

*Dissertation
On*

**FRACTIONAL FACTORIAL ANALYSIS AND EMPIRICAL
MODELING OF CARDIOPULMONARY RESPONSES DURING
LIFTING OPERATIONS**

*Submitted in partial fulfillment of the requirement for
the award of degree of*

**MASTER OF ENGINEERING
IN
PRODUCTION AND INDUSTRIAL ENGINEERING**

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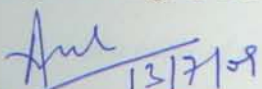
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DECLARATION

I hereby declare that the thesis entitled "FRACTIONAL FACTORIAL ANALYSIS AND EMPIRICAL MODELING OF CARDIOPULMONARY RESPONSES DURING LIFTING OPERATIONS" is an authentic record of my study carried out as requirements for the award of degree of ME (Production and Industrial Engineering) at Thapar University, Patiala, under the guidance of Dr. Ajay Batish, Associate Professor and Mr. Ravinder Kumar Duvedi Lecturer, Department of Mechanical Engineering, Thapar University, Patiala during July 2008 to June 2009. The matter embodied in this thesis has not been submitted in part or full to any other university or institute for the award of any degree.



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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge & belief.


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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) developed a lifting equation in 1981 (Revised in 1991) to indicate “safe” occupational lifting limits. The equation uses a series of lifting multipliers (parameters) to calculate corresponding recommended task weight limits. In the present work, the interactions effect of lifting parameters has been studied by using a parameterization approach to measure the effect of interaction between factors. The main effects of load weight, frequency of lift, vertical distance of lift, horizontal distance from lift and operator and their interactions during lifting operations have been evaluated on oxygen uptake and heart rate of workers involved in continuous lifting tasks by using factorial analysis of variance and empirical modeling. As the physiological characteristics and body metabolism of Indian male workers is different as compared to other countries. Moreover due to different environmental conditions in India the work stresses involved in lifting tasks are very demanding. This factor approach has been used to study the effects of various factors at appropriate levels and their interactions among variables. Plots of significant factors, S/N ratio and empirical modeling have been used to determine the best-fit relationship between the response and the model parameters.

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ABBREVIATIONS

NIOSH	-	National Institute of Occupational Safety and Health
MSD	-	Musculoskeletal Disorder
MMH	-	Manual Material Handling
ANOVA	-	Analysis of Variance
DOF	-	Degree of Freedom
S/N	-	Signal to Noise Ratio
WMSD	-	Work-related Musculoskeletal Disorder
CO	-	Cardiac Output
SV	-	Stroke Volume
RMR	-	Resting Metabolic Rate
MET	-	Metabolic Equivalent
MHAC	-	Material Handling Assessment Chart

NOTATIONS

OA	-	Orthogonal Array
CO	-	Cardiac Output
SV	-	Stroke Volume
A	-	Horizontal Distance
B	-	Load Weight
C	-	Lifting Frequency
D	-	Operator
E	-	Vertical Distance
SS	-	Sum of Squares
CI	-	Confidence Interval
MAF	-	Maximum Acceptable Frequency

ERGONOMIC ANALYSIS OF WORKPLACE –AN OVERVIEW

1.1 INTRODUCTION

The term ergonomics is derived from two Greek words, ‘ergon’ meaning work and ‘nomoi’ meaning natural laws. The importance of ergonomics lies in the fact that with the use of ergonomically-designed devices, stress-related issues can be brought down to a minimum. For instance, an ergonomically-designed keyboard can reduce repetitive stress injuries like Carpal Tunnel Syndrome, a disorder caused by repeating the same action (such as data entry) that can result in inflammation. Ergonomic keyboards are split down the middle, and have a design which allows you to comfortably rest your palms and wrists while typing. It has assumed a great importance in manufacturing industry.

The effect of ergonomic factors on employee morale, his health, safety and productivity is increasingly being recognized. In developed countries, ergonomics has become an essential component of not only the workplace design from anatomical, physiological and psychological points of view but from a broader perspective of all human interactions. “Ergonomics is more sorely needed, easier to implement, and potentially far more effective in industrially developing countries (IDCs) than where its efforts are presently most concentrated in the less populated, more affluent, technologically advanced world”[1] developing countries, however, ergonomics is used in very restricted sense. The reason for this state are: age old practices in vague, lack of awareness both on the part of employers and employees, resistance to and risk of change etc. are some of the probable reasons.

According to Helander [2],”ergonomics and human factors use knowledge of human abilities and limitations to the design of systems, organizations, jobs, machines, tools, and consumer products for sale, efficient and comfortable end use.”The emergence of macro ergonomics has strongly contributed to the increasing interest in work organization in ergonomics field [3]. The objective of ergonomics is to improve performance as well as health and safety. Some work organizations are more efficient at achieving optimal performance and health and safety goals.

According to the U.S. Department of Labor, handling is defined as: Seizing, holding, grasping, turning, or otherwise working with the hand or hands. Manual material handling (MMH) work contributes to a large percentage of the over half a million cases of musculoskeletal disorders reported annually in the United States [4]. Musculoskeletal disorders often involve strains and sprains to the lower back, shoulders, and upper limbs. Manual material handling is one of the major causes of severe industrial injury [5]. It has been estimated that more than a quarter of all injuries related to industrial work are directly associated with MMH activities [6]. Many of these injuries arise from improper handling of materials. The direct and indirect costs are enormous, and the human suffering associated with low back injuries is immeasurable.

Low back pain and injuries attributed to manual lifting activities continue to be one of the leading occupational health and safety issues in workplaces across the nation. According to the National Safety Council, overexertion injuries represent more than 30 percent of all workplace injuries. In addition, overexertion injuries of the back, shoulders and knees are some of the most costly to workers' compensation systems. Musculoskeletal Disorders (MSDs) are the most common cause of occupational ill health in Great Britain, currently affecting 1.0 million people a year and costing society £5.7 billion [7].

Considering the cost in man-hours, rehabilitation, and the chances of reoccurrence, prevention of Low Back Pain has been a major focus in job design [8]. Scientific evidence shows that effective ergonomic interventions can lower the physical demands of MMH work tasks, thereby lowering the incidence and severity of the musculoskeletal injuries they can cause

It has been found that measures used to determine low back disorder risk (referred as “exposure measures”) fell into four major categories: (1) compressive forces on the spine, (2) lifting frequency, mass, or duration, (3) lifting ratios or indices, and (4) measures of posture. [9]

1.2 TYPES OF PROBLEMS IN ERGONOMICS

The categorization of industrial Ergonomics problems can often aid to be their solution. The different types of problems have different solution methodologies. By classifying problems into one of six basic groups, the beginning of a solution is more easily undertaken [10]. Since ergonomics is the study of people, it is convenient to think of industrial ergonomics problems by the type of body system that is affected. Different types of ergonomic problems affect different body systems, so that is a useful categorization for ergonomic concerns.

1.2.1 Physical Size: Anthropometry

Anthropometry is the science dealing with the measurement of human body dimensions. Measures of stature, body weight, arm reach, and eye height are just a few of the body dimensions that are available through the science of anthropometry. Anthropometric problems are those that deal with a physical conflict between the person and some aspect of the work area. Problems with the workplace and work space are the most common anthropometric problems. These problems are characterized as problems involving fit, where someone is too large or too small to fit the equipment. These problems can be resolved with the use of data about expected populations and the work area that will accommodate them.

1.2.2 Endurance: Cardiovascular

Endurance problems are characterized by the stress that they place on the cardiovascular system. This stress may come from a heavy job requiring extensive physical effort and the resulting need to get oxygen and energy to the muscles. Similarly, heat stress can result in the need for extra blood flow to cool parts of the body, causing increased circulatory load with an accompanying elevation of the heart rate. In both of these cases, the concern is from the elevated heart rate and increased blood pressure, which can result in a heart attack or stroke. Endurance problems can result in the establishment of work/recovery cycles or of standards for a fair day's work. Designing tasks and jobs to conform to a predetermined expenditure of energy (or kilocalorie expenditure) is a suitable way to resolve endurance problems.

1.2.3 Strength: Biomechanical

Strength problems are often characterized by the need for large muscular effort. Typically, strength problems manifest themselves through injuries on the job. Although most of the work in this area is in the correction of existing problems (those that have resulted in injuries), there is increasing effort to design new jobs so that there are few stressful lifting situations present. The identification of such problems before an injury occurs is a good preventive measure, although it is difficult to predict all injury-prone situations with a high degree of certainty. Strength problems can be analyzed through biomechanical techniques or through the psychophysical methodologies. When a strength problem is identified, the use of strength information can help to assess the severity of the problem. The same information can help to predict the success and suitability of alternative solutions.

1.2.4 Manipulative: Kinesology

Manipulative problems are characterized as an inability to perform the fine motions required on the job or a difficulty in performing, tasks at the required speed. These problems usually show up in assembly tasks or tasks requiring fine control of dials and instruments. Assembly errors, alignment problems, and dropped pieces are the outcome of manipulative problems.

1.2.5 Environmental: External

Environmental problems are those which involve the surroundings of the worker. Heat stress, cold stress, lighting, noise, and vibration are the typical environmental problems that one will experience in the practice of industrial ergonomics. When there are problems between the person and the environment, usually some changes must be made to the environment, the work regimen must be altered, or physical training such as heat acclimatization must be introduced.

1.2.6 Cognitive problems

Cognitive problems typically show up as operating errors of some type the limits of short-term memory and the associated difficulty with long and complicated strings of numbers are common cognitive difficulties. Similarly, perceptual problems associated with vision and hearing can result in errors. When situations occur that

violate the human mind's ability to function properly, these errors can be predicted. These problems should not be confused with motivational problems, since system-induced operating errors will occur even with highly motivated workers.

1.3 ERGONOMIC RISK FACTORS

Although the causes of any particular case of musculoskeletal disorders (MSD) are exceedingly difficult to identify with complete accuracy, certain risk factors are typically discussed in the field of ergonomic studies. The primary occupational risk factors for MSD includes the following factors

- Repetition
- Force
- Mechanical stresses
- Posture
- Vibration
- Cold temperature
- Extrinsic stress

It is essential to understand just what a risk factor is, or rather is not. A risk factor itself is not necessarily a causation factor for any particular MSD. Many times, it is not simply the presence of a risk factor, but the degree to which the risk factor is expressed that may lead to MSDs. Similarly, to the extent an MSD case is attributable to a risk factor, often it will be a combination of multiple risk factors, rather than any single factor, which contributes to or causes an MSD. It is also important to note, in evaluating any particular case of an MSD, that risk factors may be experienced by the affected individual during non-occupational activities. In addressing any ergonomic issue, it would be a mistake to focus solely on the workplace. Further, not every person exposed to any or all of these risk factors will develop an MSD. Nevertheless, because these are common factors that may give rise to an MSD in some combination and in some people, these seven risk factors are discussed in greater detail below:

1.3.1 Repetitions: Repetition rate is defined as the average number of movements or exertions performed by a joint or a body link within a unit of time. Repeated identical or similar motions performed over a period of time could cause over-extension and overuse of certain muscle groups, which could lead to muscular fatigue. Interestingly, symptoms often relate not to the tendon and muscle groups involved in repetitive motions, but to the stabilizing or antagonistic tendon and muscle groups used to position and stabilize the extremity in space.

1.3.2 Force: Force is the mechanical or physical effort to accomplish a specific movement or exertion. For example, using the hands instead of a clamp to hold an object, while performing a task such as placing an interproximal composite restoration. The amount of force required by an activity can sometimes be magnified causing even more muscular fatigue.

1.3.3 Mechanical Stresses: Mechanical stresses are defined as impingement or injury by hard, sharp objects, equipment or instruments when grasping, balancing or manipulating. Mechanical stresses are encountered when working with forearms or wrists against the edge of a desk or work counter. The muscles and tendons are impinged when pressed into the sharp edge. Using the hand as a hammer to close a lid securely also creates mechanical stresses, especially if the lid has raised surfaces or sharp edges.

1.3.4 Posture: Posture is the position of a part of the body relative to an adjacent part as measured by the angle of the joint connecting them. Postural stress is 'assuming an extreme posture at or near the normal range of motion. Posture is one of the most frequently cited occupational risk factors. There is a neutral zone of movement for every articulating joint in the body. For each joint the range of motion is defined by movements that do not require high muscular force or cause undue discomfort. Injury risks increase whenever work requires a person to perform tasks with body segments outside their neutral range in a deviated posture.

1.3.5 Vibration: Vibration has been found to be an etiological factor in work environments utilizing tools vibrating in the frequency band of 20 to 80 Hz. For exp. dental hand pieces and powered automatic instruments operate at higher frequencies in the 5000 to 10,000 Hz range, and duration of exposure to vibratory force during dental procedures is relatively short. Thus, it would appear that the exposure to this risk factor in dentistry is relatively small.

1.3.6 Cold Temperature: Low temperatures reduce manual dexterity and accentuate the symptoms of nerve-end impairment.

1.3.7 Extrinsic Stress: Extrinsic stress, or sometimes called organizational factors, can be defined as the way in which work is structured, supervised and processed. Extrinsic stress reflects the objective nature of the work process. It may include such variables as job variety, job control, workload, time pressure, and financial constraints. In general manufacturing, some studies show a relationship between extrinsic stress factors and a higher incidence of MSDs.

1.4 CARDIOVASCULAR SYSTEM OF HUMAN BODY

Blood is pumped from the left ventricle of the Heart to capillaries in the periphery via the arterial vessels of the systemic (or greater) circulation and returns via the veins to the right heart. It is then expelled from the right ventricle to the lungs via the pulmonary (or lesser) circulation and returns to the left heart. The distribution of blood to the organs arranged in parallel in the systemic circulation is determined by their functional priority (vital organs) and by the current needs of the body. Maintaining adequate cerebral perfusion (approx. 13% of the resting cardiac output) is the top priority, not only because the brain is a major vital organ, but also because it is very susceptible to hypoxic damage. About 20 to 25% of the cardiac output is distributed to the kidneys. This fraction is very large relative to the kidney weight (only 0.5% of body mass). Renal blood flow is primarily used to maintain renal excretory and control functions. During strenuous physical *exercise*, the cardiac output increases and is allotted mainly to the *skeletal muscle*. During digestion, the *gastrointestinal tract* also receives a relatively high fraction of the cardiac output [11]. Naturally; both of these organ groups cannot

receive the maximum blood supply at the same time. To fully understand the cardiovascular system of human body some terms related to the human cardiovascular system are explained below.

1.4.1 Cardiac Output (CO). The cardiac output is calculated as heart rate (HR) time's stroke volume (SV). Under normal resting conditions, the CO is approx. $70 \text{ [min}^{-1}] \times 0.08 \text{ [L]} = 5.6 \text{ L/min}$ or, more precisely, a mean 3.4 L/min per m^2 body surface area. An increase in HR (up to about 180 min^{-1}) and/or SV can increase the CO to $15\text{--}20 \text{ L/min}$.

1.4.2 Cardiac Cycle: The resting heart rate is $60\text{--}80$ beats per minute. A cardiac cycle therefore takes roughly 1 s . It can be divided into four distinct phases: (I) contraction phase and (II) ejection phase, both occur in *systole*; (III) relaxation phase and filling phase (IV), both occurring in *diastole*. At the end of phase IV, the atria contracts.

1.4.3 VO2 Max: As the effort increases when someone exercise, the amount of oxygen consumed to produce energy (and hence the rate at which one exhale carbon dioxide) increases. However, there is a maximum level of oxygen consumption, beyond which increases in exercise intensity don't lead to further increases in oxygen consumption. This level of oxygen consumption is called the VO2 max. (The initials simply stand for volume of oxygen.)

VO2 max has been defined as: "***the highest rate of oxygen consumption attainable during maximal or exhaustive exercise***" It is measured in milliliters per kilogram of body weight per minute (ml/kg/min). As exercise intensity increases so does oxygen consumption. However, a point is reached where exercise intensity can continue to increase without the associated rise in oxygen consumption. It is generally considered the best indicator of cardio respiratory endurance and aerobic fitness. Aerobic power, aerobic capacity and maximal oxygen uptake are all terms used interchangeably with VO2 max. VO2 max is usually expressed relative to bodyweight because oxygen and energy needs differ relative to size. At this point the volume of oxygen inhaled is equal to the volume of oxygen exhaled.

