles. The primary sources of HAVs during this stationary period are the idling engines and the impact of the materials loaded into the dump box. Vibrations are also produced by pounding the LHD buckets to level the material being loaded.

Loaded Hauling: During this phase, the LPDTs transport their loads on uneven haul roads to their designated disposal areas. Here, vibration transmission is caused by the operation of the engines and the movement of LPDTs over unpaved roads.

Unloading: During this phase, the ore/waste is emptied into the predetermined disposal zones. The LPDTs are manipulated in forward and backward directions to empty the material with slanted buckets, and the buckets are returned to their original position after unloading.

Empty Hauling: In this phase, the empty vehicle is moved to the predetermined loading location. During this phase, vibrations are transferred owing to the operation of the engines and the movement of the LPDT on rugged road surfaces.

2. LHDs

The LHD operations can be divided into four job components: mucking, driving with a loaded bucket, unloading, and empty run (Tammy Eger et al., 2011).

Mucking: Muck is the fragmented ore or rock from blasting the work face (Tatiya, 2013). Mucking operation involves loading the bucket of the LHD with muck which consists of driving over very rough terrain.

Loaded hauling: In this stage, LHD with a loaded bucket will travel to a designated dumping yard or Low profile Dump Truck (LPDT) parking area to unload the materials in the bucket.

Unloading: The LHD will unload the ore in the bucket to the LPDT or the overburden at the mined-out areas for backfilling.

Empty hauling: In this stage, LHD with an empty bucket will return to the mucking area.

6.1.3 Time motion analysis

Time-Motion study of the LPDT and LHD operations was carried out with inputs from the operators and the mine engineers to determine the time consumed by each machine to perform the job components of their respective work cycles, the details of which are tabulated in Table 6.3.

Table 6.3: Time consumed by the LPDTs and LHDs to perform an individual component of their work cycle in each shift

Sl.No	Vehicle Identification code	Time consumed by the LPDTs and LHDs to perform an individual component in each shift in minutes				Total working time in each shift in minutes
		Loading	Loaded Travel	Unloading	Empty Travel	
1	T5	40	160	16	152	368
2	T6	40	160	16	152	368
3	T7	50	160	30	145	385
4	T8	50	160	30	145	385
5	T16	85	145	20	120	370
6	T17	85	145	20	120	370
7	T19	60	175	20	155	410
8	T21	60	175	20	155	410
9	T22	60	175	20	155	410
10	T101	30	175	15	150	370
11	T102	30	175	15	150	370
12	T104	30	175	15	150	370
13	L-5	110	135	25	125	395
14	L-6	125	130	28	121	404
15	L-8	115	135	25	125	400
16	L-11	105	135	30	127	397
17	L-12	110	135	25	130	400
18	L-15	105	130	25	120	380
19	L-14	105	135	35	120	395
20	L-16	100	125	35	115	375

6.1.4 HAV data

RMS acceleration is the primary parameter for measuring HAVs expressed in m/s^2. The RMS acceleration data was collected by firmly strapping the triaxial accelerometer on the operator's hand in contact with the steering device of the machinery. The data was collected from 12 LPDTs with steering wheels and 8 LHDs with a joystick as the steering device. Special care was taken to ensure that the hand wielding the accelerometer was in constant contact with the steering device during the measurement process. The measurement was carried out for individual components of the work cycle to identify the contribution of each component to the overall HAV value and the details of which are presented in Tables 6.4 and 6.5.

Table 6.4: wrms acceleration values (m/s^2) for LPDT operations

Sl. No	Vehicle Identification code	Loaded Hauling			Empty Hauling			Loading			Unloading		
		a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}
1	T5	1.7	1.1	2.5	2.1	1.7	3.2	2.5	1.1	1.7	2.1	1.7	3.2
2	T6	1.8	1.1	2.4	2.0	1.4	2.9	2.4	1.1	1.8	2.0	1.4	2.9
3	T7	2.0	1.1	2.3	2.2	1.5	3.0	2.0	1.1	2.3	2.2	1.5	3.0
4	T8	1.8	1.0	2.3	2.4	1.4	3.2	1.8	1.0	2.3	2.4	1.4	3.2
5	T16	2.0	1.3	2.2	2.2	1.5	2.9	2.2	1.3	2.0	2.2	1.5	2.9
6	T17	1.6	1.1	2.2	2.2	1.6	3.1	2.2	1.1	1.6	2.2	1.6	3.1
7	T19	1.4	0.8	1.6	1.8	1.1	2.2	1.6	0.8	1.4	1.8	1.1	2.2
8	T21	1.3	0.8	1.5	1.6	0.9	1.7	1.5	0.8	1.3	1.6	0.9	1.7
9	T22	1.4	0.9	1.7	1.1	1.1	2.2	1.7	0.9	1.4	1.1	1.1	2.2
10	T101	1.4	0.9	1.6	1.5	1.2	2.2	1.6	0.9	1.4	1.5	1.2	2.2
11	T102	1.4	0.9	1.5	1.8	1.2	2.3	1.5	0.9	1.4	1.8	1.2	2.3
12	T104	1.4	0.8	1.6	1.4	1.1	2.2	1.6	0.8	1.4	1.4	1.1	2.2

Table 6.5: wrms acceleration values (m/s^2) for LHD operations

Sl. No	Vehicle Identification code	Mucking			Unloading			Loaded Hauling			Empty Hauling		
		a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}	a_{hx}	a_{hy}	a_{hz}
1	L-5	2.5	1.7	1.9	1.7	1.1	1.3	1.1	1.6	2.1	1..5	1.4	2.3
2	L-6	2.9	1.7	2.0	1.8	1.2	1.5	1.2	1.5	1.7	1.4	1.3	2.1
3	L-8	2.4	1.5	1.7	1.7	1.1	1.4	1.2	1.5	1.7	1.4	1.5	1.9
4	L-11	2.2	1.5	1.7	1.5	1.2	1.2	1.1	1.2	1.8	1.5	1.2	2.0
5	L-12	2.1	1.4	1.5	1.5	1.2	1.3	1.1	1.3	1.5	1.4	1.2	1.9
6	L-15	2.2	1.3	1.4	1.3	1.1	1.4	1.1	1.4	1.5	1.3	1.1	1.6
7	L-14	2.2	1.4	1.5	1.3	1.1	1.5	0.9	1.0	1.3	1.2	1.3	1.5
8	L-16	1.7	1.0	1.2	1.2	0.8	1.0	0.8	0.9	1.4	1.0	0.9	1.3

6.2 Results and Discussions

6.2.1 Analysis of HAV data

LPDTs

Loaded and Empty Hauling

Tables 6.1 and 6.3 provide information on the LPDTs examined in the study, the time required by the LPDTs to accomplish every job component of a particular work cycle, and the overall working time of each LPDT in an 8-hour shift, respectively. LPDTs designated T5 and T6 needed the most time for both hauling tasks but only performed four work cycles every shift. In each shift, the LPDTs designated T19, T21, and T22 clocked in at 410 minutes with the fastest timing. It is evident from Table 6.3 that the time required for a loaded trip exceeds that of an empty one. During empty hauling, the average speed of LPDTs is 11.75 percent higher than during loaded hauling.

Table 6.4 presents the RMS acceleration values for all three vibration axes for loaded and unloaded hauling activities. Referring to Figures 6.1 and 6.2, it is evident that the z-axis is the predominant vibration axis during empty and loaded hauling activities. It is also apparent that the z-axis was the primary axis impacting the A(8), as the hauling tasks required significant time.