1.4.4 Resting Metabolic Rate: Resting metabolic rate (RMR) is the energy required to perform vital body functions such as respiration and heart rate while the body is at rest. About 50 to 75% of one's daily energy expenditure can be attributed to resting metabolic rate. The Metabolic Equivalent of Task (*MET*), or simply Metabolic Equivalent, is a physiological concept expressing the energy cost of physical activities as multiples of Resting Metabolic Rate (RMR) and is defined as the ratio of metabolic rate (and therefore the rate of energy consumption) during a specific physical activity to a reference rate of metabolic rate at rest, set by convention to $3.5 \text{ ml O}_2 \cdot \text{kg}^{-1} \text{ min}^{-1}$ or equivalently $1 \text{ kcal (or 4.184 kJ) } \cdot \text{kg}^{-1} \text{ hr}^{-1}$. By convention 1 MET is considered as the resting metabolic rate obtained during quiet sitting. MET values of physical activities range from 0.9 (sleeping) to 18 (running at 17.5 km/h).

One MET is equal to 50 kcal per hour per square meter of body surface of a resting individual. Unit of measurement of heat production by the body; 1 MET = 50 kcal/hour/m² body surface area.

1.4 ORGANISATION OF THE THESIS

The thesis has been divided into six chapters. Brief description of the contents of each chapter is as under:

Chapter 1 introduces the manual material handling systems and explains the type of problems encountered in the implementation of ergonomics. Ergonomic risk factors and the cardiovascular system of the human body have been discussed in this chapter.

Chapter 2 covers an extensive literature review on the topic and its related areas. Also, summary of the thesis and problem formulation has been discussed

Literature review has been divided into the following categories:

1. Manual Material Handling
2. Lifting Task
3. Lifting and Carrying Task
4. Analysis Using NIOSH lifting Equation.

Chapter 3 discusses the design of the study, its phases and procedural steps. A brief description of the methodology, tools and techniques used have been covered in this chapter.

Chapter 4 presents the analysis and results of the oxygen uptake. Results after Analysis of Variance (ANOVA) and Taguchi signal-to-noise ratio are outlined in this chapter. Main effects and interaction plots for oxygen uptake are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 5 presents the analysis and results of the heart rate. Results after Analysis of Variance (ANOVA) and Taguchi signal-to-noise ratio are outlined in this chapter. Main effects and interaction plots for heart rate are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 6 covers the empirical modeling carried out as an outcome of the analysis. Detailed multiple regression analysis have been discussed in this chapter. Predictors equations have been generated for the heart rate and oxygen uptake and explained in this chapter.

Chapter 7 explains the results, conclusion and recommendations from the experimental work. Scope of future work has also been discussed in this chapter.

One last section of this thesis lists the complete references used in this work.

CHAPTER 2

LITERATURE REVIEW

2.1 REVIEW OF LITERATURE

Ergonomics is now being recognized as a separate and vital subject in industrial working. It has a very wide domain ranging from physical factors like measurements to physiological, psychological and finally the human-human interactions. Each one of these areas has become a separate branch of study. Work is being done in all these areas. In India, however, very limited research is being carried out.

2.2 CATEGORISATION OF LITERATURE REVIEW

The review of literature has been divided into following categories:

- 1).Manual Material Handling
- 2).Lifting Tasks
- 3).Lifting and Carrying Tasks
- 4).Analysis Using NIOSH lifting Equation

2.2.1 Manual Material Handling

The emphasis on ergonomics in manual material handling (MMH) tasks arises from the potential risks of workplace accidents and injuries. The tasks include diverse activities such as lifting, lowering, holding, pushing, pulling, carrying, and turning of weights.

Lariviere Christian [12] evaluated if chronic low back pain patients performed manual material handling tasks differently from control subjects. A 12-kg box was lifted (freestyle) from the floor to the hips (1) in front (symmetric task) or (2) to a shelf located at 90 degree on the right (asymmetric task) and was lowered back to the floor. A 3D biomechanical analysis involving the assessment of L5/S1 loading, posture of segments, inertial parameters, and EMG was performed. There was no difference between the groups for postural (trunk and lower limb angles), inertial (trunk velocity and acceleration), and L5/S1 loading (moments and compression) variables. The patients showed abnormally low left lumbar erector spine (symmetric task, lowering) or high left thoracic erector spine (all tasks) EMG activation.

D. Imbeau [13] carried out an ergonomic study to better understand impact of stock management practices on manual material handling practices in two warehouse superstores leading. Results indicate that an imbalance between the amount of stock and the available storage space results in three types of consequences:

- (1) Risk factors related to the development of musculoskeletal disorders
- (2) Increased risks of accidents, particularly related to loss of balance and falls from heights.
- (3) Impacts on productivity and quality of service offered to customers in the form of time wasted, stock losses and customer dissatisfaction.

G. Cooper [14] has performed detailed analysis of the loads applied by the ambulance workers when loading/unloading ambulance stretchers. Cooper measured the forces required of the ambulance workers for each system using a load cell in a force handle arrangement and performed the kinetic analysis of each stretcher loading system. The postures and forces exerted by the ambulance workers were analyzed using biomechanical assessment software to examine if the workloads at any stage of the process are harmful. Comparison of the kinetic analysis and measurements shows very close agreement for most of the cases. The force analysis results were evaluated against derived failure criteria. The evaluation was extended to a biomechanical failure analysis of the ambulance worker's lower back using 3DSSPP software developed at the Centre for Ergonomics at the University of Michigan. The critical tasks of each ambulance worker during the loading and unloading operations for each system were identified and design recommendations to reduce the forces exerted based on loading requirements from the kinetic analysis were given.

Fadi A. Fathallah [15] studied the belt system, (GRIPSystem™) which has been developed to assist movers who operate in pairs while lifting heavy and awkward furniture. He evaluated the effectiveness of this manual device in reducing key low back disorders risk factors. The participants lifted three household furniture items, at three varied weights, with and without the lifting device, while trunk kinematics and 10 muscle EMG signals were recorded. The results showed the device significantly lowered

the kinematics and muscle activity of the lower back, as well as the risk of LBDs. Other potential benefits of the device were discussed. Further studies to confirm the device's effectiveness in reducing LBDs in the moving industry has been emphasized

Fredericks K Tycho [16] conducted a study of a simulated metal pouring operation commonly found in small foundries based on activities. Two laboratory experiments were conducted to evaluate two objectives: (1) to study the effects of different mold heights and carrying distances on physiological responses, and (2) to determine maximum acceptable task frequencies (MAF) for metal pouring. Both objective and subjective measures were used in the study. The objective measures included oxygen uptake, heart rate, and blood pressure while subjective measures included ratings of perceived exertion. Ten healthy males served as participants for these experiments. Results indicated that carrying distance had a significant effect on both heart rate and oxygen consumption. Results also indicated that the participants selected a MAF which was as much as 25% lower than the expectations present at the foundry on which this experiment was modeled.

John Rasmussen [17] showed in computational investigations that seat pan inclination and friction coefficient have a complex combined influence on muscle activity and spinal joint forces. Forward seat pan inclination appears to cause muscle fatigue unless sufficient friction is present, and in this case loses much of its beneficial effect for the spinal joint loads and leads to tissue shear forces that may be uncomfortable or even harmful.

Marc Grasmueck [18] studied that age of the assembly workers influences the choice of workplace. He found that older worker should be mainly in jobs with a 'very favorable' expert rating, younger workers in jobs with '(very) unfavorable' ratings. Accordingly, age and job strain in this case were not independent variables. Older workers still complain of lumbar spine symptoms despite low demands imposed by their present jobs. This seems to indicate long-term cumulative effects. Head-neck-shoulder symptoms occur more frequently in older workers working under unfavorable

conditions. Symptoms affecting the head–neck–shoulder region, the lumbar spine and the upper limbs were co-variable with body height and body mass index.

Ajay Baatish, Tejinder. P. Singh [19] described an assessment tool for analysing material handling tasks and its application for material handling tasks prevalent in engine bearing industry. After a close observation of material handling tasks spread over many days, a list of tasks and parameters/variables affecting those tasks was made. Ergonomic conditions present in these tasks and their deficiencies were then identified and on the basis of the relationships between the tasks and their affinities, categories were developed. Using the data of those categories and various conditions and parameters, an assessment tool called MHAC (material handling assessment chart) was developed.

Li Way Kai, Gao Yang [20] studied combined manual materials handling (MMH) tasks, under two different frequencies and four lifting and lowering height combinations, in Beijing, China. Eight male construction workers performed a box handling task repetitively for an hour either at once or twice per minute. On each day, the task consisted of: lifting a box of ceramic tile weighting 23 kg from a specified height, carrying it for 8.5 m, lowering the box to a specified height, and then walking 8.5 m back. The specific heights included: lifting the box from floor and lowering it onto the floor (F–F); lifting from the floor and lowering to the knuckle height (F–K); lifting from knuckle height and lowering onto the floor (K–F); and lifting from knuckle height and lowering to the knuckle height (K–K). Oxygen uptake, heart rate, and ratings of perceived exertion (RPE) for whole body were measured during the task. Additionally, actual energy expenditure of the box handling for an hour was calculated from the oxygen uptake measured, whereas the predicted energy expenditure was estimated using the valid regression equations available in the literature. Statistical analysis demonstrated that both task frequency and lifting and lowering heights influence oxygen uptake, heart rate, and the RPE ($p < 0.05$). The RPE during the task frequency of twice per minute was higher than that of once per minute. The RPE for the F–F and F–K conditions were both higher than that of the K–K condition. The difference between the actual and predicted energy expenditures was not statistically significant.

2.2.2 Lifting and Lowering Tasks

Ekholm Jan [21] investigated the muscular load on the ankle and knee in 72 different packing work postures. The principle used was as follows; if the load moment about a joint is divided by the counteracting maximum muscular moment, a muscular strength utilization ratio (MUR) was obtained. The MUR was calculated for a large, an average-sized and a small man depending on whether they were all either strong, of mean strength, or weak, thus giving nine MUR values for each posture.

M M. Ayoub [22] presented a two dimensional whole-body lifting simulation model. The simulation models contain three major computation units: trajectory formulation, dynamics of motion unit, and nonlinear optimization unit. Kinematic and kinetics are calculated in the dynamics unit. Objective and constraint functions are evaluated in the optimization unit. Optimal motions are generated by minimizing the objective function, subject to the constraints. Human motion simulation allows generation of dynamic human motions on computers. Biomechanical stresses can be estimated using the motions generated on a computer without actually collecting joint coordinate data. The model assumes that humans perform lifting activities based on minimization of physical work, subject to various constraints.

J Kollmitzer [23] investigated effects of stance condition on postural control during lifting. Any voluntary motion of the body causes an internal perturbation of balance. Nineteen healthy subjects repeatedly lifted and lowered a load between a desk and a shelf. The base of support was varied between parallel and step stance. Ground reaction force and segmental kinematics were measured. In parallel stance postural response consisted of axial movements in the sagittal plane. Such strategy was accompanied by increased posterior shear forces after lift-off. Lifting in step stance provided extended support in anterior/posterior direction. The postural control mechanisms in the sagittal plane are less complex as compared to parallel stance. However, lifting in step stance was asymmetrical and thus accompanied by distinct lateral transfer of the body. Lateral shear forces were larger as compared to parallel stance. Both lifting techniques exhibit positive and negative aspects. We cannot recommend either one as being better in terms of postural control.

Lee Tzu Hsien [24] conducted a laboratory study to determine the minimal acceptable handling time interval (MAHTI) for 4 h of endurance manual materials handling tasks using a psychophysical approach. Nine experienced male subjects were recruited to perform manual materials handling tasks with three load weights (10, 15, and 20 kg) and six ranges (floor to knuckle, FK; knuckle to floor, KF; knuckle to shoulder, KS; shoulder to knuckle, SK; floor to shoulder, FS; shoulder to floor, SF). Subjects were asked to adjust the handling time interval to the minimum that they could perform without becoming strained, uncomfortable, tired, weakened, overheated, or out-of-breath for 4 h of the endurance handling period. The results showed that the heavier load produced a large MAHTI, and the overall descending sequence of MAHTI values for the six ranges was FS, KS, SF, FK, KF, and SK. The MAHTI for each lifting task was significantly higher than that of its corresponding lowering task ($p < 0.05$). All MAHTI data were further verified by tests run on an additional nine subjects; this showed that the psychophysically determined MAHTIs were appropriate with no apparent underestimation.

Lilli Kirkeskov Jensen [25] measured the effect of a participatory ergonomics implementation strategy consisting of information, education, and facilitation on the use of new tools and working methods in the floor laying trade. There was a reduction in the degree of self reported pain in the knees among the floor layers using the new working methods weekly or daily compared to those using them never or occasionally. The musculoskeletal complaints did not increase from any other region and the quality and the productivity of the work were not decreased.

Allan Wrigley [8] demonstrated the ability of principal component analysis to identify differences in lifting technique. Principal component analysis was applied to sixteen kinematic and kinetic waveforms describing the two-dimensional motion of the trunk and load. The principal component scores for each variable were used as the dependent measures in a one-way ANOVA to determine group differences. Significant group differences ($p < 0.05$) were found for five of the principal component scores capturing associated kinematic waveform patterns related to the control and placement of the box on the shelf, and associated kinetic waveform patterns related to the relative timing of

extension moment generation in the sacral and thoracic regions. Principal component analysis was able to identify important biomechanical differences where traditional analysis failed.

Gwanseob shin [26] examined the responses in trunk kinematics and ground reaction forces of older and younger subjects during lifting. Age-related changes in trunk kinematics in lifting have received little attention despite a documented increased risk of musculoskeletal injury with age. A lumbar motion monitor was used to measure the subjects' trunk kinematics and a force platform was used to measure the ground reaction forces during the lifting motion. The results of this study showed that age had a significant ($p < 0.05$) effect on the transverse plane (axial twisting) trunk kinematics variables (peak velocity and peak acceleration) but did not affect ground reaction forces or other trunk kinematics variables.

Ciriello Vincent M. [27] studied the effects of high frequency (20 lifts/min) on MAWs (maximum acceptable weights) of lifting. The results confirmed that MAWs of lifting with the large box was significantly affected by frequency. The effects of lifting with an extended horizontal reach decreased MAW 22% and 18% for the mid and center lift and the effects of the 20 lifts/min frequency resulted in a MAW that was 47% of a 1 lift/min MAW. Incorporating these results in future guidelines should improve the design of MMH tasks for female workers.

Hagins. Marshaal [28] studied that anecdotal evidence suggests that people hold their breath during lifting tasks in order to increase intra abdominal pressure (IAP) and thereby increase lumbar stability. Moreover, Studies have shown that voluntary control of the breath influences IAP and that increases in IAP are related to increases in lumbar stability. He enrolled 20 healthy subjects to describe inspired volume and categories of airflow direction (inspiration, expiration, or breath hold) during two self-paced lifts of crates loaded at 5, 15, and 25% of body weight. When the breath pattern was examined across all loads there was a significant increase in the magnitude of inspired volume and the frequency of occurrence of inspiration immediately prior to lift-off. When examining the effect of load on breath patterns, there was a significant increase of inspired volume

and occurrence of breath holding when lifting the heavy load compared to the medium and light loads. His results suggested that: (1) distinct patterns of natural breath control occur during lifting tasks; and (2) breath control is responsive to the timing and magnitude of load lifted.

Reiser Raoul [29] has determined the effects of lifting from a sloped floor surface (both facing up and down) on the lumbar region and compare with the level surface. Secured in a milk crate, the men lifted 25 kg while the women lifted 15 kg. A top-down inverse-dynamics model calculated the net moment at L5/S1. Subject-selected foot placement relative to the crate was significantly affected by lifting condition ($p < 0.001$) with subjects tending to stand further from the load as slope changed from downhill to uphill. Maximum L5/S1 moments were not affected by lifting condition ($p = 0.330$). However, the static contribution from mass location significantly increased when facing up hill ($p < 0.001$).

Cirillo Vincent. M [30] investigated the effects of a back belt with maximum resistance to the circumferential expansion on psychophysically determined maximum acceptable weights (MAWs) and forces (MAFs) for a variety of lifting, lowering, pushing, pulling, and carrying tasks. A psychophysical methodology was used whereby the subjects were asked to select a workload they could sustain for eight hours without “straining themselves or without becoming unusually tired, weakened, overheated or out of breath.” The results revealed that the MAWs and MAFs of all tasks performed by women and all but one MAF of one task performed by men were not significantly affected by the back belt use. Based on these results, the use of a back belt did not change the perception of the subject’s physical demands of the task since they chose similar psychophysically acceptable loads.

2.2.3 Lifting and Carrying Tasks

Andre Plamondona [31] presented a study on “In-the-hole (ITH) drilling” a heavy repetitive mining task, which has been identified as having a relatively high incidence and severity rate of musculoskeletal injuries. The purpose of this study was to examine how the load experienced by ITH drill operators changed when lifting a vertical drilling

rod (1.61 m, 35 kg) using two rod heights and four different foot positions. It was found that the vertical height of the rod had the most significant impact on back loading, while the effect of the initial foot positioning relative to the rod was limited by the technique adopted by the drillers. Moreover, it was found that some of the subjects used techniques less strenuous for the back than others. Finally, the asymmetrical lifting component was found to be the most negative aspect of lifting an ITH drill rod compared to a standard symmetrical lift (NIOSH).

Ciriello Vincent [4] investigated maximum acceptable initial and sustained forces while performing a 7.6m pushing task at a frequency of 1 per minute on a magnetic particle brake treadmill versus pushing on a high-inertia pushcart. The results revealed that the maximum acceptable sustained forces of pushing determined on the high inertia cart were significantly higher (21%) than the forces determined from the magnetic particle brake treadmill. These results were countered by an 18% decrease in maximum acceptable forces for the criterion magnetic particle brake treadmill task, perhaps due to secular changes in the industrial population.

Chung .K. Min., Lee. J. Yui [32]. Investigated the physiological workload involved in backpack-mode carrying, especially focusing on the effects of load weight and stairway transport. In South Korea Food Industry the deliveries of a broad line of soft drink products involved the use of a hand truck and, in many cases, a backpack mode of carriage. To measure heart rate and oxygen uptake while carrying on the back, a laboratory experiment was conducted and safety guidelines for such tasks were proposed, based on the experimental results. Eight healthy male subjects performed backpack-mode carrying, weight between 40 and 60 kg: (1) on level ground, (2) upstairs and (3) downstairs. The results showed that stairways involved an increased physiological burden, and that a load of 60 kg entailed a significantly higher physiological cost than carrying a load of 40 kg. Although backpack-mode carrying has some biomechanical advantages, the worker should be advised to carry a load of less than 40 kg, to avoid a high physiological load. During backpack-mode carrying, it is also recommended that a delivery person makes more trips with a light load rather than fewer trips with a heavier load per trip.

Swei-Pi Wu [33] examined the effects of container width, carrying rate, and distance on the maximum acceptable weight carried (MAWC) and the resulting responses (heart rate and rating of perceived exertion) to a 1-h work period of carrying tasks. The results obtained lead to the conclusions; the container width significantly affected the MAWC, heart rates and overall RPE values. Although the heart rates increased with the container width, the MAWC and the overall RPE values did not decrease with the container width.

Wilson, S.E [34] described two regions of spine motion, a neutral zone where lumbar rotation can occur with little resistance and an elastic zone where structures such as ligaments, facet joints and intervertebral disks resist rotation. In vivo, the passive musculature can contribute to further limiting the functional neutral range of lumbar motion. Movement out of this functional neutral range could potentially put greater loads on these structures. In this study, the range of lumbar curvature rotation was examined in twelve healthy, untrained volunteers at four torso inclination angles. The lumbar curvature during straight-leg lifting tasks was then defined as a percentage of this range of possible lumbar curvatures. Subjects were found to remain neutrally oriented during the flexion phase of a lifting task.

Liang Ma [35] analyzed that when three axial (isometric) complex moments were applied, ‘extension + lateral bending right + twisting counter-clockwise’ induced high co activation of about 349N (about 50% of the total muscle force), and the magnitude of the antagonistic moment was 21.9Nm (about 41% of the external moment). He suggested that results from his study will be useful for diagnostic, preventive, and rehabilitative purposes in the analysis of manual materials handling tasks.

M. Raison [36] developed a human body model that permitted a non-invasive determination of the joint efforts produced by a seated subject performing maximum ramp pushing efforts. The joint interactions during these experiments were provided by a dynamic inverse model of the human body, using symbolically generated recursive Newton–Euler formalism. The theoretical investigation was presented in two steps, with increasing complexity and relevance:

1. Quasi-static analysis: this approximates internal joint efforts, using static equations at each sample, without taking the postural chain dynamic effects into account.
2. Dynamic analysis: this takes the dynamic effects into consideration and thus presents the advantage of a more relevant description of the motion as well as a more accurate determination of the forces and torques produced at each joint during the transient effort.

Liu Bor-Shong [37] suggested that the effect of walking speed was strongly significant for all physiological indices (MANOVA results). In addition, there was a significant interaction between load position and walking grade on oxygen consumption. However, carrying heavy loads close to the trunk can affect lung function. Thus, load placement is an important factor in physiological response to load carriage, and optimum choice of upper or lower position when distributing items in a backpack may be dependent on the walking grade.

Hoozemans Marco [38] quantified the relative effect of the magnitude and direction of the exerted push force and of trunk inclination on the mechanical load at the low back using a regression analysis for correlated data. He showed that the magnitude and direction of the exerted push force and the trunk inclination significantly and independently affect low back load. It was concluded that for the ergonomic evaluation of pushing tasks, the inclination of the trunk should be considered, in addition to the magnitude and direction of exerted forces.

E. Pennestri [39] presented a musculo-skeletal model of the upper limb. The limb is modeled as a three-dimensional 7 degrees-of freedom system, linked to the shoulder, which has been considered as frame. The upper limb model is made up of four links corresponding to the most important body segments: the humerus, the ulna, the radius and the hand, considered as a single rigid body. Particular attention has been paid to the modeling of joints in order to mimic all the possible arm and forearm movements (including pronation-supination). The model also includes 24 muscles. The kinematic analysis has been performed including an ergonomics index to take into account the posture and joint physical limits. Moreover an optimization criterion based on minimum activation pattern has been included in order to find muscular activation coefficients. The results of the proposed methodology concerning muscular activations have been

compared to those coming from processed EMG signals, which have been acquired during experimental tests.

2.2.4 Analysis of Lifting Tasks using NIOSH Lifting Equation

The National Institute for Occupational Safety and Health (NIOSH) developed a lifting equation in 1981 to indicate “safe” occupational lifting limits [40]. This equation was revised in 1991. The equation uses a series of lifting multipliers (parameters) to calculate corresponding recommended task weight limits. Due to the nature of risk factor interactions, the limits obtained from the NIOSH equation may not be appropriate for all lifting tasks.

Kwan S. Lee [41] examined whether the revised weight limit recommended by the U.S. NIOSH can be used for Korean workers. The psychophysical experiment and the validation experiment in sagittal plane where lifting frequency and lifting height varied was performed. Young male college students and field workers participated in the experiment. The load constant obtained in this investigation was about the same as the one recommended in the NIOSH equation, which means that young, healthy, Korean males are well protected by the NIOSH equation.

Peter Vink [42] compared the results of the NIOSH, ACGIH TLV, Snook, 3DSSPP and WA L&I lifting assessment instruments when applied to a uniform task (lifting and lowering milk cases with different capacities). The reasons for instrument differences are presented so that practitioners can better select the methods they need and interpret the results appropriately.

Saurin Tarcisio Abreu [43] presented an ergonomic assessment on the operation of two types of suspended scaffolds (traumatic type injuries). They are referred to as light scaffold and heavy scaffold—the difference lying in their dimensions a number of gears. The assessment criteria were: workers’ perceptions of effort; body posture assessment (OWAS method); heart rate elevations (HRE); percentage of the available heart rate range (PHRR); scaffolds’ speed and, repetitiveness of movement in the scaffolds’ levers. For instance, HRE was 52 beats per minute (bpm) and PHRR was 50.7% on average for workers operating the light scaffold. Concerning the heavy scaffold, HRE was 45 bpm

and PHRR was 42.2% on average. All of those values are substantially higher than the acceptable limits of 35 bpm for HRE and 33% for PHRR proposed in the literature. Failures in the scaffolds' design as well as the lack of attention directed towards ergonomics in regulations were determined to be relevant root causes for detected poor working conditions.

Tapan Bagchi [44] examined the effect of lifting parameters and their interactions as follows: lifting frequency, vertical lifting distance, and load weight. The recorded working heart rates were normalized based on the maximum heart rate obtained during maximum aerobic power measurement. MANOVA result showed that the main effects were significantly ($p < 0.0001$) related with normalized working heart rate and the interaction effects of different lifting parameters contributed 10.01% of total variance of normalized working heart rate and concluded that the interaction effects between different lifting parameters must be considered in addition to the effects of individual lifting parameters for further research.

T.Jones [45] compared and examined some facts:

- (1) Compared the results of 5 ergonomic risk assessment methods calculated with quantified physical exposure information,
- (2) Examined the effect of multiple definitions of the posture and exertion variable on the risk assessment methods,
- (3) described the variability in risk assessment scores between workers,
- (4) Examined the ability of risk assessment component scores to differentiate between facilities with significantly different levels of exposure, and
- (5) Examined the association between risk output and recorded incidence rates.
- (6) Quantified physical exposure information was used to calculate the RULA, REBA, ACGIH TLV, Strain Index and OCRA procedures based on multiple posture and exertion variable definitions. Posture and exertion variable definition was observed to have a significant effect on the component scores and/or risk output of all methods assessed. Meaningful variability in risk assessment scores was observed between workers. Components of all assessments, with the exception of the ACGIH TLV, differentiated between facilities assessed. Average risk index scores of the SI and OCRA

procedures were observed to increase as recorded incidence of injury increased; however statistical significance was not demonstrated.

2.3 SUMMARY OF THE LITERATURE REVIEW

Manual material handling (MMH) work contributes to a large percentage of the over half a million cases of musculoskeletal disorders reported annually in the United States. Musculoskeletal disorders often involve strains and sprains to the lower back, shoulders, and upper limbs. Many researchers [12], [32], [34], [38] have studied the lifting and manual material handling tasks to analyze affect of loading on back (L5/S1) which is the major reason of the MSD's. Also, some research [14] has been conducted to determine the effects of lifting from a sloped floor surface (both facing up and down) on the lumbar region and its comparison with the level surface.

Some studies have been [16] conducted to measure simulated metal pouring operation commonly found in small foundries and measured oxygen uptake, heart rate, and blood pressure of workers during manual material handling tasks. Some studies [20] have been conducted to analyze combined manual materials handling tasks to measure oxygen uptake and heart rate.

Many researchers [5], [15] have pointed that in NIOSH lifting equation the interaction effect of different multipliers calculated in multiplicative manner might not be appropriate for all lifting tasks to indicate the associated risk factors due to various kinds of interactions associated among risk factors. Studies [44] have been conducted to examine the effect of lifting parameters and their interactions and it has been concluded that the interaction effects between different lifting parameters must be considered in addition to the effects of individual lifting parameters for further research.

The literature emphases to study further interaction affects of various lifting parameters given in NIOSH equation. Also NIOSH guidelines could not account the biomechanical spinal loading for low-lying object lifting, which was better fitted with consideration of interaction effects. Oxygen uptake during various material handling tasks has been measured by some researchers. But very little literature is available on cardiopulmonary response measurement of Indian male workers during MMH tasks. As the physiological characteristics and body metabolism of Indian male workers is different as compared to

other countries. Moreover due to different environmental conditions in India the work stresses involved in lifting tasks are very demanding.

2.4 PROBLEM FORMULATION

The National Institute for Occupational Safety and Health (NIOSH) developed a lifting equation in 1981 (Revised in 1991) to indicate “safe” occupational lifting limits. The equation uses a series of lifting multipliers (parameters) to calculate corresponding recommended task weight limits. In the present work, the interactions effect of lifting parameters has been studied by using a parameterization approach to measure the effect of interaction between factors. Therefore the purpose of the study is to evaluate the main effects of load weight, frequency of lift, vertical distance of lift, horizontal distance from lift and operator and their interactions during lifting operations by using factorial analysis of variance. The effect has been studied on pulmonary oxygen uptake and heart rate of workers involved in continuous lifting tasks. This factor approach has been used to study the effects of various factors at appropriate levels and their interactions among variables. Plots of significant factors, S/N ratio and empirical modeling have been used to determine the best-fit relationship between the response and the model parameters.

3.1 METHODOLOGY

The experimental analysis was conducted using the design of experiments techniques. Although full factorial designs could be used wherein all the possible combinations could be tested, yet fractional factorial analysis methods have been implemented for this experimental work. The Taguchi method has been used to overcome the limitations of full factorial analysis by simplifying and standardizing the fractional factorial design [46]. The effect of various lifting parameters and their interactions were studied using a parameterization approach developed by Taguchi.

3.2 PROCEDURES OF TAGUCHI METHOD

The brief procedure of Taguchi method is as under:

- Establishment of objective function
- Selection of factors and/or interactions to be evaluated
- Identification of uncontrollable factors and test conditions
- Selection of number of levels for the controllable and uncontrollable factors
- Selection of the appropriate orthogonal array (OA)
- Assignment of factors and/or interactions to columns
- Execution of experiments according to trial conditions in the array
- Analyze results
- Confirmation experiment

3.3 ESTABLISHMENT OF OBJECTIVE FUNCTION

The objective of the study is to evaluate the main effects of load weight, frequency of lift, vertical distance of lift, horizontal distance from lift and operator and their interactions during lifting operations to exert the lowest stress on the workmen to minimize the risk of subsidence. The stress state of the workmen heart rate and pulmonary oxygen uptake were used as output for fractional factorial experimental analysis to describe such tasks.

3.4 DESIGN OF EXPERIMENTS AND SELECTION OF ORTHOGONAL ARRAY SYSTEM

Degrees of Freedom

A degree of freedom in a statistical sense is associated with each piece of information that is estimated from the data. Degree of freedom is a very important value because it determines the minimum number of treatment conditions. It is equal to the sum of:

(Number of levels-1) for each factor

(Number of levels-1) × (Number of level-1) for each interaction

At least seven treatment conditions are needed for two levels, and 17 conditions are needed for three level. The maximum degree of freedom is equal to $df = l^f$

Where l = number of levels

f = number of factors

Factor of interest and their levels

Using cause and effect analysis the factors which may affect the response parameters (heart rate, pulmonary oxygen uptake) with their levels were identified. Some factors like nature of grip, asymmetric angle, origin of lifting were kept constant during the experimental study. The lists of factors studied with their levels are shown in the Table 3.1. In this study the operator was subject who performed the lifting tasks.

Table 3.1: Factor interested and their Levels

FACTORS	LEVELS		
	Level-1	Level-2	Level-3
Horizontal distance (cm), <i>A</i>	25	40	55
Load weight(kg), <i>B</i>	13	18	23
Lifting frequency(lifts/min), <i>C</i>	3	5	7
Operator, <i>D</i>	1	2	3
Vertical distance(cm), <i>E</i>	Knee (55 cm)	Waist (100 cm)	Shoulder (150 cm)

Apart from the individual affect of all these factors some of the interactions between the main factors were also studied. These interactions were:

- Load weight vs. Lifting frequency, $B \times C$
- Load weight vs. Vertical distance, $B \times E$
- Frequency vs. Vertical distance, $C \times E$

The minimum required degrees of freedom in the experiment are the sum of all the degrees of freedom of factors and interactions. In the present experimental setup, there are three levels for all five factors. The number of degree of freedom associated with these five factors and three two-level interactions are 22 as shown in Table 3.2. As the degrees of freedom required for the experiment is 22, the orthogonal array to be selected should have more than 22 degrees of freedom. The most suitable orthogonal array that can be used for this experiment is L_{27} , which has 26 degrees of freedom assigned to its various columns. The remaining four degree of freedom were used to measure error contribution

Table 3.2: Degrees of Freedom

Factor	A	B	C	D	E	B x C	B x E	C x E	Total
Degree of Freedom	2	2	2	2	2	$2 \times 2 = 4$	$2 \times 2 = 4$	$2 \times 2 = 4$	22

3.5 ORTHOGONAL ARRAY

Taguchi's orthogonal arrays are experimental designs that usually require only a fraction of the full factorial combinations. The arrays are designed to handle as many factors as possible in a certain number of runs compared to those dictated by full factorial design. The columns of the arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occur same number of times. Orthogonal designs allow estimating the effect of each factor on the response independently of all other factors. Once the degrees of freedom are known, the next step, selecting the orthogonal array (OA) is easy. The number of treatment conditions is equal to the number of rows in the orthogonal array and it must be equal to or greater than the degrees of freedom. In this

experiment, the assignment of factors and interactions was carried out using MINITAB. The treatment conditions as suggested by MINITAB using Taguchi Linear Graphs and triangular tables for this particular experiment are listed in Table 3.3. In 5th column the names of operators participated in the study are given. The linear graph used for assignment of factors in L_{27} array is shown in Figure 3.1. The L_{27} array has 13 columns and each column has two degrees of freedom associated with it. Since interactions degrees of freedom are multiplication of the degrees of freedom of interacting factors, each two factor interaction has 4 degrees of freedom. So for this reason two columns of L_{27} array have been merged to assign interaction. In the linear graph, each vertex of the triangle represents a column in L_{27} array. Factor B has been assigned to column 1, factor C has been assigned to column 2 and factor E to column 5. Each connecting line of the triangle represents interaction and also the column merged for the purpose. Column 3 and 4 were merged to measure the interaction of factor $B \times C$, column 6 and 7 and column 8 and 11 were merged to measure the interaction of factor $B \times E$ and $C \times E$ respectively. The remaining factors A and D were assigned to column 9 and column 10 respectively. The unassigned columns were used to measure the error contribution.