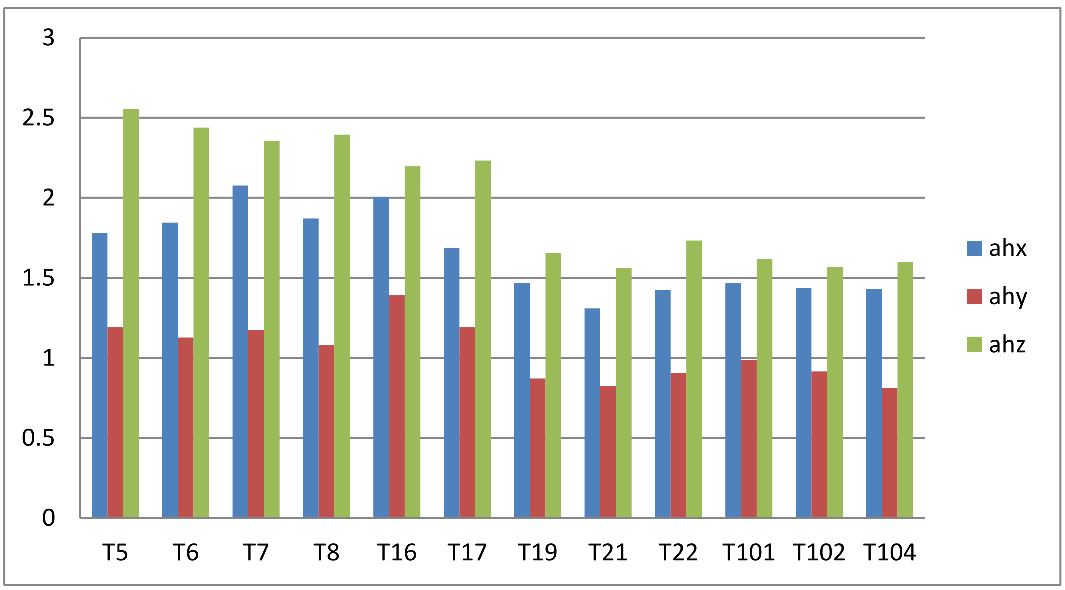


Fig 6.1: wrms values in m/s^2 for loaded hauling in LPDTs

The LPDT designated T5 had shown the highest vibration response in the z-axis, followed by T6, T8, and T7, respectively. The least vibration response was recorded in LPDTs designated T21 and T102 while hauling with a full load.

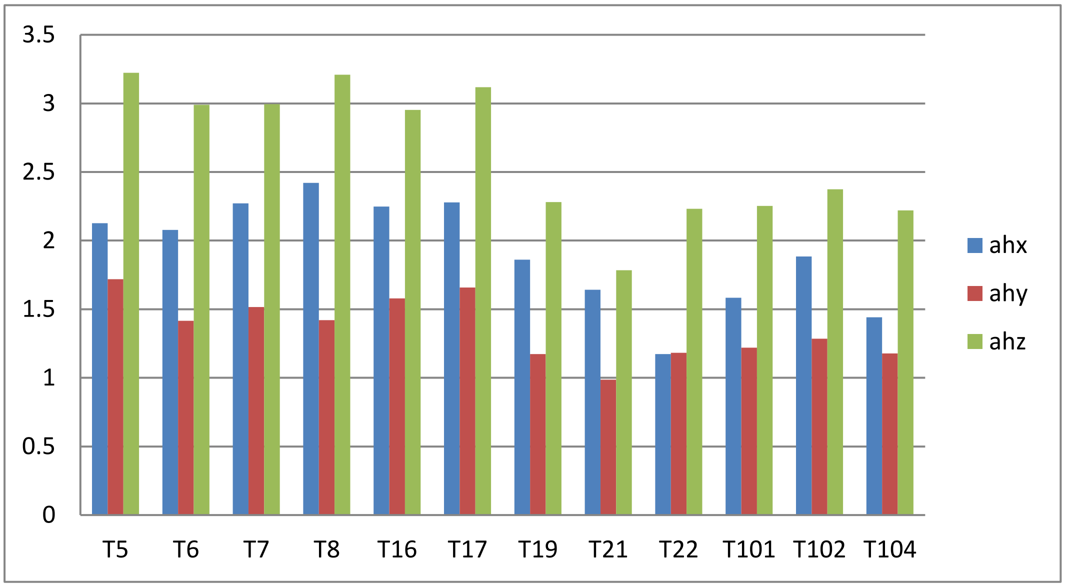


Fig 6.2: wrms values in m/s^2 for empty hauling in LPDTs

During the empty hauling, LPDT designated T5 had the highest vibration values, followed by T8 and T17, respectively. The least vibration readings were recorded in T21. Z-axis was the dominant axis during empty hauling, followed by the x and y-axes.

It is evident from the figure that the mean total vibration values (a_{hv}) are 25.23 percent higher during empty transport than during loaded transport. This can be linked to the fact that the load in the vehicles acts as a dampening factor to attenuate the vibrations generated by loaded trucks while being transported.

Loading and Unloading

The time required to load LPDTs during each work cycle is summarized in Table 6.3, which reveals that LPDTs designated T7 and T8 need the most time due to the large dump box and the comparatively small-sized LHD used for loading. The T101, T102, and T104 30-ton LPDTs were the fastest to fill due to their compact dump boxes.

Table 6.4 contains the wrms vibration values for loading and unloading procedures. Fig. 6.3 reveals that the z-axis is the primary vibration axis for just two LPDTs, T7 and T8, whereas the x-axis was the dominant axis for the remaining LPDTs. Vibrations in this phase are determined mainly by the size and direction of rocks falling into the dump box, not by the interaction between the vehicle and the haul road. The LPDTs T16 and T17 exhibited the greatest vibration responses up to 3.18m/s^2.

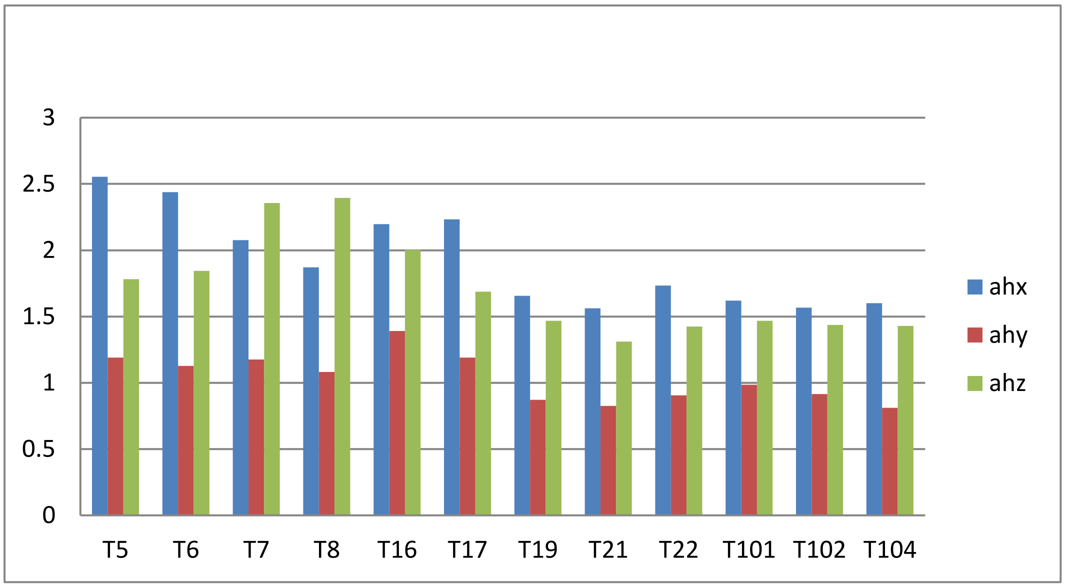


Fig 6.3: wrms values in m/s^2 for loading in LPDTs

The unloading procedure took the shortest time in the entire work cycle. The LPDTs were set to reverse direction, with the dump box elevated to clear the load under gravitation. The z-axis was the predominant vibration axis during this stage, as seen in Fig 6.4. The LPDT T5 had the strongest vibration response.

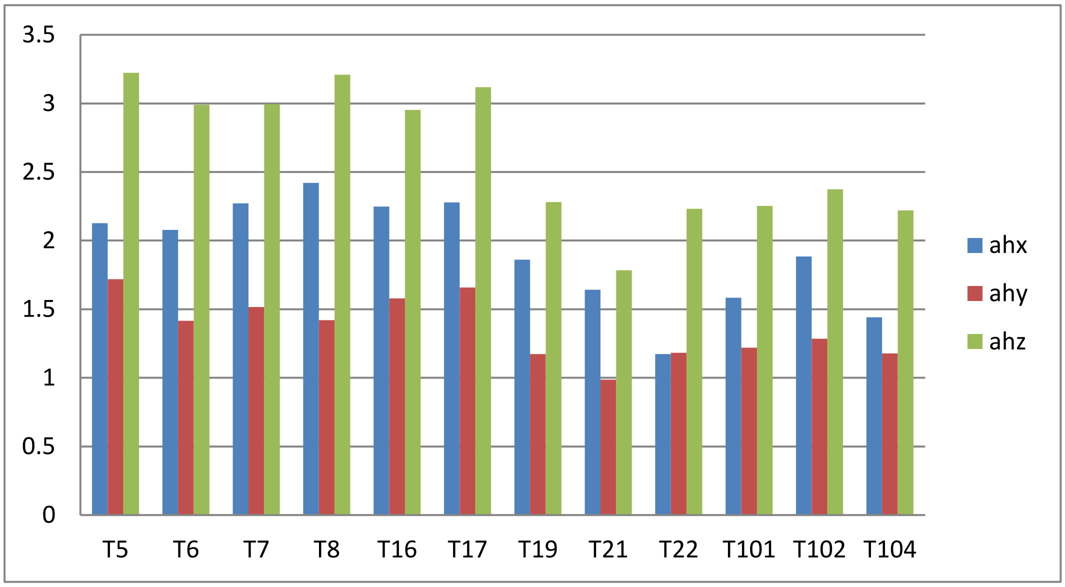


Fig 6.4: wrms values in m/s^2 for unloading operation in LPDTs

LHDs

Vibrations transmitted to the operators' hands through the joystick of the LHDs were measured by mounting a hand strap-on triaxial accelerometer on the hand for different job components of LHD operations. The variation of the vibrations in the three measurement axes, x, y, and z, for each job component, are presented in the following plots with the corresponding vibration values.