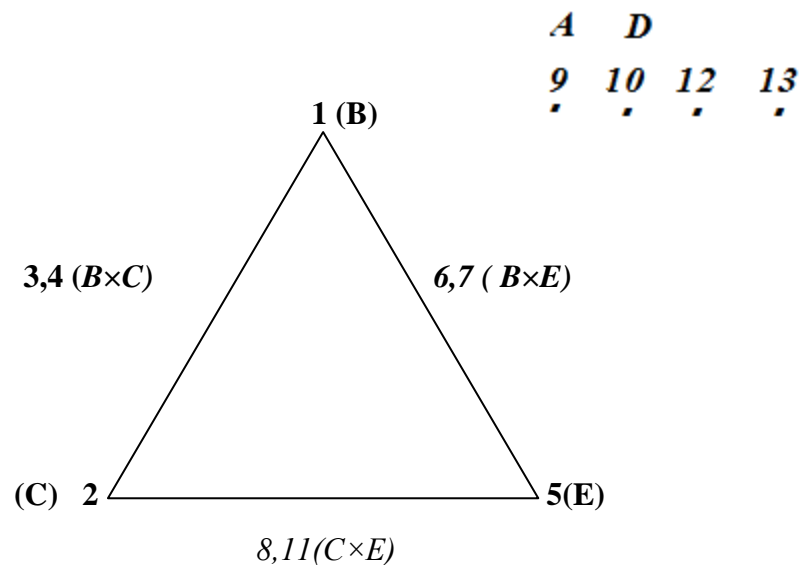


Figure 3.1: L27 Linear Graph

Table 3.3: L27 Experimental Design

Trial no.	Horizontal distance (cm)	Weight (cm)	Frequency (lifts/min)	Operator	Vertical distance (cm)
1	25	13	3	Dharampal	55
2	25	13	5	Jaswinder	100
3	25	13	7	Amit	150
4	40	18	3	Dharampal	100
5	40	18	5	Jaswinder	150
6	40	18	7	Amit	55
7	55	23	3	Dharampal	150
8	55	23	5	Jaswinder	55
9	55	23	7	Amit	100
10	40	23	3	Amit	55
11	40	23	5	Dharampal	100
12	40	23	7	Jaswinder	150
13	55	13	3	Amit	100
14	55	13	5	Dharampal	150
15	55	13	7	Jaswinder	55
16	25	18	3	Amit	150
17	25	18	5	Dharampal	55
18	25	18	7	Jaswinder	100
19	55	18	3	Jaswinder	55
20	55	18	5	Amit	100
21	55	18	7	Dharampal	150
22	25	23	3	Jaswinder	100
23	25	23	5	Amit	150
24	25	23	7	Dharampal	55
25	40	13	3	Jaswinder	150
26	40	13	5	Amit	55
27	40	13	7	Dharampal	100

3.6 EXPERIMENTAL DETAILS

Three male workers, having at-least seven years of working experience in an engineering workshop participated in laboratory simulation study. They were selected as they were not having any history of chronic or acute illness, hypertension or any other major health issues, and were not under any prescribed medication. The subjects were selected from the same age-group with almost same kind of daily work stress. A complete medical and physical check-up of the subjects was carried out. Resting metabolic rate of all the three subjects was measured to ensure that no one is having very high or very low metabolism.

The resting metabolic values were recorded on the same equipment on which the responses were measured. The demographic details of the subjects are given in the Table 3.4. The subjects were instructed not to take any stimulant for at-least 2 hours prior to the study and also throughout the experiment. The subjects were clothed in their traditional dress as they regularly do in their place of work.

3.7 EXPERIMENTAL SET UP

The effect of four different lifting parameters (horizontal distance, load weight, frequency of lift, and vertical distance of lift) and the effect of operator were analyzed using the *L27* Taguchi orthogonal design in the laboratory simulation study. Each factor was varied at three levels with horizontal distance (25cm, 40cm, 55cm), load weight (13kg, 18kg, 23 kg), vertical distance (knee=55cm, waist=100cm, shoulder=150 cm), lifting frequency (3lifts/min, 5lifts/min, 7 lifts/min) and operator (I,II and III). Each subject carried out asymmetrical lifting of load from the ground position for all trial conditions. The rectangular shaped container (16”×10”) made of Galvanized steel was used for lifting. A mixture of sand and student test jobs used in the University Workshop was used as the load material for this experiment. Each operator carried out lifting as per the requirements of the treatment conditions for the period of 20 minutes. At least one hour break was given between the experiments to fully recover from the fatigue stresses. The experiments were conducted in the Industrial Engineering laboratory of Thapar University. The heart rate (beats/min) and the pulmonary oxygen uptake (ml/min/kg) by the body were considered as the principal response parameters. Two repetitions for each of the 27 experiments were performed to calculate the signal to noise ratio using Taguchi design.

Table 3.4: Demographic Details of the Subjects

Subject	Age (years)	Height (cm)	RMR (resting metabolic rate) Kcal/day
1	32	175	1765
2	29	172	1832
3	34	168	1790
Mean	31.6	171.6	1795.6

3.8 MEASUREMENT APPARATUS

The heart rate and the oxygen uptake were measured using the *Cosmed pulmonary function equipment*. It measured the responses simultaneously. It produces two curves one for heart rate and other for oxygen uptake vs. time span. Two kinds of face masks were provided with the instrument, one for measuring resting metabolic rate and other for direct measurement of pulmonary oxygen uptake. The later one was used for measurement of the response. Face oxygen mask was put on the subjects with the help of belt to ensure that no leakage of oxygen take place. The mask was connected through a wire to the main instrument. A belt provided with the instrument was put around the chest of the subject. A heart rate probe was clamped to the belt; the other end of the probe was connected to the main unit to measure the variation in heart rate vs. time. Time of experiment was noted on the stop watch, and measuring tape was used to measure anthropometrical data. Figure 3.2 shows the operator lifting the load weight during the experimental study.



Figure 3.2: Image of Operator Lifting the Load Weight

3.9 ANALYSIS OF RESULTS

Signal-to-noise ratio

The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments. From the analysis point of view, there are three possible categories of the response characteristics explained below.

r is the number of tests in a trial (noise of repetitions regardless of noise levels)

$\sum_{i=1}^r y_i^2$ = summation of all response values under each trial

MSD = Mean square deviation

y_j = Observed value of the response characteristic

y_o = nominal or target value of the results

The three different response characteristics are given by the following.

1) Higher is Better. The S/N for higher the better is given by:

$$(S/N)_{HB} = -10 \log (MSD_{HB})$$

$$\text{Where } MSD_{HB} = \frac{1}{r} \sum_{j=1}^r \left(\frac{1}{y_j^2} \right)$$

MSD_{HB} = Mean Square Deviation for higher-the-better response.

2) Nominal is Better. The S/N for nominal is better is:

$$(S/N)_{NB} = -10 \log (MSD_{NB})$$

$$\text{Where } MSD_{NB} = \frac{1}{r} \sum_{j=1}^r (y_j - y_o)^2$$

3) **Lower is Better.** In this design situation, the heart rate, and oxygen uptake consumed is the type of “lower is better”, which is a logarithmic function based on the mean square deviation (MSD), given by

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left[\left(\frac{1}{r} \sum_{i=1}^r y^2_i\right)\right]$$

$$\text{Where } MSD_{LB} = \frac{1}{r} \sum_{j=1}^r (y_j^2)$$

Measurement of F-value of Fisher’s F ratio

The principle of the *F* test is that the larger the *F* value for a particular parameter, the greater the effect on the performance characteristic due to the change in that process parameter. *F* value is defined as:

$$F = \frac{MS \text{ for a term}}{MS \text{ for the error term}}$$

Depending on F-value, P-value (probability of significance) is then calculated.

Computation of average performance:

Average performance of a factor at certain level is the influence of the factor at this level on the mean response of the experiments. For example, to compute the average performance of the factor *A* at level 1 (denoted as A1), results for trials including factor *A1* were added and then divided by the number of such trials.

Analysis of variance

The knowledge of the contribution of individual factors is critically important for the control of the final response. It calculates parameters known as sum of squares (*SSs*), pure *SS*, degree of freedom (*DOF*), variance, *F*-ratio and *p*-value of each factor. The analysis required for this purpose was done by the Software MINITAB15. The Sum of Squares (*SS*) is a measure of the deviation of the experimental data from the mean value of the data.

Let ‘*A*’ be a factor under investigation

$$SS_T = \sum_{i=1}^N (y_i - \bar{T})^2$$

Where N = Number of response observations, \bar{T} is the mean of all observations y_i is the i , th response

Factor Sum of Squares (SS_A) - Squared deviations of factor (A) averages from overall average

$$SS_A = \left[\sum_{i=1}^{k_A} \left(\frac{A_i^2}{n_{Ai}} \right) \right] - \frac{T^2}{N}$$

Where

A_i = Average of all obseravtions under A_i level = A_i / n_{Ai}

T = sum of all observations

\bar{T} = Average of all observations = T / N

n_{Ai} = Number of obseravtions under A_i level

Error Sum of Squares (SS_e) - Squared deviations of observations from factor (A) averages

$$SS_e = \sum_{j=1}^{k_A} \sum_{i=1}^{n_{Ai}} (y_i - \bar{A}_j)^2$$

3.10 REGRESSION ANALYSIS

Regression analysis is used to establish relationship between two variables. The response variable y is the independent variable or variable of interest, and the predictor variable x is the independent variable. An objective of regression analysis is to develop a regression model, relating y to x that can be used to predict values of the response variable. As in case of the simple linear regression model relating y to x is:

$$y = \beta_0 + \beta_1 x + \epsilon$$

The two parameters of the model are β_0 , the y -intercept, and β_1 , the slope of the line. β_0 is the mean value of y when x is zero. β_1 is the change in the mean value of y for one unit change in value of x . The random error, ϵ , accounts for the variability in y that is not explained by the independent variable x . This variability could be due to other important independent variables or to some random phenomenon. The model assumes that errors are independent, that is, the error associated with any one observation has no effect on the error associated with any one observation. The model also assumes a normal probability distribution of ϵ , with zero mean and constant variance σ^2 for all values of x .

General linear model

In this type of experiment more than one variable is significantly affecting the response variable and a multiple linear regression model may better estimate or predict the value of a response variable. The general form of linear regression model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots \beta_k x_k + \epsilon$$

Where $\beta_0, \beta_1, \dots, \beta_k$ are the parameters wish to estimated and ϵ is the random error term. ϵ accounts for the variability in y that the independent variables in the model do not explain.

Multicollinearity

In multiple regression analysis, knowing the type and strength of the relationship between each pair of variables is important. A matrix plot of the response variable verses each independent variable and a correlation analysis provide useful information about the relationships. A high correlation is required between y and each x . But if the correlation is high between any pair of independent variable, the regression coefficients may be statistically affected. This problem is called multicollinearity.

Residual analysis

Residual analysis helps to determine whether the regression model is misspecified, whether there are unusual observations or outliers, and whether any assumptions are violated. The model assumes that:

- Errors are independent
- Probability distribution of ϵ is normal, with zero mean and a constant variance σ^2 for all values of x_1, x_2, \dots, x_k

The residual is the difference between the observed and fitted value of the response. A plot of the residuals versus the fitted values or an independent variable may indicate a non-random pattern in the residuals, or may indicate outliers or unusual observations. A normal probability plot and histogram gives information on the normality of the random errors.

CHAPTER 4

ANALYSIS OF OXYGEN UPTAKE

4.1 INTRODUCTION

The effects of the four lifting parameters (lifting frequency, load weight, horizontal distance from object and the vertical distance of lifting) and the operator with their interactions were evaluated using ANOVA and factorial design analysis. In addition, plots of the significant factors and interactions were developed to show significance in the statistical procedure. The purpose of ANOVA and significant factor plot was to identify the important parameters in estimation of oxygen uptake calculations. An alpha level of 0.05 was used for all statistical tests.

The calculated dependent variables were: (1) change in heart rates, (2) pulmonary oxygen uptake. Two trials for each of the 27 experiments were completed to be able to measure the signal to noise ratio. All the statistical calculations and the plots were completed using the Minitab15 software. The results obtained from the *Cosmed pulmonary function equipment* measurement apparatus are provided in Figure 4.1- Figure 4.27. The figures provide response output for heart rate and pulmonary oxygen uptake of the workers for all the 27 treatment conditions.

Table 4.1: Results for Oxygen Consumption

Tri al no.	H.D (cm)	Weight (kg)	Frequency (lifts/min)	operator	V.D (cm)	Oxygen uptake (ml/kg/min)		Mean oxygen uptake (ml/kg/min)
						Response I	Response II	
1	25	13	3	1	55	6.8	7	6.9
2	25	13	5	2	100	6.9	6.4	6.65
3	25	13	7	3	150	14	14.1	14.05
4	40	18	3	1	100	7.2	7.2	7.2
5	40	18	5	2	150	12.3	11.7	12
6	40	18	7	3	55	13.1	12.7	12.9
7	55	23	3	1	150	10.3	10.5	10.4
8	55	23	5	2	55	12	12	12
9	55	23	7	3	100	16.8	15.5	16.15
10	40	23	3	3	55	8.4	9.2	8.8

11	40	23	5	1	100	13.5	13	13.25
12	40	23	7	2	150	17.5	18	17.75
13	55	13	3	3	100	8.2	7.4	7.8
14	55	13	5	1	150	9.7	10.6	10.15
15	55	13	7	2	55	10.5	10.5	10.5
16	25	18	3	3	150	9.5	9.7	9.6
17	25	18	5	1	55	10.2	10	10.1
18	25	18	7	2	100	12.8	13.3	13.05
19	55	18	3	2	55	8	8.4	8.2
20	55	18	5	3	100	9.8	10	9.9
21	55	18	7	1	150	15.4	14.5	14.95
22	25	23	3	2	100	10.2	9.9	10.05
23	25	23	5	3	150	15	15.4	15.2
24	25	23	7	1	55	14.4	13.8	14.1
25	40	13	3	2	150	8	7	7.5
26	40	13	5	3	55	8.2	8.5	8.35
27	40	13	7	1	100	12.6	13.3	12.95