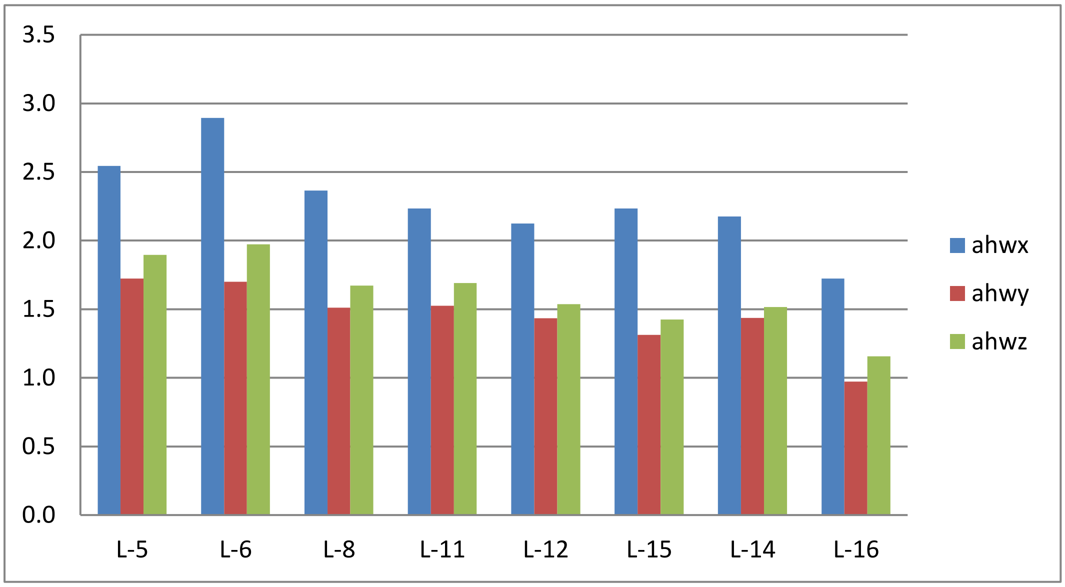


Fig 6.5: wrms values in m/s^2 for mucking in LHDs

The variations in vibration levels in each of the three measurement axes for the mucking operation are presented in Fig 6.5. It is clear from Fig 6.5 that the x-axis was the dominant axis of vibration for mucking, with the highest recorded vibration value of $2.9m/s^2$ in the LHD designated L-6. Also, the mucking operation produced higher vibration levels among the components of the work cycle, which may be attributed to the movement of the LHDs on very rough and uneven terrain caused by the blasted ore or waste rock and the interaction of both the bucket and tires of the LHD with the surface of the mine.

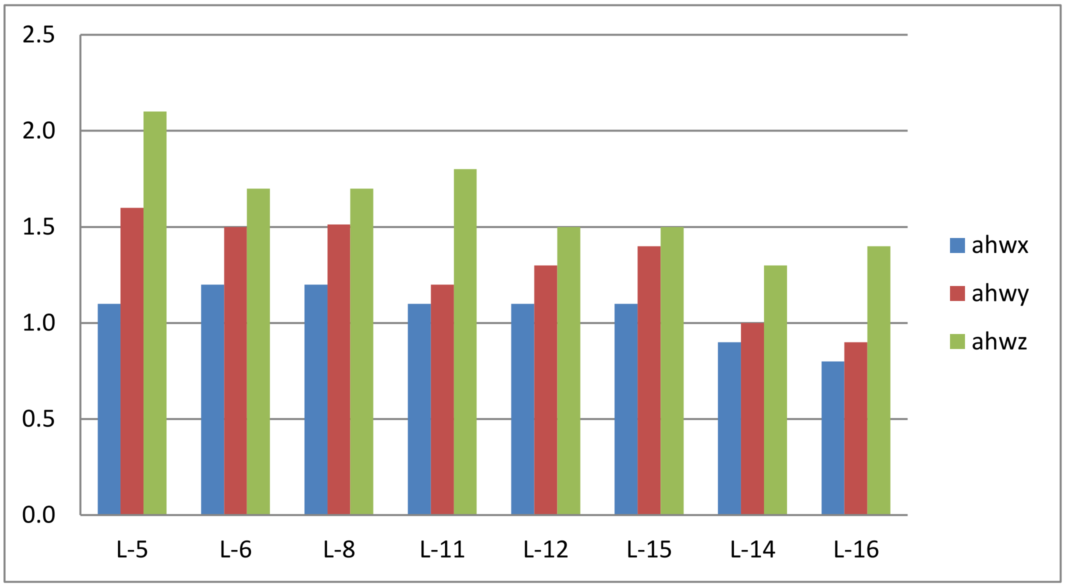


Fig 6.6: wrms values in m/s^2 for loaded hauling in LHDs

The mucking was followed by loaded hauling to dump the ore/waste rock to the designated dumping areas. Z-axis was dominant during loaded carrying with $2.1m/s^2$ in L-6 followed by y and x-axes, respectively, as shown in fig 6.6. Loaded hauling had minor vibration responses during the movement of the LHDs.

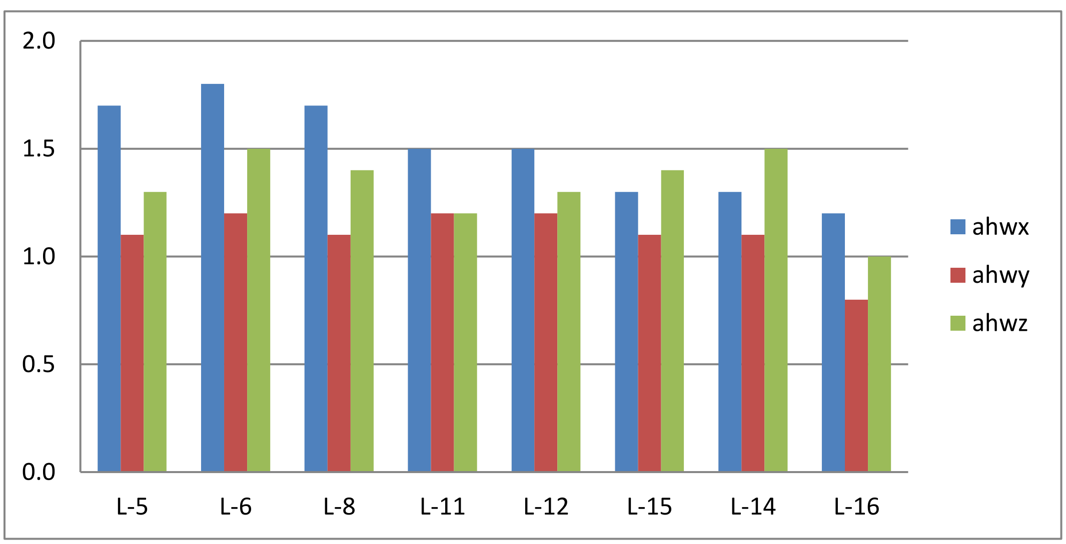


Fig 6.7: wrms values in m/s^2 for unloading operation in LHDs

Unloading the ore/waste rock was the operation with minor vibrations and a minimal time component in the LHD work cycle. It is clear from Fig 6.7 that the x-axis was the dominant vibration axis.

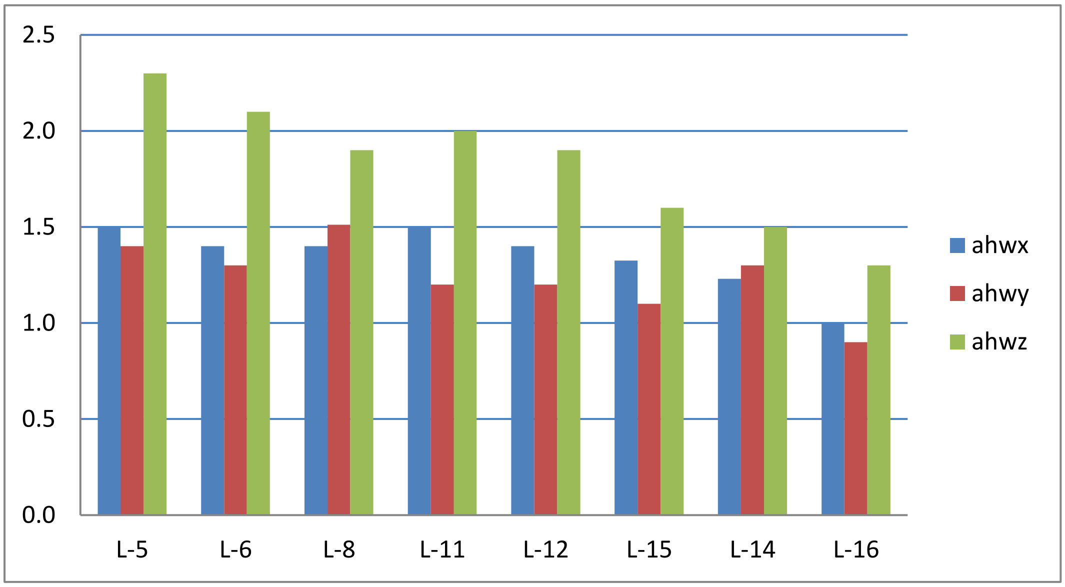


Fig 6.8: wrms values in m/s^2 for empty hauling in LHDs

After unloading the ore/waste rock, the LHDs returned to their respective loading areas with empty buckets. Fig 4.8 shows that the vibration responses were high compared to loaded hauling in this phase, with higher vibration values in the z-axis followed by x and y-axes.

6.2.2 Total daily vibration exposure A(8) in m/s^2 and the percentage contribution of the job components towards A(8)

The total daily vibration exposure A(8) is calculated using equation 2.3, and the corresponding A(8) values are presented in tables 6.9 and 6.10 for LPDTs and LHDs, respectively.

LPDTs

Table 6.6: A(8) in m/s^2 for the LPDTs

Vehicle Identification code	T5	T6	T7	T8	T16	T17	T19	T21	T22	T101	T102	T104
A(8) in m/s^2	3.3	3.1	3.2	3.2	3.0	3.0	2.4	2.2	2.3	2.3	2.4	2.2

The total daily vibration exposure A(8) in the LPDTs is encapsulated in Table 6.6. LPDTs T5, T6, T7, T8, T16, and T17 have A(8) values more than the EAV, the highest being 3.3 m/s^2 recorded in T5.

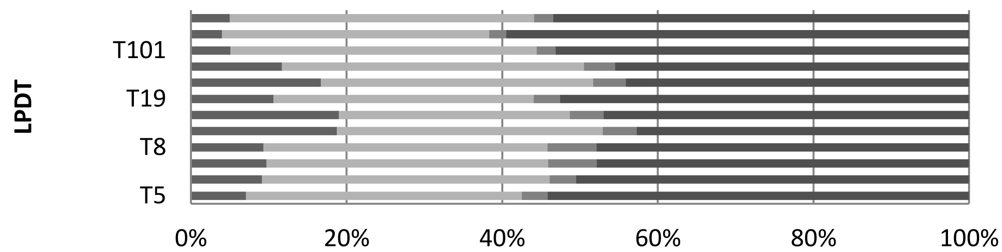
The total percentage contribution of the individual component of the LPDT work cycle to A(8) is presented in Figure 6.9, and it is evident that the substantial contributions to A(8) were made by hauling activities, with empty hauling contributing the most. The unloading activity made minimal contribution to A(8), which may be ascribed to the shorter amount of time required for the task.

The average percentage contribution for loading operations is 10.51%. The most significant contribution to A(8) by loading operation can be seen in LPDT T17, followed by T16, because of the prolonged duration required to equally distribute the larger ore boulders within the relatively large dump box with a capacity of 60 tons utilizing LHDs with a capacity of 17 tonnes. Because of their low dump box capacity of 30 tons, the LPDTs T101, T104, and T101 have the lowest contribution to A(8) from loading.

The average percentage contribution of loaded haulage to A(8) is 35.74 percent, with a maximum contribution of 39.33 percent in LPDT T101 and the lowest contribution of 29.68 percent in LPDT T17.

The most significant and lowest percentage contributions towards A(8) were 6.29 percent and 2.17 percent, respectively, while unloading the LPDTs T8 and T102 with a mean of 3.89 percent.

Hauling the LPDTs in their empty state contributes the most to A(8). The average percentage contribution is 49.90%. T102 has the highest rate of 59.51 percent, while T16 has the lowest rate of 42.71 percent due to its shorter travel time during empty hauling.



	T5	T6	T7	T8	T16	T17	T19	T21	T22	T101	T102	T104
Loading	7.09	9.15	9.71	9.31	18.75	19.02	10.63	16.7	11.7	5.08	4.02	5.01
Loaded Travel	35.42	36.95	36.17	36.52	34.18	29.68	33.43	34.99	38.79	39.33	34.3	39.06
Unloading	3.35	3.41	6.26	6.29	4.36	4.32	3.35	4.21	4.01	2.42	2.17	2.48
Empty Travel	54.14	50.49	47.86	47.88	42.71	46.98	52.59	44.1	45.5	53.17	59.51	53.45

% contribution of job components towards A(8)

Fig 6.9: Percentage contribution of job components towards A(8) in LPDTs

LHDs

Table 6.7: A(8) in m/s^2 for the LHDs

Vehicle Identification code	L-5	L-6	L-8	L-11	L-12	L-15	L-14	L-16
A(8) in m/s^2	2.8	2.9	2.6	2.5	2.3	2.2	2.1	1.7

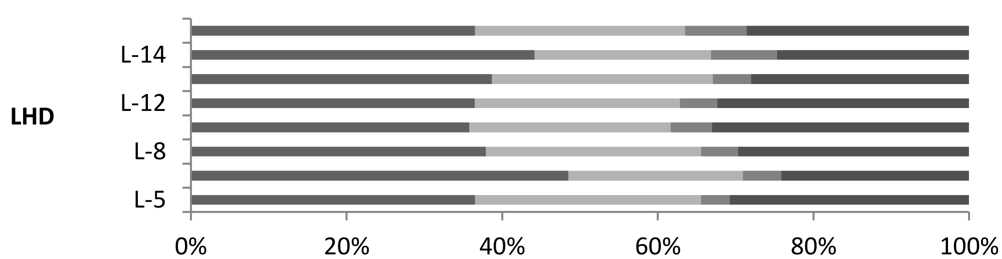
The total daily vibration exposure A(8) in the LHDs is encapsulated in Table 6.7. LHDs L-5, L-6, and L-8 recorded A(8) values more than the EAV, the highest being 2.9 m/s^2 recorded in L-6.

The total percentage contribution of the individual job components of an LHD job cycle towards A(8) is shown in Fig 6.10. It can be noticed that the mucking operation was the highest contributor, followed by empty traveling. The mean percentage contribution towards A(8) by mucking operation is 39.33%. The highest percentage contribution of 48.52% can be seen in the LHD designated L-6, followed by L-14.

The mean percentage contribution of loaded hauling towards A(8) is 26.16%, with the highest contribution percentage of 29.02% in LHD designated L-5 and the least of 22.42% in the L-6.

The highest and the lowest percentage contributions of 8.52% and 3.7% were found towards A(8) while unloading in the LHDs L-14 and L-5, respectively, with a mean of 5.60%.

The highest contribution to A(8) after mucking is made by empty traveling. The mean percentage contribution of 28.91%. The highest being 33.06% in the LHD designated L-11 and the lowest of 24.16% in L-6.



	L-5	L-6	L-8	L-11	L-12	L-15	L-14	L-16
Mucking	36.53	48.52	37.93	35.78	36.47	38.7	44.17	36.54
Loaded Travel	29.02	22.42	27.61	25.87	26.37	28.37	22.64	26.98
Unloading	3.7	4.9	4.76	5.29	4.78	4.91	8.52	7.97
Empty Travel	30.75	24.16	29.7	33.06	32.38	28.02	24.67	28.58

% contribution of job components towards A(8)

Fig 6.10: Percentage contribution of the job components towards A(8) in LHD

6.2.3 Statistical Analysis of machine parameters and A(8)

After examining the HAV data from the field study, Analysis of Variance was used to identify the parameters that strongly influence A(8), as shown in Table 6.8.