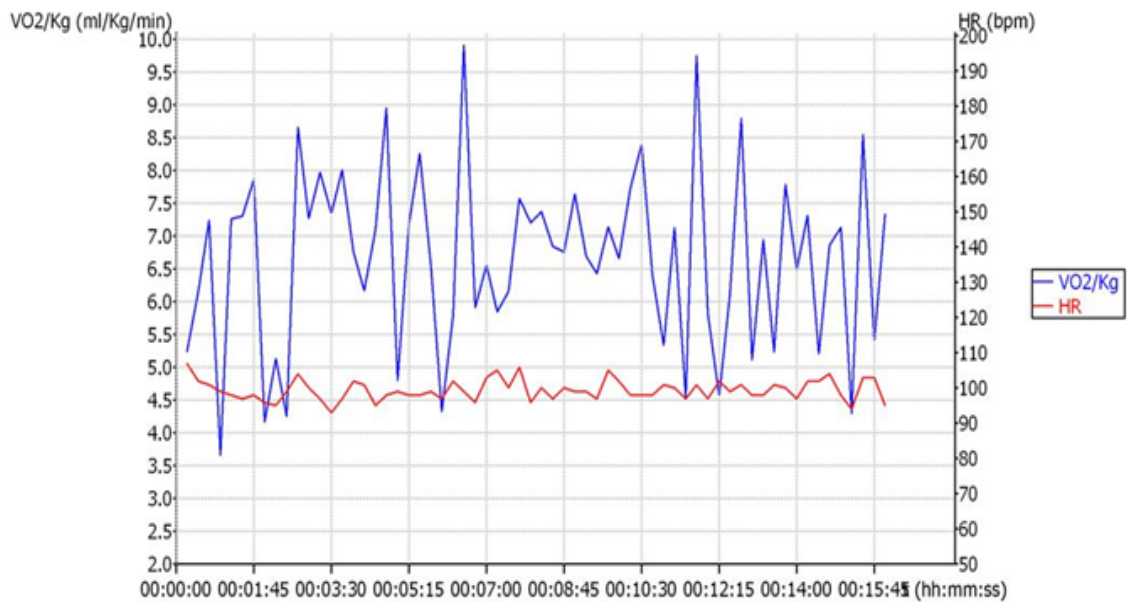


Figure 4.1: Cosmed output for Trial 1

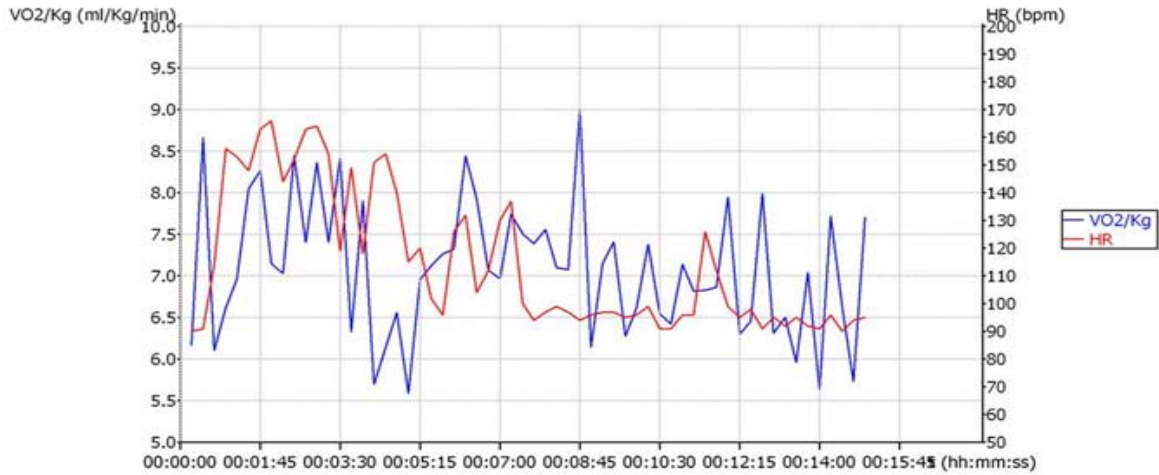


Figure 4.2: Cosmed output for Trial 2

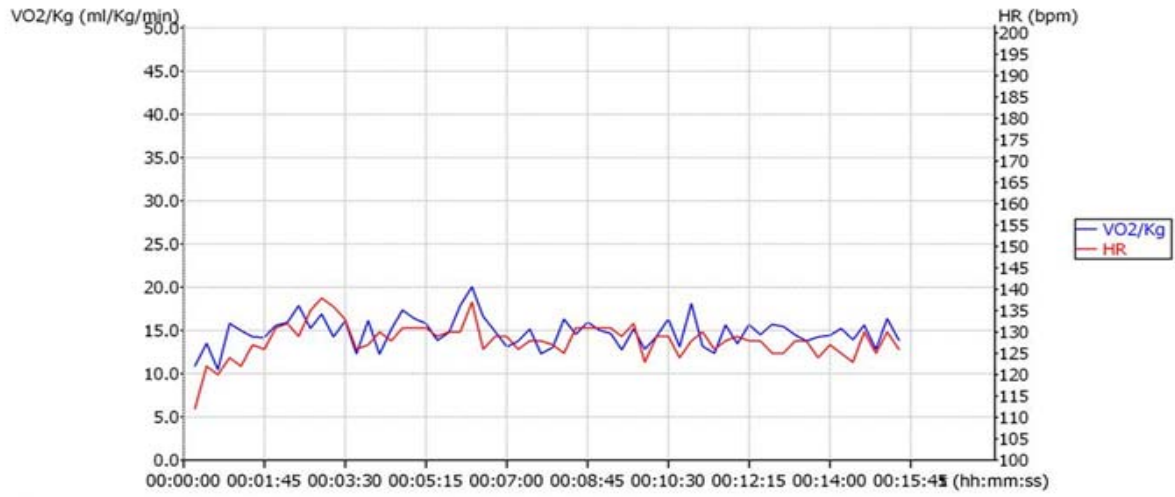


Figure 4.3: Cosmed output for Trial 3

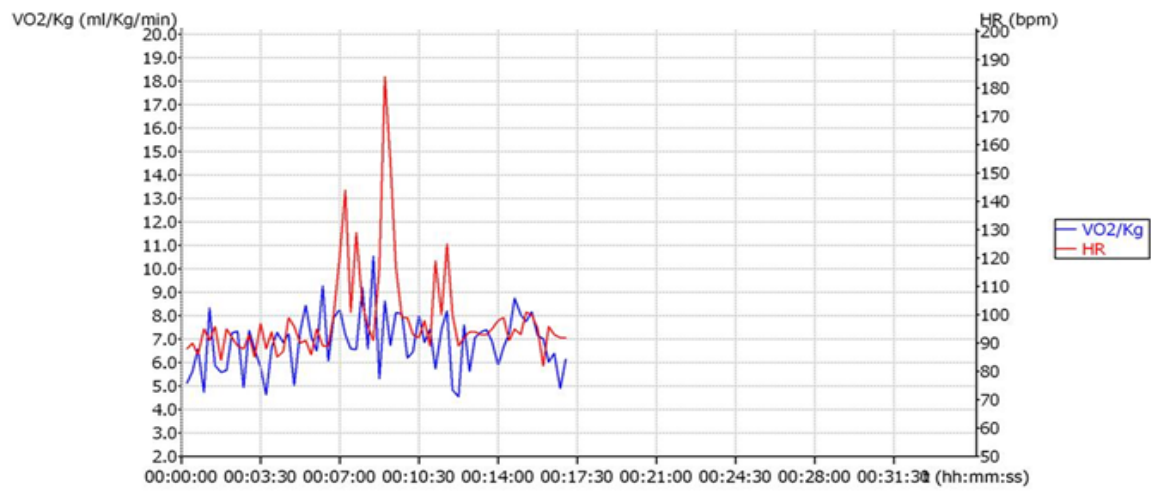


Figure 4.4: Cosmed Output for Trial 4

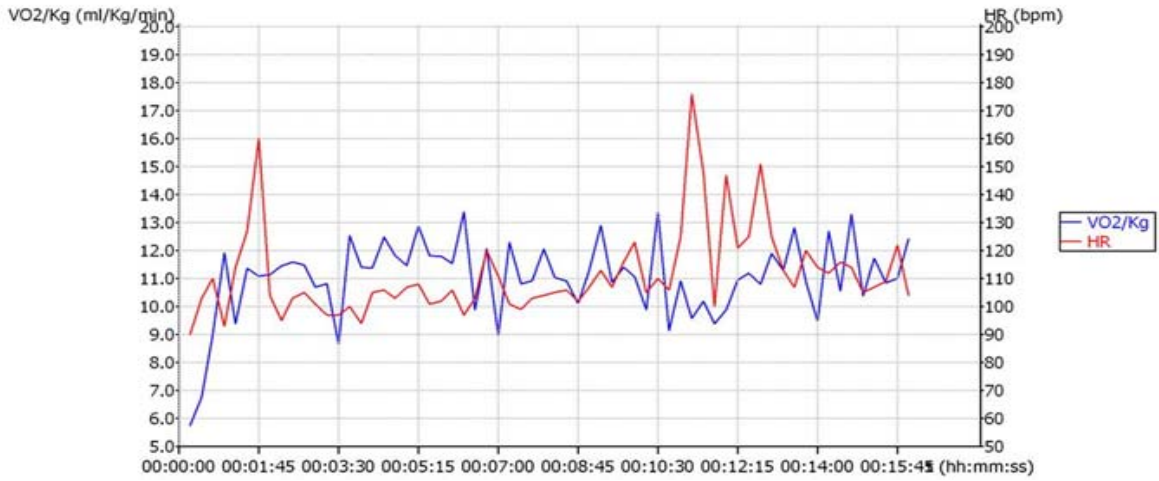


Figure 4.5: Cosmed Output for Trial 5

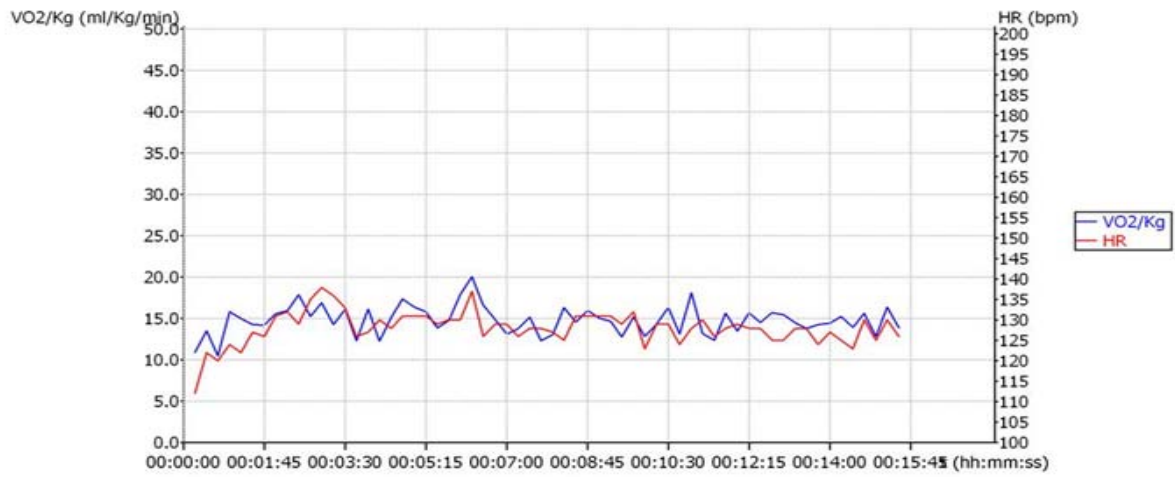


Figure 4.6 Cosmed output for Trial 6

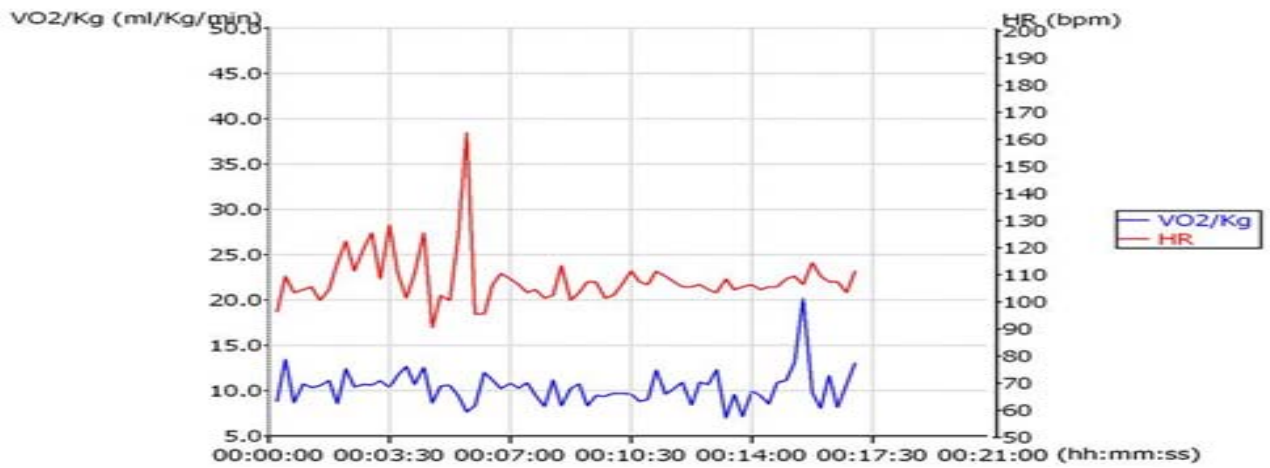