Table 6.8: ANOVA Table for A(8)

Source	**Type of variable**	**DF**	**P-Value**	**Contribution**	**Remarks**
Regression		3	0.000	78.04%	
Capacity in tons	Continuous	1	0.000	22.24%	**Significant**
Total working hours	Continuous	1	0.000	38.42%	**Significant**
Loading conditions	Categorical (loaded=0,empty=1)	1	0.000	17.38%	**Significant**
Error		36		21.96%	
Total		39		100.00%	

A multiple regression model was developed using Minitab 18 with a confidence level of 95% to assert the relationship between the dependent variable A(8) and the predictor variables (haulage capacity, total working hours, and machine conditions of loaded and empty). P-values less than or equal to 0.05 are considered statistically significant. The regression model has a coefficient of determination of 78.04 percent. Table 6.9 shows the multiple regression model for A(8).

Table 6.9: Model Summary for A(8)

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0.323582	78.04%	76.21%	4.72894	72.45%

The regression model's coefficient of determination (R-sq) was 0.7804(78.04%), implying a significant correlation between the dependent and chosen independent variables. Also, the model's adjusted coefficient of determination (R-sq(adj)) was 76.21%, implying that the model is reliable even if new independent variables are added, which can significantly increase the R-sq values.

6.2.4 Assessment of Health Risks based on the European Union (EU) Directive 2002/44/EC

The health risk associated with the operation of the LPDTs and LHDs was assessed using the guidelines provided by the European Union (EU) Directive 2002/44/EC by taking into account the two limits, namely Exposure Action Value (EAV) and Exposure Limit Value (ELV), and the results are summarised in table 6.10.

Table 6.10: Assessment of Health risks based on the European Union (EU) Directive 2002/44/EC

<table>
<tr><th rowspan="2">Sl.No</th><th rowspan="2">Vehicle Type</th><th rowspan="2">Vehicle Identification code</th><th rowspan="2">A(8) in m/s^2</th><th colspan="2">Time to reach EAV</th><th rowspan="2">Health Risk</th><th colspan="2">Time to reach ELV</th><th rowspan="2">Health Risk</th></tr>
<tr><th>Hours</th><th>Mins</th><th>Hours</th><th>Mins</th></tr>
<tr><td>1</td><td rowspan="12">LPDT</td><td>T5</td><td>3.3</td><td>4</td><td>35</td><td>Y</td><td>18</td><td>22</td><td rowspan="16">N</td></tr>
<tr><td>2</td><td>T6</td><td>3.1</td><td>5</td><td>12</td><td>Y</td><td>20</td><td>49</td></tr>
<tr><td>3</td><td>T7</td><td>3.2</td><td>4</td><td>53</td><td>Y</td><td>19</td><td>32</td></tr>
<tr><td>4</td><td>T8</td><td>3.2</td><td>4</td><td>53</td><td>Y</td><td>19</td><td>32</td></tr>
<tr><td>5</td><td>T16</td><td>3.0</td><td>5</td><td>33</td><td>Y</td><td>22</td><td>13</td></tr>
<tr><td>6</td><td>T17</td><td>3.0</td><td>5</td><td>33</td><td>Y</td><td>22</td><td>13</td></tr>
<tr><td>7</td><td>T19</td><td>2.4</td><td>8</td><td>41</td><td>N</td><td colspan="2" rowspan="6">>24</td></tr>
<tr><td>8</td><td>T21</td><td>2.2</td><td>10</td><td>20</td><td>N</td></tr>
<tr><td>9</td><td>T22</td><td>2.3</td><td>9</td><td>27</td><td>N</td></tr>
<tr><td>10</td><td>T101</td><td>2.3</td><td>9</td><td>27</td><td>N</td></tr>
<tr><td>11</td><td>T102</td><td>2.4</td><td>8</td><td>41</td><td>N</td></tr>
<tr><td>12</td><td>T104</td><td>2.2</td><td>10</td><td>20</td><td>N</td></tr>
<tr><td>13</td><td rowspan="4"></td><td>L-5</td><td>2.8</td><td>5</td><td>12</td><td>Y</td><td>20</td><td>49</td></tr>
<tr><td>14</td><td>L-6</td><td>2.9</td><td>4</td><td>53</td><td>Y</td><td>19</td><td>32</td></tr>
<tr><td>15</td><td>L-8</td><td>2.6</td><td>5</td><td>57</td><td>Y</td><td>23</td><td>47</td></tr>
<tr><td>16</td><td>L-11</td><td>2.5</td><td>6</td><td>52</td><td>N</td><td colspan="2"></td></tr>
</table>

17	LHD	L-12	2.3	8	00	N	>24	
18		L-15	2.2	8	41	N		
19		L-14	2.1	9	27	N		
20		L-16	1.7	13	51	N		

Note: **Y**=Yes and N=No.

The results in Table 6.13 clearly indicate that the LPDTs designated T5, T6, T7, T16, T17, and T19, along with three LHDs L-5, L-6, and L-8 producing HAV values greater than that of the stipulated limits of EAV, i.e., 2.5 m/s2 of the EU Directive 2004. But none of the LPDTs and LHDs had vibration levels more than that of the ELV of 5m/s2. The operators of the 5 LPDTs and 3 LHDs with A(8)values more than the recommended EAV were at risk of developing possible health issues.

6.3 Summary

A range of field and machine circumstances creates mining equipment vibrations. The degree and severity of vibrations can be related to vehicle type, road condition, speed, state of the vehicle, maintenance, operator skill, and so on. The current research focuses on the vibrations transmitted to the operators' hands via the steering systems of LPDTs and LHDs in an underground metal mine. The measurements and analysis of HAV were performed in accordance with ISO 5349:2001 rules, and the health risks associated with the related HAV exposure were assessed in accordance with European Union (EU) Directive 2002/44/EC guidelines. Based on the HAV exposure and associated health hazards while operating LPDTs in an underground metal mine, the following observations can be made:

The primary job component that contributed to the high HAV levels in the entire work cycle of the LPDTs was empty hauling, with the z-axis having the highest vibration value. Furthermore, vibration levels were higher on the z-axis during unloading and loaded travel situations. The higher vibration values in the z-axis are substantiated in studies conducted on army trucks (Akmar and Aziz, 2017) and tractors (Goglia et al., 2003) in off-road conditions.

During loading operations, the x-axis vibration levels were higher due to falling boulders from the LHDs and pounding by the LHDs to spread the load in the dump box evenly.

Empty hauling had the highest proportion of daily vibration exposure, with the highest being 59.51% in T102, followed by loaded hauling, loading, and unloading.

HAV levels in six LPDTs surpassed the EAV limit of 2.5m/s^2.

The job component analysis of the LHDs has shown the mucking operation produced the highest level of vibrations, followed by empty hauling and loaded hauling, respectively, which can be attributed to the fact that the LHDs moved on rough terrain caused by the blasted ore and rock fragments. The X-axis was the dominant axis during mucking, and the Z-axis was predominant during the hauling operations.

The mucking operation was the highest contributor to the overall daily vibration exposure A(8), ranging from 35.78% to 48.52%, followed by empty and loaded hauling operations. The minimum contribution to A(8) came from unloading operations.

Out of the 8 LHDs considered for the study, 3 LHDs were producing vibrations more than that of the specified daily limits with respect to RMS acceleration values.

Statistical analysis of multiple regression and ANOVA have demonstrated that the machine parameters had a significant relationship with A(8). Vehicle working hours had the most substantial influence (38.42%), followed by capacity in tons (22.24%) and loading conditions (17.38%).

The health risk assessment based on the EU Directive 2004 showed that the operators of the LPDTs designated T5, T6, T7, T16, T17, and T19, LHDs designated L-5, L-6, and L-8 were at risk of developing health issues in line with the EAV limits. But none of the machines exceeded the ELV limits.

CHAPTER-7

ASSESSMENT OF MUSCULO-SKELETAL DISORDER RISK OF THE MOBILE MINE EQUIPMENT OPERATORS EXPOSED TO HAND TRANSMITTED VIBRATIONS

HTV exposure is believed to contribute to musculoskeletal complications of the upper limbs at the fingers, wrists, elbows, shoulders, and, sometimes, the neck. This study aims to assess the increased risk for exposure to Hand Transmitted Vibrations (HTVs) associated with MSDs of the upper extremities of workers in an underground metal mine using a case-control approach.. Case-control studies are used to compare two groups of individuals with an outcome disease or a condition subject to exposure to a particular factor, substance, and/or a working state. The study explains the impact of exposure on the occurrence of disease. The exposed group is considered the case group, and the other is the control group.

7.1 Methodology

7.1.1 Selection of Participants

The case-control study was carried out involving 80 male workers at the same mine. The research enrolled MME operators, office employees, supervisors, engineers, mechanical engineering, and logistics personnel. The case group consisted of 40 MME operators exposed to HTVs regularly, and the control group consisted of the remaining participants without any exposure to vibrations.

7.1.2 Data collection

The investigators obtained prior approval from the mine's management to conduct the research. The aim and significance of the study were presented to participants in both local and English languages. The participants' anthropometric and body discomfort data was collected in the presence of the mine's safety officer at the vocational training facility. The body discomfort data was collected using the Cornell Musculoskeletal Disorder Questionnaire (CMDQ) (male version) for sitting positions (refer to appendix).

The HAV readings were gathered in compliance with ISO 5349-2:2001 requirements using an SV 105B Tri-axial Hand Accelerometer. Data was collected by connecting the accelerometer to the SV106 human vibration analyzer, meeting the ISO 5439-1:2001 standards.

7.1.3 Statistical analysis

The statistical tool IBM-SPSS version 26 was used to evaluate the acquired field data to make statistical conclusions to calculate the relative risk of MSDs in the upper extremities of the MME operators. Binary logistic regression was used to determine the factors significantly affecting the dependent variable since the relationship between predictor and response variables is usually categorical. Binary logistic regression models are employed when the dependent variable is binary, expecting only one of two different and incompatible values. Typically, the binary response variables are coded as '1' for the existence of a disorder and '0' for its absence. A general form of a binary logistic regression model is given in equation(7.1) to calculate the OR of having been exposed to a risk factor if you have the disease by evaluating the 14 independent variables (risk factors) (mentioned in table 7.2) against the health endpoint of interest.

$$\ln(p\backslash 1-p)=B+B_1x_1+B_2x_2+\ldots\ldots\ldots\ldots\ldots\ldots B_{14}x_{14} \qquad (7.1)$$

Where p is the probability of MSD risk in the upper extremities; B is the constant; B_1, B_2,......B_{14} are the coefficients corresponding to the predictor variables x_1, x_2,..., x_{14}.

7.2 Results and Discussions

7.2.1 Questionnaire data

A descriptive statistical analysis was performed to summarize the anthropometric and personal data of both the case and control groups and is presented in Table 7.1.

Table 7.1: Descriptive statistics of the anthropometric and personal data of the participants

Anthropometric Data	Cases			Controls		
	Mean	Range	SD	Mean	Range	SD
BMI	25.01	21-28.71	1.83	23.87	18.41-28.7	2.36
Age in years	33.05	26-45	4.45	29.27	25-36	2.81
Experience in years	11.90	05-23	4.33	9.27	5-16	2.81

The musculoskeletal discomfort data from the participants were collected using CMDQ. The CMDQ and anthropometric data were categorized into two groups and coded accordingly. Participants with musculoskeletal discomfort scores of more than 10 in any body part were coded 1, and those with scores below or equal to 10 were coded 0. The anthropometric variables and individual habits were also considered in the study and were categorized and coded for statistical analysis. Participants who used tobacco were coded 1, and those who didn't use it were coded 0. Similarly, the anthropometric variables were coded and depicted in Table 7.2, which shows the number and percentage of participants in both case and control groups considered in the present study.

Table 7.2: Categorization and coding of anthropometric and CMDQ data for case and control groups

Sl. No	Factors	Category	Coding	Case Group Nos	Case Group %	Control Group Nos	Control Group %
1	Neck	Yes	1	24	60	06	15
		No	0	16	40	34	85
2	Right	Yes	1	27	67.5	06	15

	Shoulder(rs)	No	0	13	32.5	34	85
3	Left Shoulder(ls)	Yes	1	19	47.5	03	7.5
		No	0	21	52.5	37	92.5
4	Upper Back(ub)	Yes	1	19	47.5	05	12.5
		No	0	21	52.5	35	87.5
5	Upper Right Arm(ura)	Yes	1	07	17.5	02	05
		No	0	33	82.5	38	95
6	Upper left Arm(ula)	Yes	1	00	00	00	00
		No	0	40	100	40	100
7	Right Fore Arm(rfa)	Yes	1	00	00	00	00
		No	0	40	100	40	100
8	Left Fore Arm(lfa)	Yes	1	00	00	00	00
		No	0	40	100	40	100
9	Right Wrist(rw)	Yes	1	28	70	06	15
		No	0	12	30	34	85
10	Left Wrist(lw)	Yes	1	29	72.5	10	25
		No	0	11	27.5	30	75
11	Body Mass Index(BMI)	>25	1	20	50	11	27.5
		<25	0	20	50	29	72.5
12	Age in years	>35	1	14	55	03	52.5
		<35	0	26	45	37	47.5
13	Experience in years	>10	1	21	52.5	20	50
		<10	0	19	47.5	20	50
14	Tobacco usage	Yes	1	25	62.5	14	35
		No	0	15	37.5	26	65

7.2.2 Assessment of HTVs and Associated Health Risks in MME Operators

The vibration data were collected from the mine involving 40 case group participants operating different MMEs using a triaxial hand accelerometer coupled with a human vibration analyzer. The data gathered comprised the frequency-weighted root mean square values for each of the basi-centric axes for each MME. The specifications and the vibration data for each MME are tabulated in Table 7.3.

Table 7.3: Hand Transmitted Vibration data of the equipment considered for the study

MME Type	Local Designation	a_{hx}	a_{hy}	a_{hz}	a_{hv} in m/s^2	A(8) in m/s^2
Low Profile Dump Trucks	LPDT5	1.929	1.345	2.565	3.48	**3.1**
	LPDT6	1.825	1.265	2.385	3.26	**2.9**
	LPDT7	1.875	1.452	2.32	3.32	**3.0**
	LPDT8	1.765	1.527	2.452	3.39	**3.0**
	LPDT16	1.569	1.487	2.326	3.18	**2.9**
	LPDT17	1.489	1.321	2.569	3.25	**2.9**
	LPDT19	1.145	0.961	1.968	2.47	2.2
	LPDT21	1.165	0.867	1.768	2.29	2.1
	LPDT22	1.324	0.912	1.652	2.31	2.1
	LPDT101	1.206	0.963	1.782	2.36	2.1
	LPDT102	1.279	0.912	1.897	2.46	2.2
	LPDT104	1.263	0.798	1.857	2.38	2.1
Load Haul Dumpers	LHD-5	1.765	1.016	2.158	2.97	**2.7**
	LHD-6	1.769	1.153	2.326	3.14	**2.8**
	LHD-8	1.462	1.025	2.128	2.78	**2.5**
	LHD-11	1.329	1.006	2.023	2.62	2.4
	LHD-12	1.269	0.961	1.853	2.44	2.2
	LHD-15	1.253	1.002	1.853	2.45	2.2

	LHD-14	1.232	0.841	1.624	2.21	2.0
	LHD-16	0.847	0.634	1.423	1.77	1.6
Scissor Lift	N-1	1.974	1.547	3.156	4.03	**3.6**
	N-3	2.037	1.483	2.968	3.89	**3.5**
	N-4	2.197	1.747	2.789	3.96	**3.6**
	N-11	1.881	1.547	2.756	3.68	**3.3**
	N-13	1.618	1.261	2.623	3.33	**3.0**
	N-14	1.661	1.228	2.526	3.26	**2.9**
Personnel Carrier	N-5(16-Seater)	1.64	1.181	3.054	3.66	**3.3**
	N-10(32-Seater)	2.27	1.532	2.965	4.04	**3.6**
MULTIMEC 6600	N-2	2.064	1.437	3.154	4.03	**3.6**
	N-6	1.97	1.341	2.967	3.81	**3.4**
	N-7	1.63	1.272	2.365	3.14	**2.8**
MULTIMEC MF-100	N-8	1.622	1.168	2.967	3.58	**3.2**
	N-9	1.634	1.125	2.234	2.99	**2.7**
	N-12	1.726	1.341	2.312	3.18	**2.9**
Explosive Carrier	CHARMEC-1	1.653	1.326	2.286	3.12	**2.8**
	CHARMEC-2	1.723	1.473	2.691	3.52	**3.2**
Scaler	SCAMEC	1.861	1.527	2.921	3.79	**3.4**
Break Down Rescue Vehicle	RBO-1	1.628	1.267	2.763	3.45	**3.1**
	RBO-2	1.603	1.159	2.452	3.15	**2.8**
	RBO-3	1.265	1.068	1.769	2.42	2.2

The results from the table indicate that the highest A(8) values of 3.6 m/s^2 were observed in two scissor lifts, designated as N-1 and N-4, and the 32-seater personnel carrier, along with multimec designated as N-2. Also, the z-axis had higher vibration levels, followed by the x and y-axes, respectively.