Figure 4.7: Cosmed Output for Trial 7

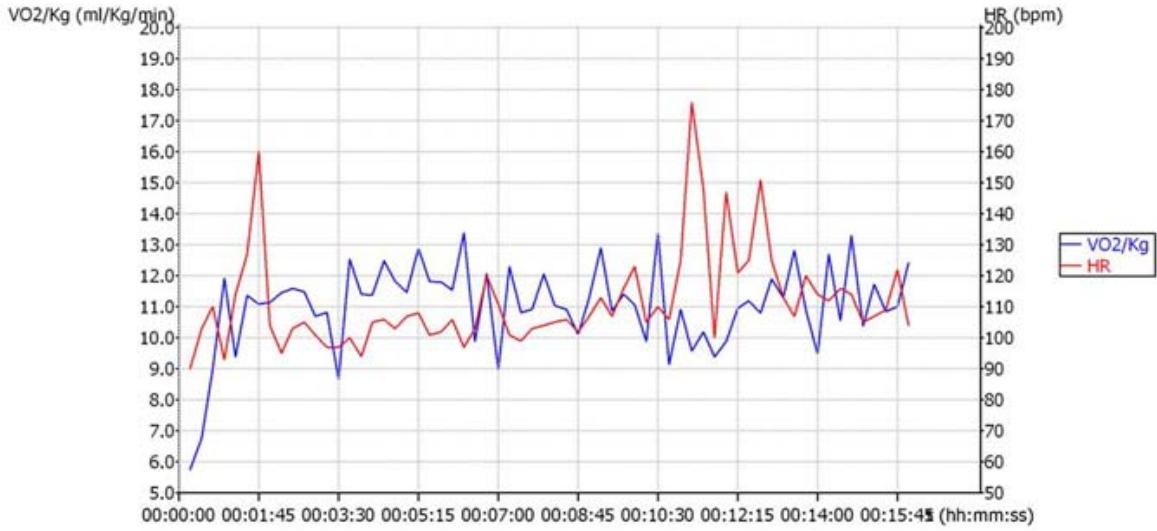


Figure 4.8: Cosmed Output for Trial 8

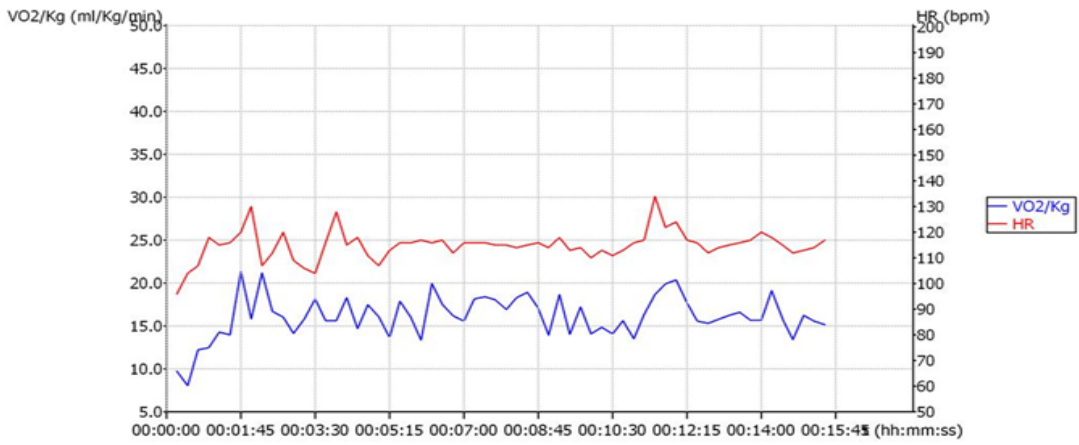


Figure 4.9: Cosmed Output for Trial 9

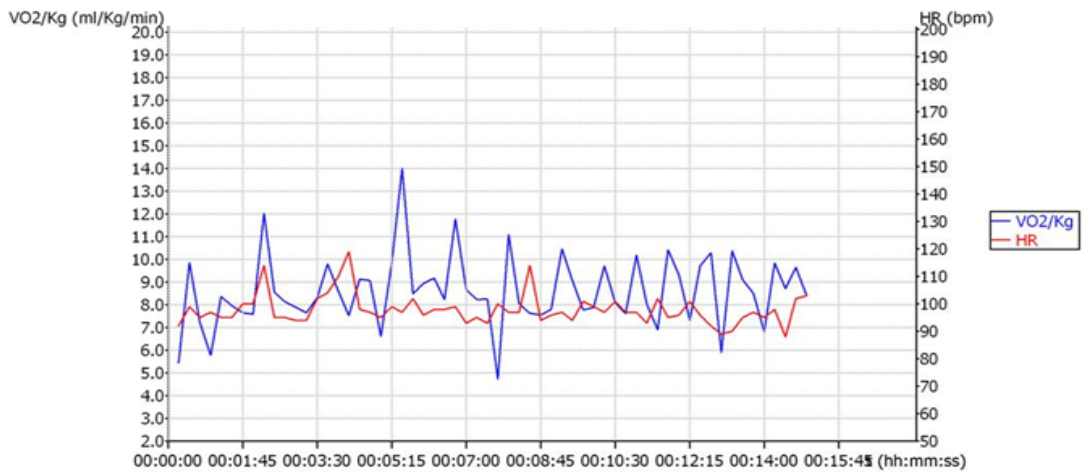


Figure 4.10: Cosmed Output for Trial 10

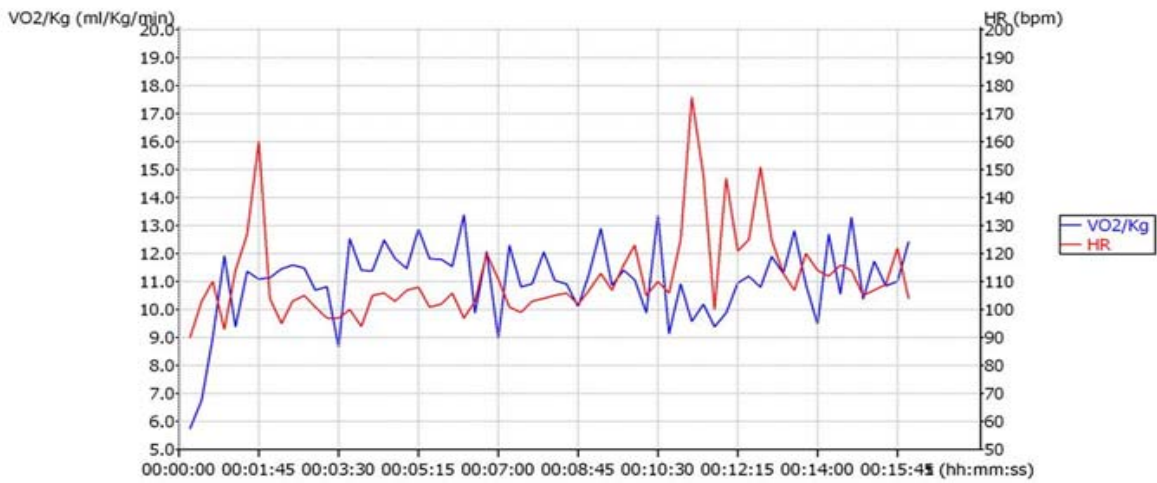


Figure 4.11: Cosmed Output for Trial 11

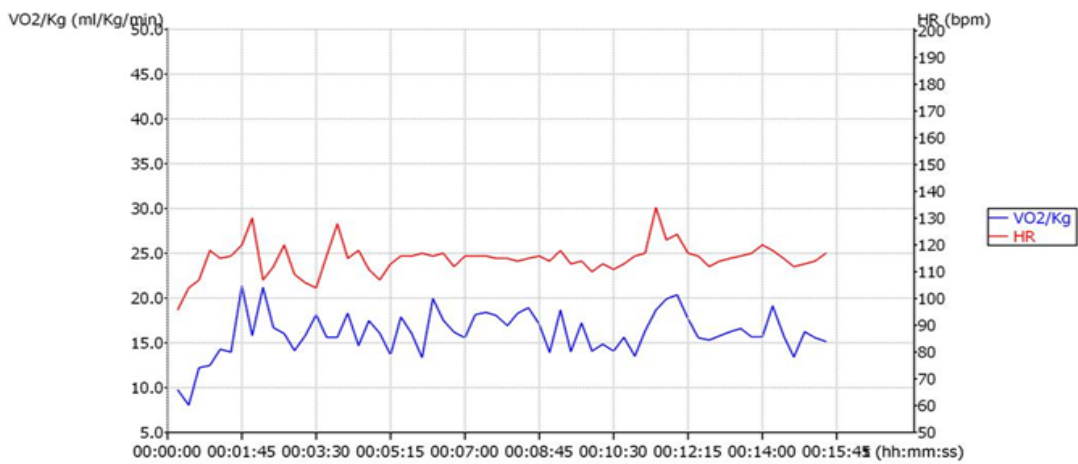
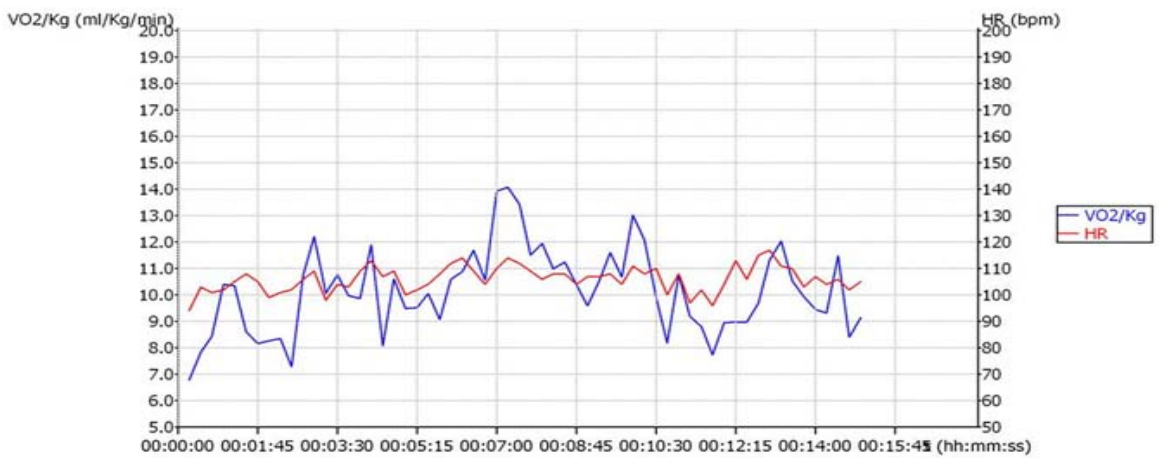
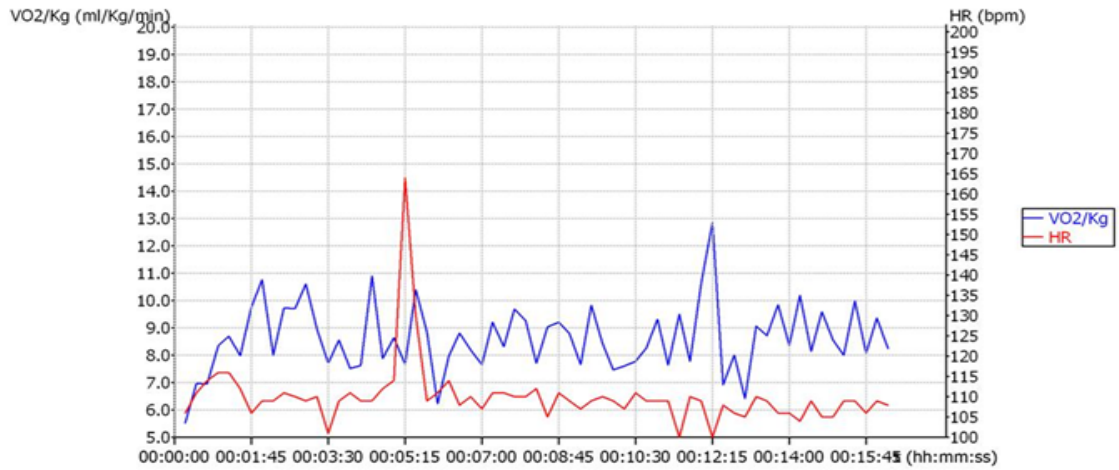
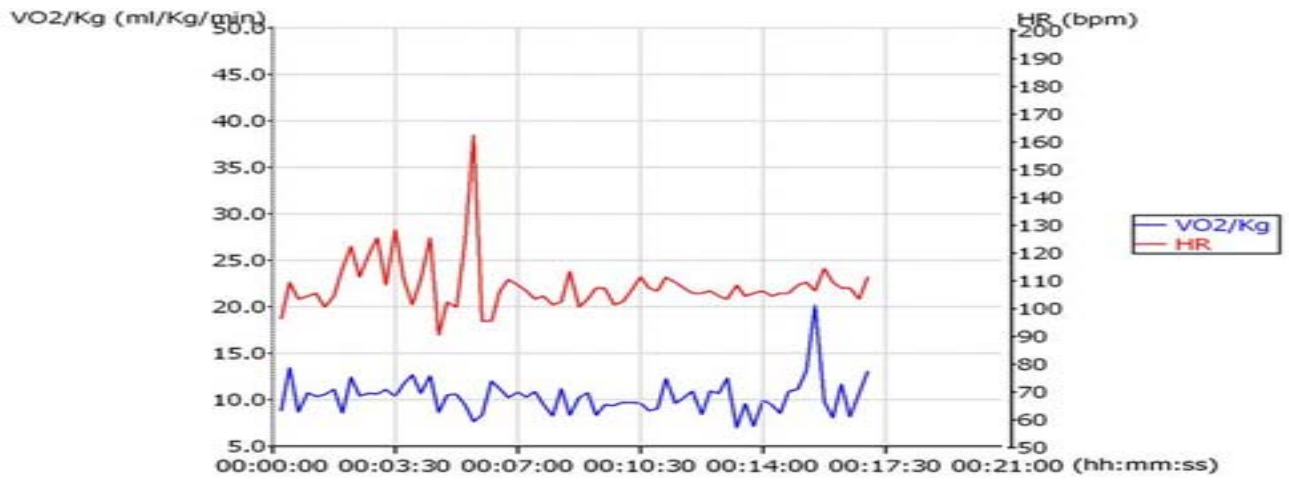