Based on the EU Directive 2001 recommendations, the EAV is 2.5 $m/s^{2,}$ and ELV is 5 m/s^2. But it is evident from Table 7.3 that 28 out of the 40 MMEs were generating HTVs exceeding the EAV of 2.5 $m/s^{2,}$ revealing 70% of operators at risk of developing health problems due to HTVs.

7.2.3 Statistical assessment for the case-control study

Binary logistic regression, including a constant and with a confidence interval level of 95%, was used to find the statistical significance between the considered predictor variables and the response variable, i.e., the MSD risk of the MME operators. Fourteen independent variables were considered for the study, which included three anthropometric factors, one individual habit of tobacco use, and ten factors (pains or discomfort in different body parts) considered from the CMDQ data. The results of the binary logistic regression are presented in Table 7.4.

Table 7.4: Binary logistic regression model for MSD risk for case and control groups

Response Variable	df	p	OR	95% C.I.for		Remarks
				Lower	Upper	
Neck	1	.951	.932	.100	8.662	Insignificant
Right shoulder	1	.713	1.479	.184	11.912	Insignificant
Left shoulder	1	**.035**	**7.565**	1.159	49.390	**Significant**
Upper back	1	.216	3.947	.449	34.702	Insignificant
Upper right arm	1	.429	6.156	.068	554.664	Insignificant
Left wrist	1	**.003**	**12.804**	2.436	67.285	**Significant**
Right wrist	1	.566	2.110	.164	27.091	Insignificant
Body mass index	1	.716	1.341	.276	6.515	Insignificant

Age	1	.486	2.653	.170	41.328	Insignificant
Experience	1	.553	.443	.030	6.526	Insignificant
Tobacco usage	1	**.007**	**9.353**	1.856	47.129	**Significant**
Constant	1	**.005**	**.001**			**Significant**

The results of binary logistic regression are presented in terms of the regression coefficient (B), significance (p), and odds ratio (Exp (B)). The results show that out of the 14 predictor variables, only four variables, including the constant, were statistically significant in the model. The odds ratios suggest that the case group is 7.56 and 12.80 times more likely to experience pain in the left shoulder and left wrist than the control group. Furthermore, participants who used tobacco were 9.35 times more prone to MSDs than those who did not.

Exposure to HTVs can cause several health hazards in the human body's vascular, nervous, and musculoskeletal systems. The study aimed to evaluate the relative health hazards to their upper extremities encountered by the MME operators (case group) compared to the other workers in the same mine who are not exposed to HTVs (control group). MME operators are exposed to HTVs regularly due to their work's sensitivity, as they have to maintain constant physical contact with the steering devices of their vehicles. The HTV measurements were carried out according to the guidelines set by ISO 5349:2001. It is evident from Table 7.3 that A(8) values for 28 MMEs were more than the stipulated EAV of 2.5 m/s^2. The A(8) values greater than 3.54 m/s^2 imply that the operators should be operating the MMEs for not more than 4 hours.

The odds ratio from the logistic regression clearly showed that the case group participants are 7.56 (95% CI, 1.159, 49.39) and OR 12.80 (95% CI, 2.436, 67.285) times more vulnerable to pains or discomforts in their left shoulders and left wrists, respectively, than the participants in the control group. Several previous studies have established a correlation between HTV exposure and disorders of the upper limbs and neck (House et al. 2009) (Åström et al. 2006). Similarly, the odds ratio for tobacco usage and the MSD risk for the users is 9.35 times higher than for non-users. The association of increased incidence of MSDs with tobacco usage has been substantiated in numerous studies (Abate et al. 2013) (Jakobsson 2008). Mine management should take appropriate precautions to protect MME operators from the adverse effects of HTVs, as the MSD risk is higher in the case group than in controls.

7.3 Summary

This study involved 80 participants, 40 each from both case and control groups. The assessment of HTVs in the case group was carried out strictly adhering to the guidelines set by ISO 5349:2001. The results show that the z-axis was the dominant vibration axis with a significant contribution to A(8). Also, 70% of MMEs produced HTVs above the EU Directive's specified limitations, putting operators at increased health risk. The MSD status of the case and control groups was assessed using CMDQ, and in-depth interviews with the participants were carried out. The left shoulder and the left wrist were the body parts that were most affected in the MME operators due to continuous HTV exposure. Regardless of its type, tobacco use exacerbated the MSD issue in those who used it.

The study concludes that the MME operators were more susceptible to MSD risks due to their exposure to HTVs. The HTV assessment and responses to the CMDQ survey can be used to validate this outcome. Even though mechanization in Indian mines is monumentally increasing, research on repercussions on the health of the operators exposed to HTV is relatively sparse. This study will help the mine management formulate policies to protect its workers from the MSD risks posed by HTV exposure.

CHAPTER-8

CONCLUSIONS AND SCOPE FOR FUTURE WORK

8.1 Conclusions

The present ergonomic study was conducted in underground metal mines in India. The study included different MMEs and their operators. The study focused on assessing the physiological demands and workloads of the MME operators in terms of oxygen uptake using the heart rate ratio (HRR) method. The study also focused on assessing two physical ergonomic risk factors, namely Hand Transmitted Vibrations (HTVs) and the work postures of the MME operators. The HTV assessment was carried out on the interface of the operator's hands and the steering devices of the MMEs. The work posture study was carried out for the driving position of the operators. The following conclusions were drawn from analyzing the ergonomic data collected from an Indian underground metal mine.

- The heart rate data of the 40 MME operators were collected from the field investigations, and respective oxygen uptake calculations were carried out. According to the study, MME operators' maximum aerobic capacity is lower than those of other industries. The LHD operators' VO_{2max} was the lowest, as they spent their whole shift underground. Also, increased age and BMI significantly affected the maximum aerobic capacity. 27.5% of MME operators had RAS above 50% of their VO_{2max}. The current study demonstrates that operating MMEs in underground mines impose a significant physiological strain on the operators.

- The results from the work posture study clearly show that the. 88.9% of the operators whose RULA scores were less than four had no MSD issues, and 11.1%of operators with RULA scores, more than four had experienced body discomfort. Among the operators having body discomfort, 22.6% had RULA scores less than or equal to 4. But most operators who experienced pain in one or more body parts had scores of 5 and above. The results from the binary logistic regression reveal a statistically significant association between MSD risk and awkward postures with a p-value of 0.020.

- HTV measurements were carried out according to the guidelines set by ISO 5349:2001. The primary job component that contributed to the high HAV levels in the entire work cycle of the LPDTs was empty hauling, with the z-axis having the highest vibration value. Furthermore, vibration levels were higher on the z-axis during unloading and loaded travel situations. The job component analysis of the LHDs has shown that the mucking operation produced the highest level of vibrations, followed by empty hauling and loaded hauling, respectively, which can be attributed to the fact that the LHDs moved on rough terrain caused by the blasted ore and rock fragments. The x-axis was the dominant axis during mucking, and the z-axis was predominant during the hauling operations.
- A case-control approach was also followed to ascertain the MSD risks among the group of operators exposed to HTVs than the non-exposed, i.e., the control group. The total daily vibration exposure A(8) of the case group was calculated. The A(8) values for 70% MMEs were more than the stipulated EAV of 2.5 m/s^2. The A(8) values greater than 3.54 m/s^2 imply that the operators should operate the MMEs for less than 4 hours. The odds ratio from the logistic regression clearly showed that the case group participants are 7.56 and 12.80 times more vulnerable to pain or discomfort in their left shoulders and wrists than the control group participants. Similarly, the odds ratio for tobacco usage and the MSD risk for the users are 9.35 times higher than for non-users.
- Like any other study, the present work has its limitations. Firstly, the sample size of the operators considered in the study was limited to 40. Hence, the results of the statistical analyses of the present study do not explain the variations for larger population sizes. Another limitation of the study pertains to the age of the operators. The operators' ages in the study varied between 26 and 45 years. The

results of this study do not address the MSD issues faced by operators above 45 years. Also, the study did not consider operators with a history of accidents or injuries. The study also excluded the operators with any health issues or co-morbidities.

8.2 Recommendations to Mitigate MSD Risks

- Better maintenance of the haul roads.
- Corrective and preventive maintenance of the machines by replacing/repairing defective parts causing higher vibration levels.
- Use of anti-vibration gloves and anti-vibration coatings on the levers and steering wheels to minimize the vibrations reaching the operator's hand-arm system.
- In the particular case of operating LHDs, the operator's exposure to vibrations can be entirely mitigated by employing the machines using remote controls, especially during mucking operations.
- Employing multi-skilled operators and adapting job rotation among the operators can also be considered to minimize exposures from the risk factors.
- Providing better ventilation by increasing the number of common rest areas, especially for operators who spend their entire shift underground.
- Providing rear-view cameras and hands-free communication equipment in the machines can help the operators maintain more neutral postures.
- Providing adequate rest breaks to bring the workloads to acceptable limits.
- Finally, In house, participatory ergonomics program should be introduced to give a thorough knowledge of ergonomic risks and ways to mitigate them.

8.3 Scope for Future Work

- The study can be extended further to mines with different geotechnical conditions, such as underground coal and open-cast mines.
- The study can be further extended to a broad spectrum of age groups among the operators.

- Simulation studies on the sub-systems of the equipment generating vibrations using neural networks.
- Structural equation modeling on the MSDs of the operators exposed to various ergonomic risk factors in underground mines.
- The ergonomic study can also be extended by considering psychosocial and organizational risk factors.

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APPENDIX-1

Table 3.3: Technical Specifications of SV 105B Tri-axial Hand-Arm Accelerometer

Performance	
Number of Axes	3
Sensitivity (± 5 %)	0.661 mV/ms^{-2} at 79.58 Hz
Frequency Response (by design guideline, ± 3 dB)	0 Hz ÷ 1500 Hz
Measurement Range	2000 m/s^2 Peak
Resonant Frequency	16.5 kHz (MEMS transducer)
Electrical Noise	< 0,14 ms^{-2} RMS, Wh weighting
Electrical	
Supply Current	< 5.0 mA
Supply Voltage	3.3 V ÷ 5.5 V
Bias Voltage	1.5 V ± 0.05 V
Output Impedance	51 Ohms
Charge / Discharge Time Constant (start-up time)	30 sec. type
TEDS Memory	installed (power supply pin)
Environmental Conditions	
Maximum Vibration	100,000 ms^{-2} shock survival for MEMS sensor
Temperature Coefficient	<±0.02%/^{0}C
Temperature	from -10 °C to +50 °C
Humidity	Upto 90% RH, non-condensed
Physical	
Sensing Element	MEMS
Cable	integrated 1.4 meters
Connector	LEMO 5-pin plug (SV 106 compatible)
Dimensions	69.6 mm x 31.4 mm, thickness from 8.3 mm to 15 mm
Weight	50-60 grams (including cable and one of the vibration contact adapters)

Table 3.4: Technical Specifications of SV 106 Human Vibration Analyser

Standards	ISO 8041-1:2017; ISO 2631-1:1997; ISO 2631-2:2003; ISO 2631-5:2004; ISO 5349-1:2001; ISO 5349-2:2001
Meter Mode	ahw (RMS HAND-ARM) ahv (VECTOR HAND-ARM) aw (RMS WHOLE-BODY) awmax (RMS MAX WHOLE-BODY) VDV, MaxVDV, awv (VECTOR WHOLE-BODY), A(8) Daily Exposure, ELV Time, EAV Time MTVV, Max, Peak, Peak-Peak
Profiles per Channel	2
Filters in Profile (1)	HP, KB, Wd, We, Wk, Wm, Wb, Wc, Wj, Wg, Wf (ISO 2631), Wh (ISO 5349)
Filters in Profile (2)	HP, Wp, Vel3 (for PPV measurement), Band Limiting Filters according to ISO 8041:2017
RMS & RMQ Detectors	Digital true RMS & RMQ detectors with Peak detection, resolution 0.1 dB
Measurement Range	Transducer dependent: 0.01 m/s^2 RMS ÷ 50 m/s^2 Peak (with SV 38V and Wd filter) 0.1 m/s^2 RMS ÷ 2000 m/s^2 Peak (with SV 105 and Wh filter)
Frequency Range	0.1 Hz ÷ 2 kHz (transducer dependent)
Data Logger	Time-history data including meter mode results and spectra
Time-Domain Recording	Simultaneous 6-channel time-domain signal recording, sampling frequency 6 kHz (optional)
Analyser	6-channel 1/1 octave real-time analysis with centre frequencies from 0.5 Hz to 2000 Hz (optional) 6-channel 1/3 octave real-time analysis with centre frequencies from 0.4 Hz to 2500 Hz (optional)
Accelerometer (optional)	SV 38V integrated tri-axial accelerometer for Whole-Body measurements SV 105 integrated tri-axial accelerometer including hand straps SV 105F integrated tri-axial accelerometer with force sensors including hand straps SV 150 integrated tri-axial accelerometer with adapter for irect attaching to hand-held power tools SV 151 integrated tri-axial accelerometer for SEAT transmissibility

	measurements
Input	2 x LEMO 5-pin: six channels Direct or IEPE type and 2 channels for force transducers
Dynamic Range	90 dB
Force Range	0.2 N ÷ 200 N (only with an optional SV 105F)
Sampling Rate	6 kHz
Display	Blanview TFT-LCD 2.4" colour display (320 x 240 pixels)
Interfaces	USB-C, Extended I/O - AC output (1 V Peak) or Digital Input/Output (Trigger - Pulse)
Power Supply	Four AA batteries (alkaline) operation time > 12 h[1] Four AA rechargeable batteries operation time > 16 h (4.8 V / 2.6 Ah)[1] (not included) USB interface min. 500 mA HUB
Memory	MicroSD card 32 GB (removable & upgradeable up to 128 GB)
Environmental Conditions	Temperature from -10 °C to 50 °C (14 °F to 122 °F) Humidity up to 90 % RH, non-condensed
Dimensions	140 x 83 x 33 mm (without accelerometer)
Weight	Approx. 390 grams including batteries (without accelerometer)

LIST OF PUBLICATIONS

	Title	Authors	Journal	Month and year of publication	Category
	Musculoskeletal Disorder Risk in the Upper Extremities of Mobile Mining Equipment Operators exposed to Hand Transmitted Vibrations in Underground Metal Mines: A Case-Control Study	Sridhar S M. Govinda Raj M. Aruna	Mining, Metallurgy and Exploration (SCI)	August 2022	1
	Maximum Aerobic Capacity and Relative Aerobic Strain among Mobile Mine Equipment Operators in Underground Mines	Sridhar S M. Govinda Raj M. Aruna	Journal of the Institute of Engineers (INDIA): Series D (SCOPUS)	December 2022	1
	Awkward Work Postures and Tobacco Usage as risk factors for Musculoskeletal Disorders among the Operators of Mobile Mining Equipment in Underground Metal Mines	Sridhar S M. Govinda Raj M. Aruna	Journal of Mines Metals and Fuels (SCOPUS)	Accepted	1
	Investigations of Hand Transmitted Vibrations and associated health risks in Load Haul Dumper Operators based on different components of a work cycle	Sridhar S M. Govinda Raj M. Aruna	Materials Today Proceedings (SCOPUS)	May 2023	3

*Category:

1: Journal paper, full paper reviewed

2: Journal paper, Abstract reviews

3: Conference/Symposium paper, full paper reviewed

4: Conference/Symposium paper, abstract reviewed

5: Others (including papers in Workshops, NITK Research Bulletins, Short notes etc.),

(If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

Sridhar S | M Govinda Raj 14/6/23

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Nationality	:	Indian
Date of Birth	:	21 May 1987
Marital Status	:	Married
Present Position	:	Research Scholar, NITK, Surathkal
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Academic Details:

M-Tech

Department	:	Masters in Engineering Management
College	:	Sri Jayachamarajendra College of Engineering, Mysore
University	:	Visveswaraiah Technological University, Belgaum
Aggregate	:	8.28 CGPA
Year of passing	:	2015

B.E

Department	:	Mechanical Engineering
College	:	Jawaharlal Nehru National College of Engineering, Shimoga
University	:	Visveswaraiah Technological University, Belgaum
Aggregate	:	60.3%
Year of passing	:	2011

Industry experience:

Company : SPCPL, Shimoga

Period : June 2011-May 2013

Designation : QC Engineer

Teaching Experience:

College : Karavali Institute of Technology, Mangalore.

Period : June 2013-May2014

Designation : Lecturer

College : Akshaya Institute of Technology, Tumkur.

Period : June 2014- June 2017

Designation : Asst. Professor

Date: 13/06/2023
Place: Surathkal **(Sridhar S)**