Figure 4.12: Cosmed Output for Trial 12



Figure 4.13: Cosmed Output for Trial 13



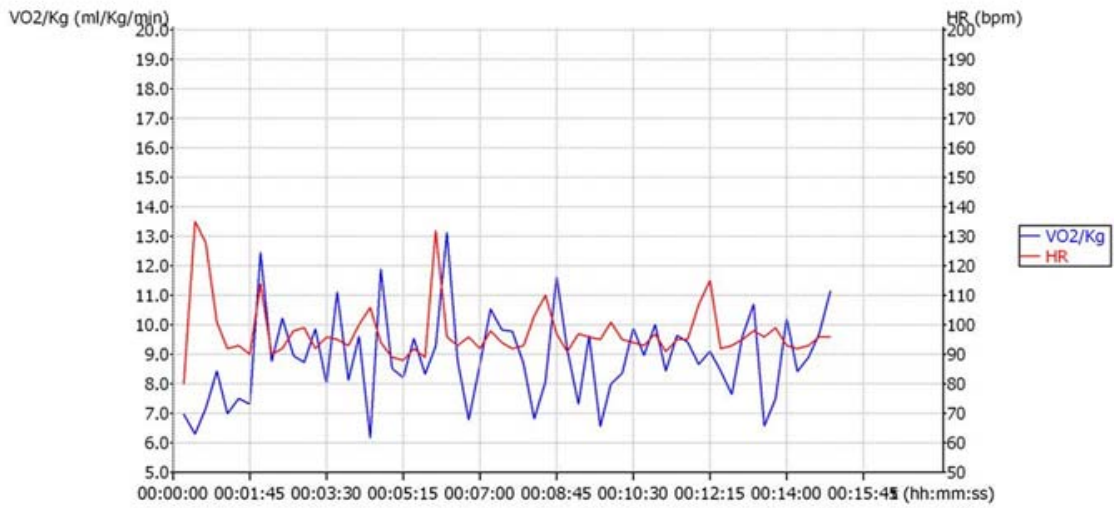


Figure 4.17: Cosmed Output for Trial 17

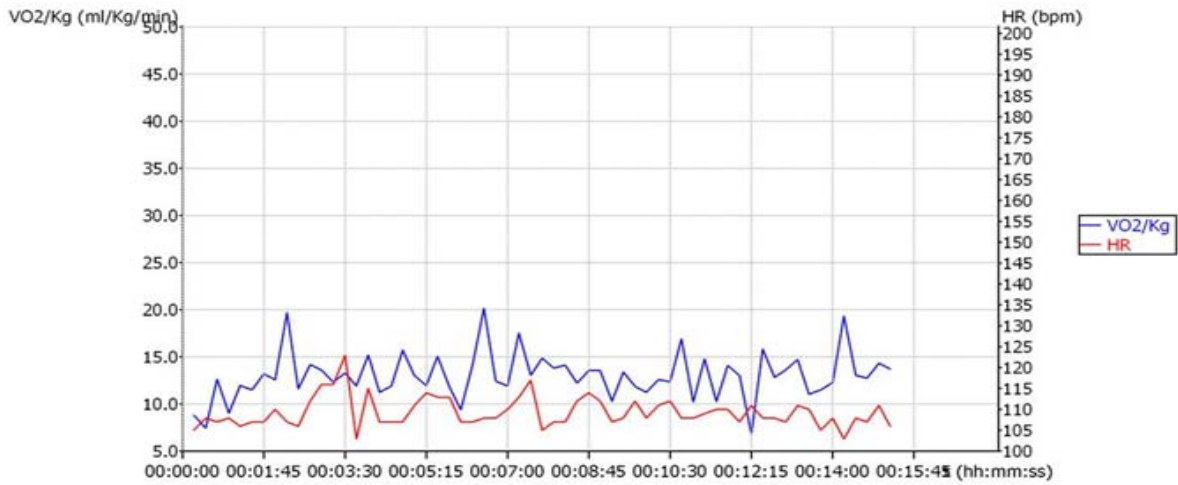


Figure 4.18: Cosmed Output for Trial 18

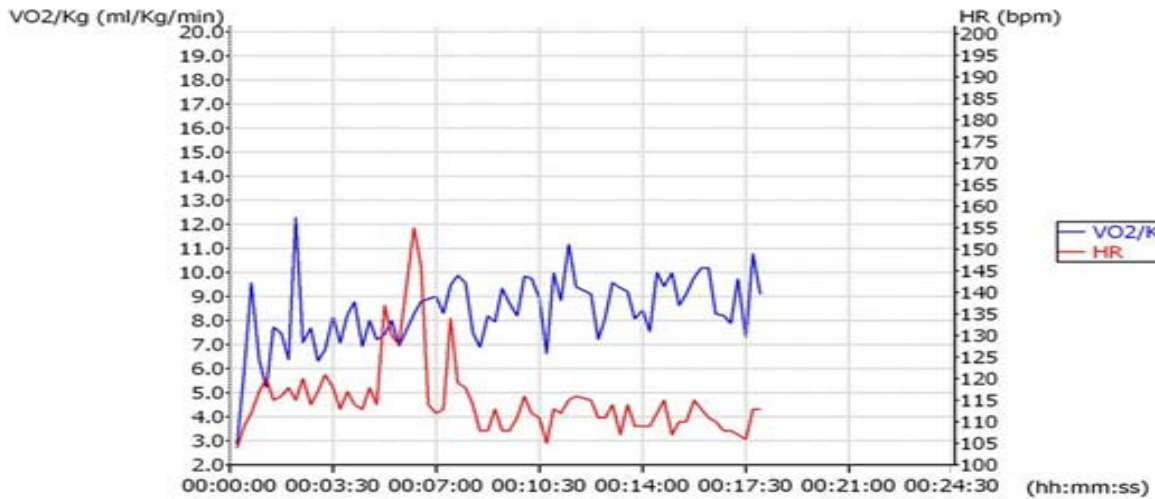


Figure 4.19: Cosmed Output for Trial 19

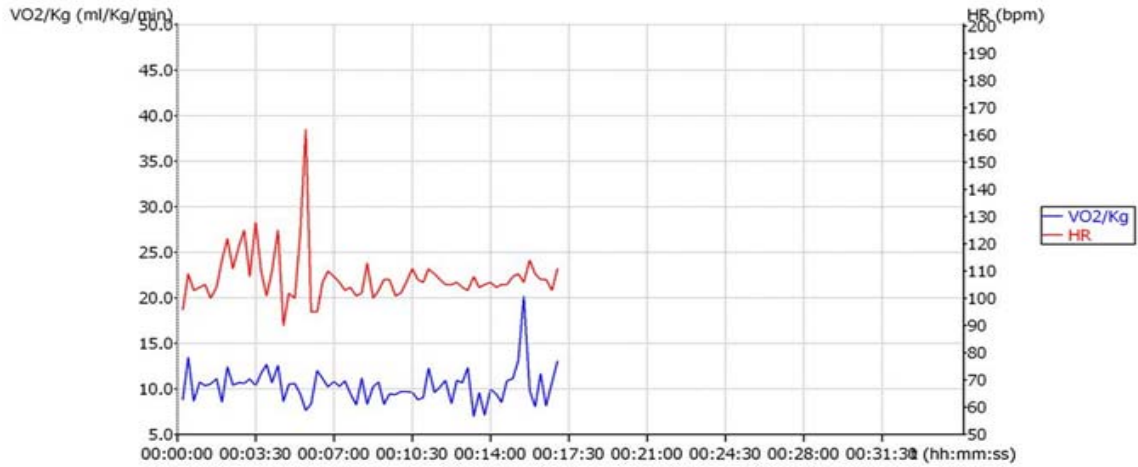


Figure 4.20: Cosmed Output for Trial 20

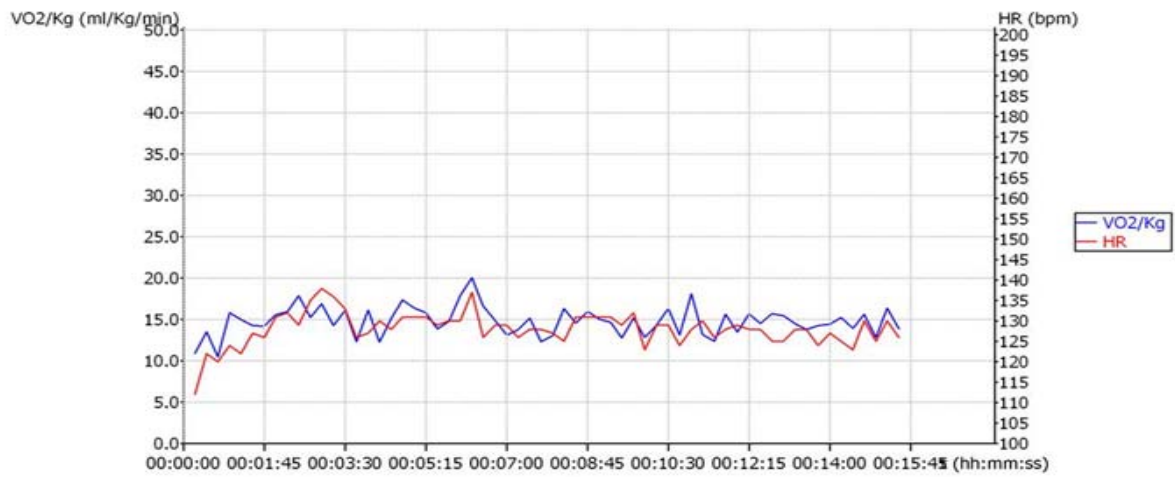


Figure 4.21: Cosmed Output for Trial 21

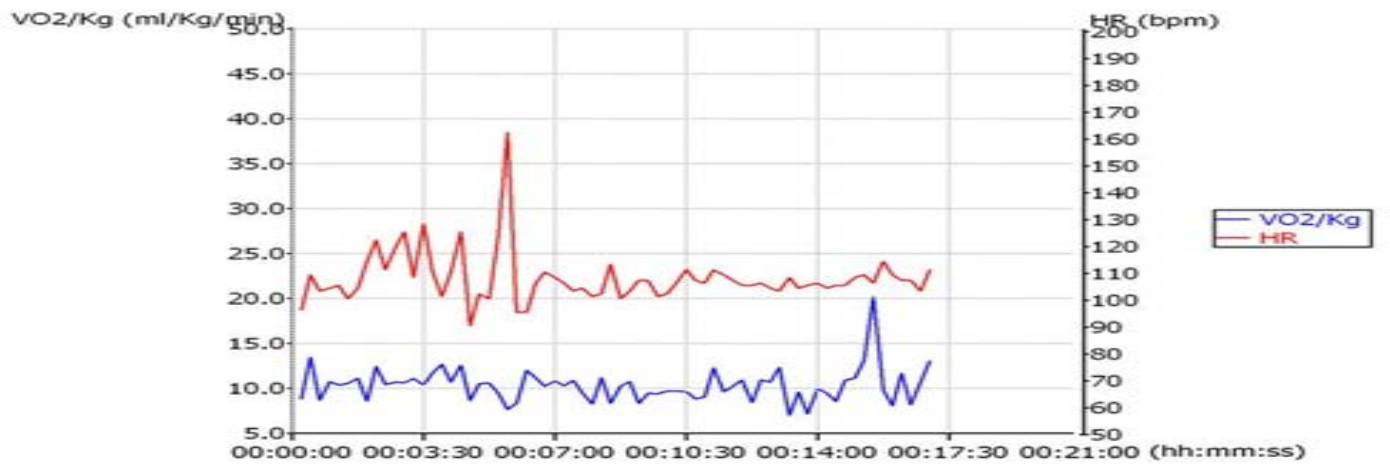


Figure 4.22: Cosmed Output for Trial 22

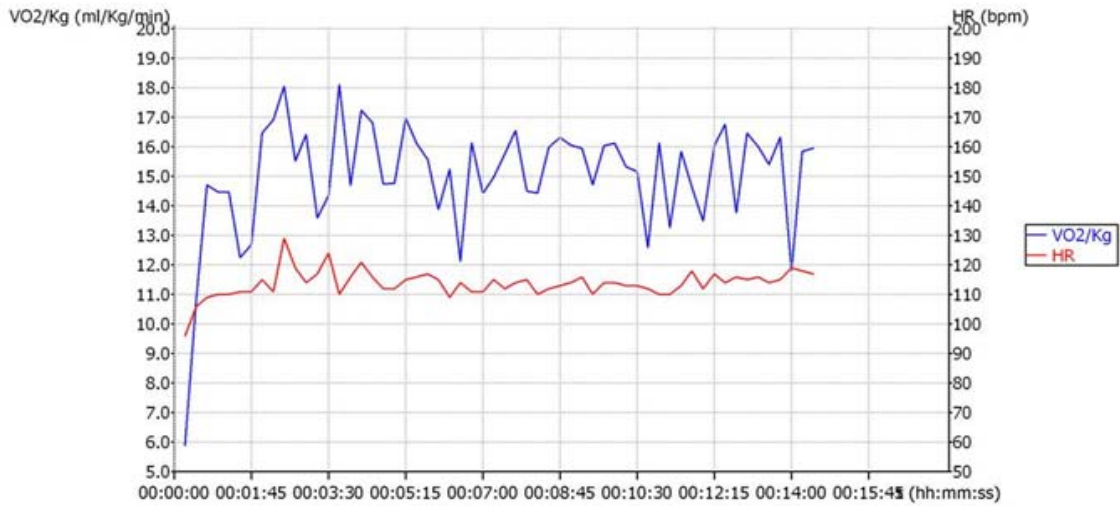


Figure 4.23: Cosmed Output for Trial 23

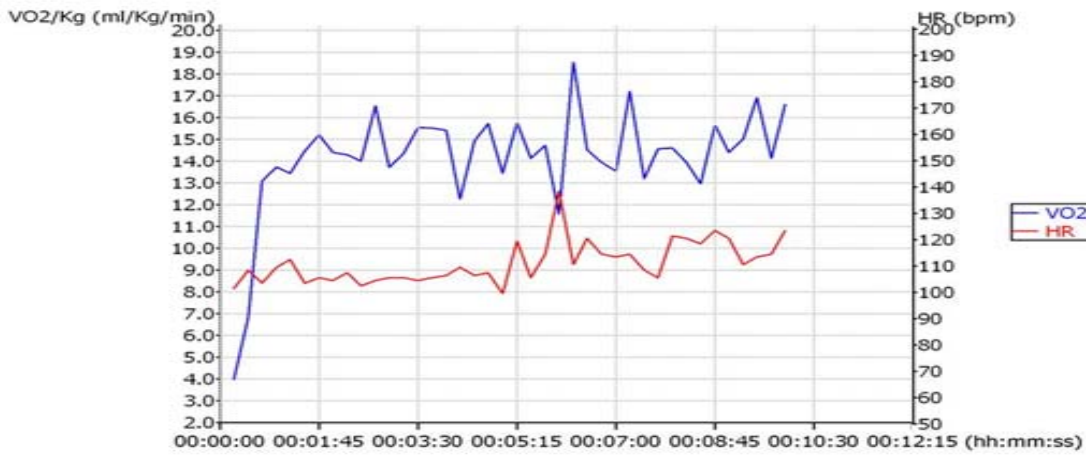


Figure 4.24: Cosmed Output for Trial 24

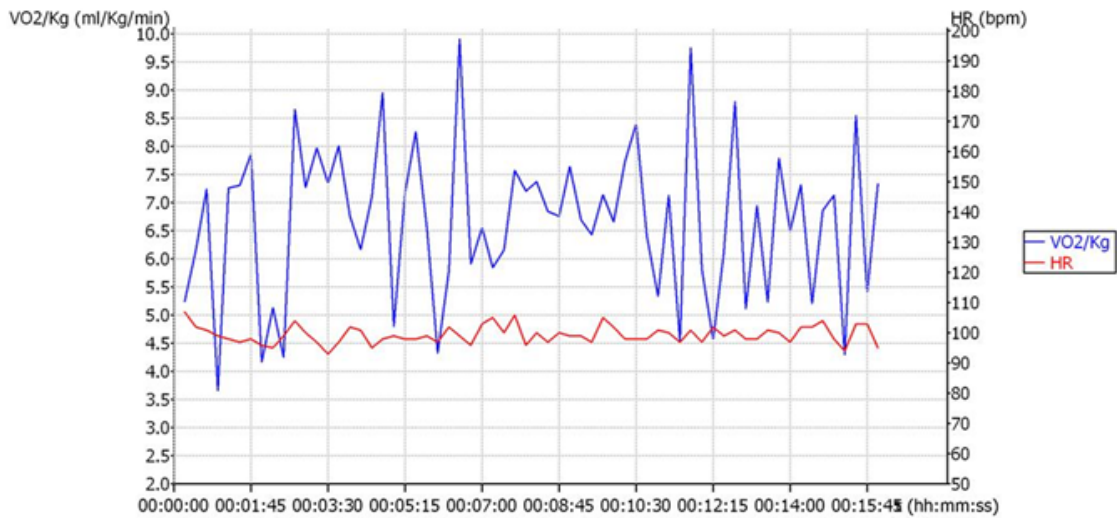


Figure 4.25: Cosmed Output for Trial 25

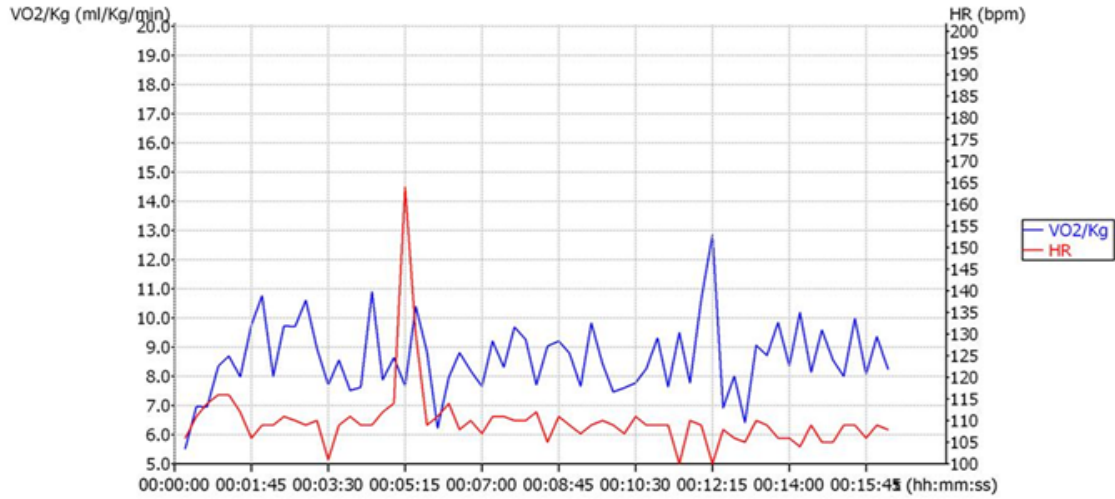


Figure 4.26: Cosmed Output for Trial 26

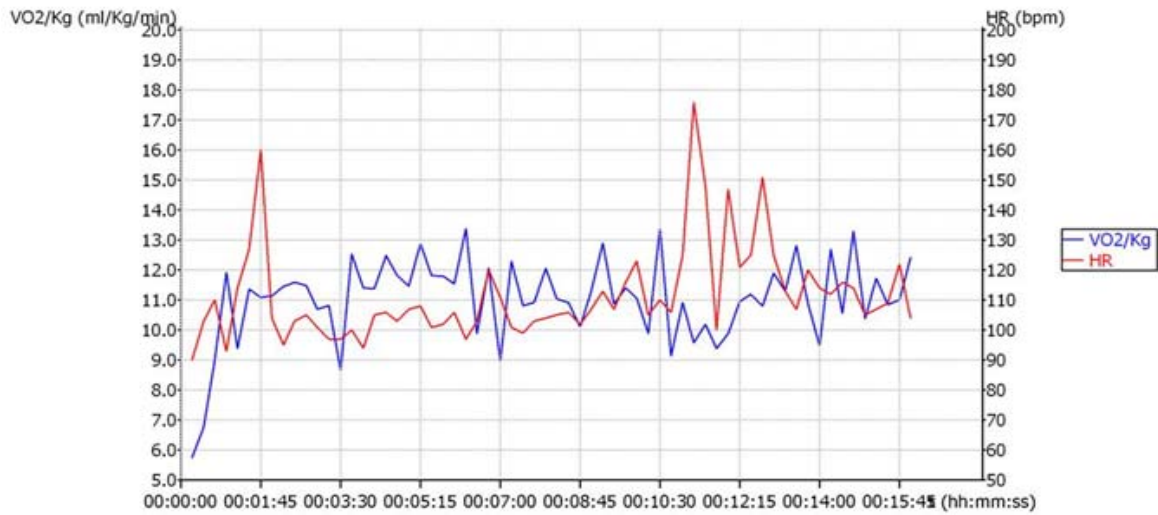


Figure 4.27: Cosmed Output for Trial 27

4.2 ANOVA FOR OXYGEN UPTAKE

The results for oxygen consumption for each of the 27 treatment conditions with one repetition are shown in Table 4.1. The experimental results for oxygen uptake were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean oxygen uptake is shown in Table 4.2. Last column of ANOVA table shows the p-value for each variable and the interactions. The principal of p value is that, those factors were significant which are having p-value less than 0.05 as α level of 0.05 (confidence level 95%) was selected. The principle of the F test is that the larger the F value for a particular parameter, the greater

the effect on the performance characteristic due to the change in that process parameter. ANOVA table shows that weight ($p=0.000$), frequency ($p=0.001$) and vertical distance ($p=0.008$) have p -values less than 0.05 and are thus significant factors affecting oxygen uptake. The change in operator and horizontal distance are insignificant factors as per ANOVA calculations. The mean values for all the five variables with their significance rank are shown in Table 4.3. The high value of means for frequency makes it the most significant factor among all the other parameters, thus indicated as rank 1 in the response table of means. Horizontal distance from the lift is the least significant factor and marked as rank 5, as it shows negligible change of each of the three levels.

Table 4.2 ANOVA for Oxygen Uptake

Analysis of Variance for Mean Oxygen uptake

Source	DF	Seq SS	Adj SS	Adj MS	F	P
H.D.	2	0.057	0.057	0.0286	0.05	0.951
Frequency	2	139.695	139.695	69.8475	123.56	0.000
Weight	2	60.795	60.795	30.3975	53.77	0.001
Operator	2	1.421	1.421	0.7103	1.26	0.377
V.D.	2	23.324	23.324	11.6619	20.63	0.008
Frequency*Weight	4	5.898	5.898	1.4746	2.61	0.188
Frequency*V.D.	4	4.861	4.861	1.2153	2.15	0.238
Weight*V.D.	4	2.744	2.744	0.6861	1.21	0.428
Residual Error	4	2.261	2.261	0.5653		
Total	26	241.057				

Table 4.3 Response Table for Means

Response Table for Means

Level	H.D.	Frequency	Weight	Operator	V.D.
1	11.078	8.494	9.428	11.111	10.206
2	11.189	10.844	10.878	10.856	10.778
3	11.117	14.044	13.078	11.417	12.400
Delta	0.111	5.550	3.650	0.561	2.194
Rank	5	1	2	4	3

4.3 MAIN EFFECT AND INTERACTION PLOTS

Main effect plot and interaction plot for mean oxygen uptake are shown in Figure 4.28. Main effect plot shows the variation oxygen uptake with each of the variable i.e., horizontal distance, frequency, weight, vertical distance and operator. *X*- axis represents the change in level of the variable and *y*- axis represent the change in the resultant response. Mean value of the response is shown by the horizontal line. Main effect plot shows the continuous change in oxygen uptake with higher levels of frequency, weight and vertical distance of lifting. The change is higher in case of frequency as compared to others factors as observed from Table 4.3 analysis of means. While the plot for horizontal distance shows a straight horizontal line, means thereby that there is no change in response with its changing levels. Also, in case of change of operator no change in oxygen uptake was observed, thereby inferring no effect on oxygen uptake. Interaction plots show that none of the interaction i.e., weight vs. frequency, weight vs. vertical distance and frequency vs. vertical distance was found to be significant for this set of experiments. Interaction plots have verified the results obtained from Table 4.2. Surface plots of weight, frequency and vertical distance verses mean oxygen uptake are shown in Figure. 4.29. *Z-axis* of surface plots represents the change in oxygen uptake by the subject. *X* and *y* axis represents the change in level of weight, frequency and vertical distance of lifting. Surface plots helps to visualize the change in response with change in two factors simultaneously.

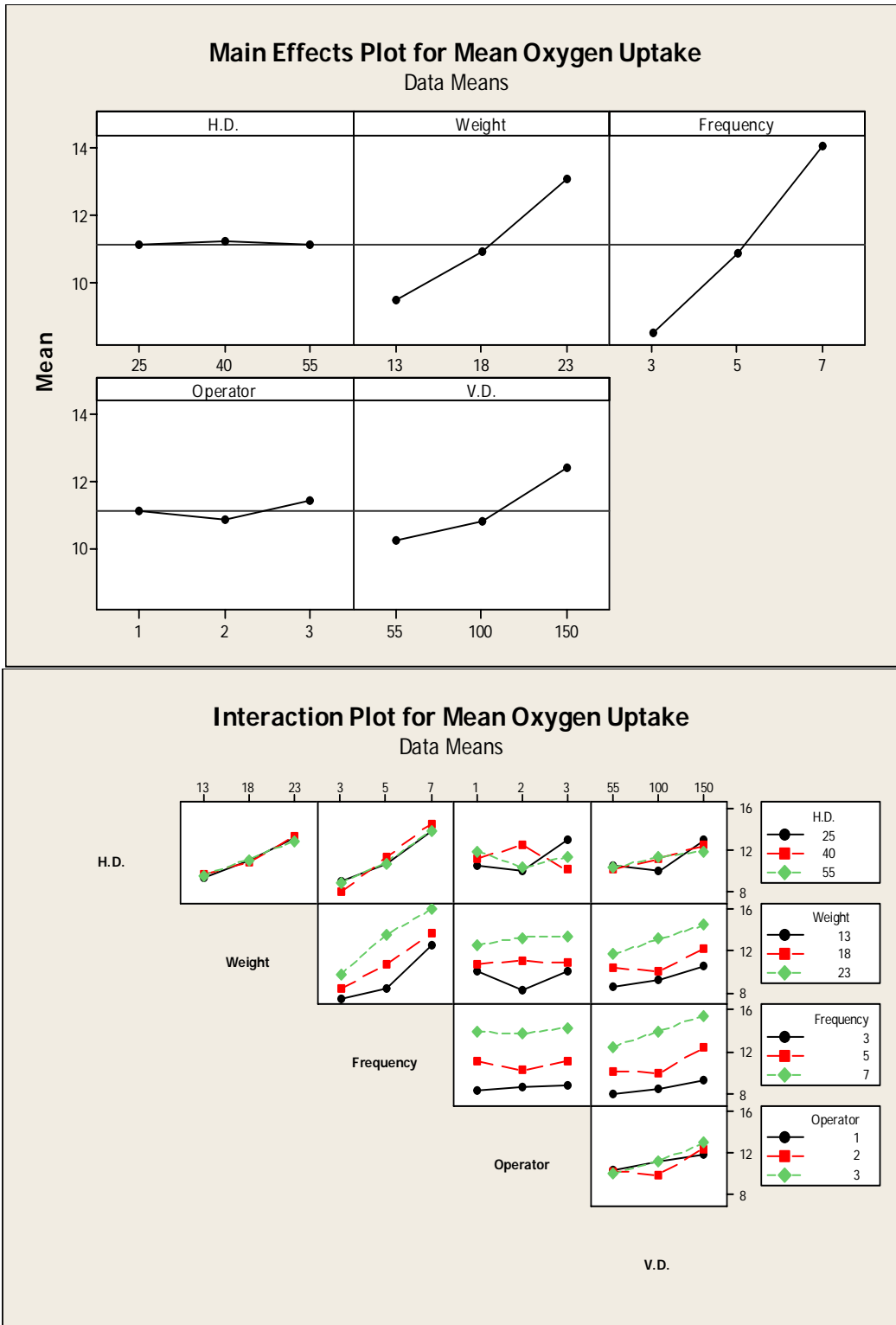


Figure 4.28: Main effect and Interaction Plot for Oxygen Uptake

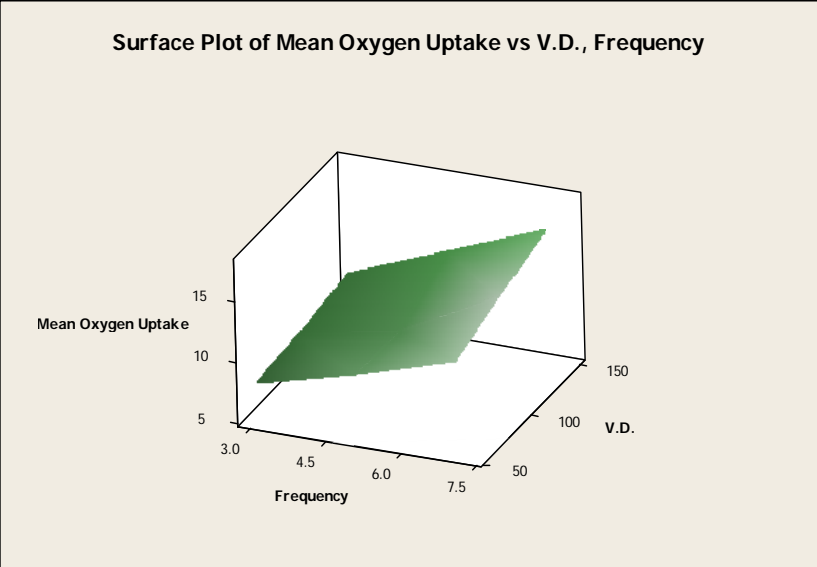
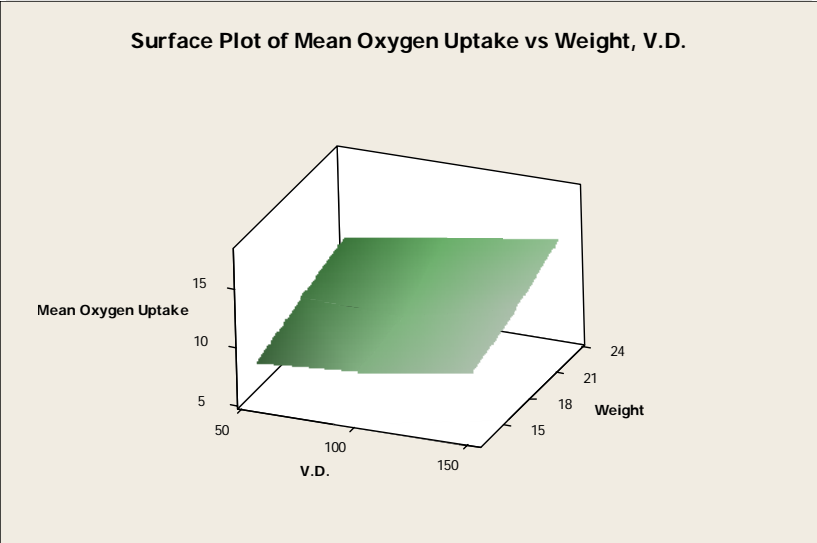
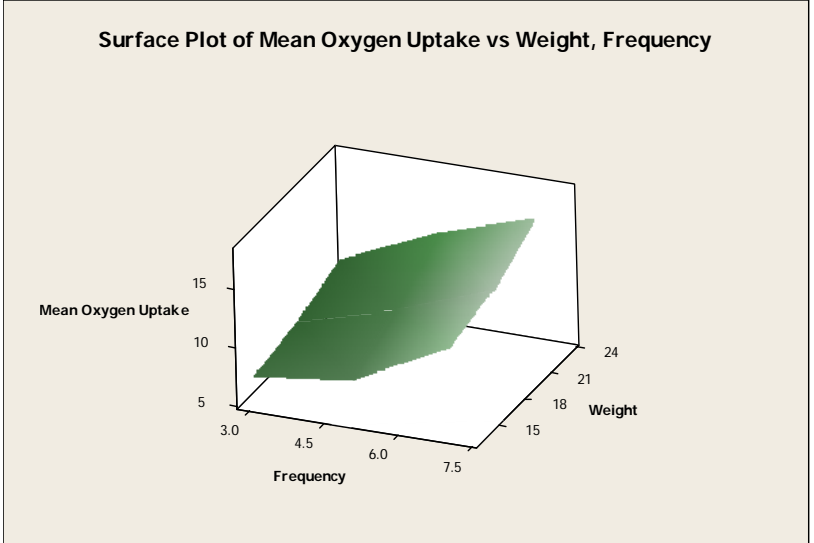


Figure 4.29: Surface plots of Mean Oxygen Uptake

4.4 RESULTS FOR S/N RATIO OF OXYGEN UPTAKE

The S/N ratio several repetitions into one value which reflects the amount of variation present. The values of all the results according to Taguchi array parameter design layout are presented in this section. The S/N ratios have been calculated to identify the major contributing factors and interactions for variation in the volume of oxygen uptake values. In this design situation, oxygen uptake is the type of ‘lower is better’, which is a logarithmic function based on the mean square deviation (MSD), given by

$$S/N_{LB} = -10 \log(MSD) = -10 \log\left[\frac{1}{r} \sum_{i=1}^r y^2_i\right]$$

Table 4.4 shows the ANOVA calculations for the S/N ratio. Again the analysis was carried out for a significant level of $\alpha=0.05$. The main effect and interaction plots are shown in Figure 4.30. The S/N ratio for all the 27 treatments conditions is given in Table 4.5. ANOVA table shows that lifting frequency ($p=0.001$), weight (0.006) and Vertical distance ($p=0.037$) are the most significant factors. Like in previous calculations, horizontal distance and operator do not contribute significantly in the variation of oxygen uptake. Since higher the S/N ratio, better is the response, for reducing the variation in oxygen uptake, frequency, weight and vertical distance should be set at lower level i.e., 3lifts/min, 13 kg and 55 cm respectively. None of the interaction was found to be significant between any factors, which mean interactions between the factors do not cause variation in the results.

Table 4.4 ANOVA for S/N Ratio

Analysis of Variance for SN ratios						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
H.D.	2	0.093	0.0929	0.0464	0.06	0.944
Frequency	2	85.991	85.9911	42.9956	54.59	0.001
Weight	2	38.487	38.4874	19.2437	24.43	0.006
Operator	2	1.139	1.1393	0.5696	0.72	0.539
V.D.	2	13.307	13.3066	6.6533	8.45	0.037
Frequency*Weight	4	3.929	3.9290	0.9823	1.25	0.418
Frequency*V.D.	4	2.546	2.5464	0.6366	0.81	0.579
Weight*V.D.	4	1.698	1.6977	0.4244	0.54	0.718
Residual Error	4	3.150	3.1504	0.7876		
Total	26	150.341				

Table 4.5: Results for S/N Ratio

Sr. no.	H.D (cm)	Weight (cm)	Frequency (lifts/min)	Operator	V.D (cm)	S/N ratio for oxygen uptake
1	25	13	3	1	55	-16.7779
2	25	13	5	2	100	-16.4626
3	25	13	7	3	150	-22.9536
4	40	18	3	1	100	-17.1466
5	40	18	5	2	150	-21.5863
6	40	18	7	3	55	-22.2128
7	55	23	3	1	150	-20.3411
8	55	23	5	2	55	-21.5836
9	55	23	7	3	100	-24.1705
10	40	23	3	3	55	-18.8986
11	40	23	5	1	100	-22.4459
12	40	23	7	2	150	-24.9848
13	55	13	3	3	100	-17.8533
14	55	13	5	1	150	-20.1378
15	55	13	7	2	55	-20.4238
16	25	18	3	3	150	-19.6459
17	25	18	5	1	55	-20.0869
18	25	18	7	2	100	-22.3138
19	55	18	3	2	55	-22.3138
20	55	18	5	3	100	-19.9131
21	55	18	7	1	150	-23.4968
22	25	23	3	2	100	-20.0443
23	25	23	5	3	150	-23.6376
24	25	23	7	1	55	-22.9863
25	40	13	3	2	150	-17.5205
26	40	13	5	3	55	-18.4351
27	40	13	7	1	100	-22.2486

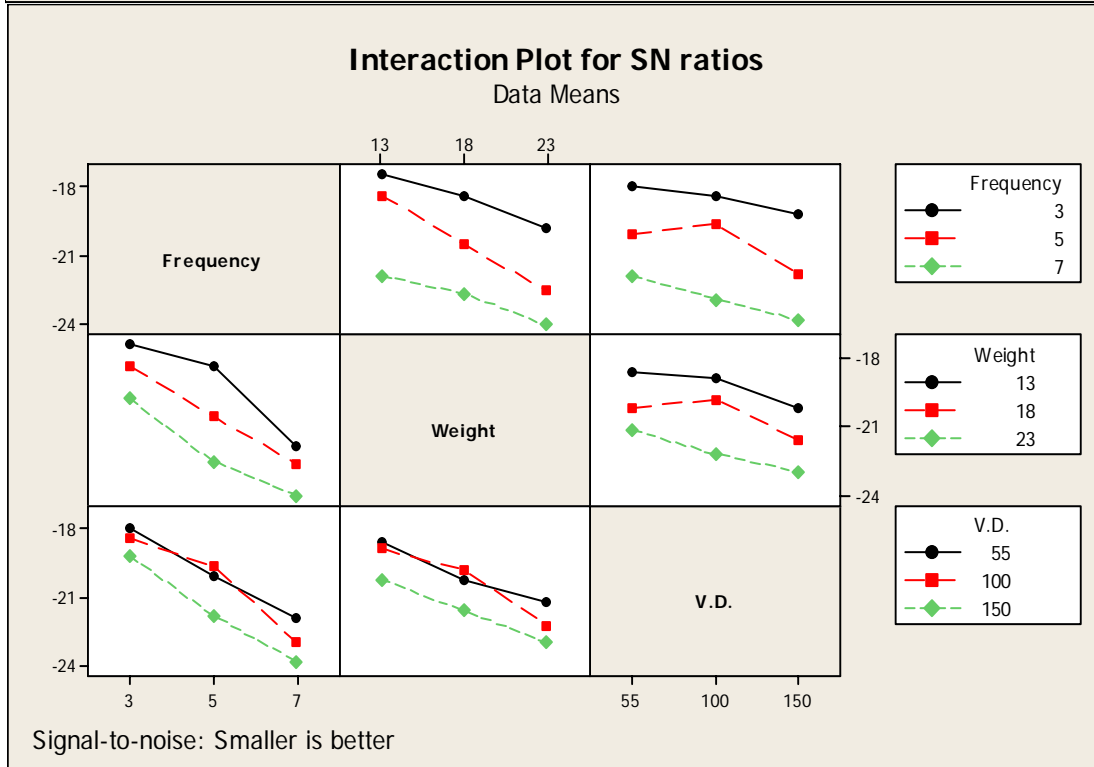
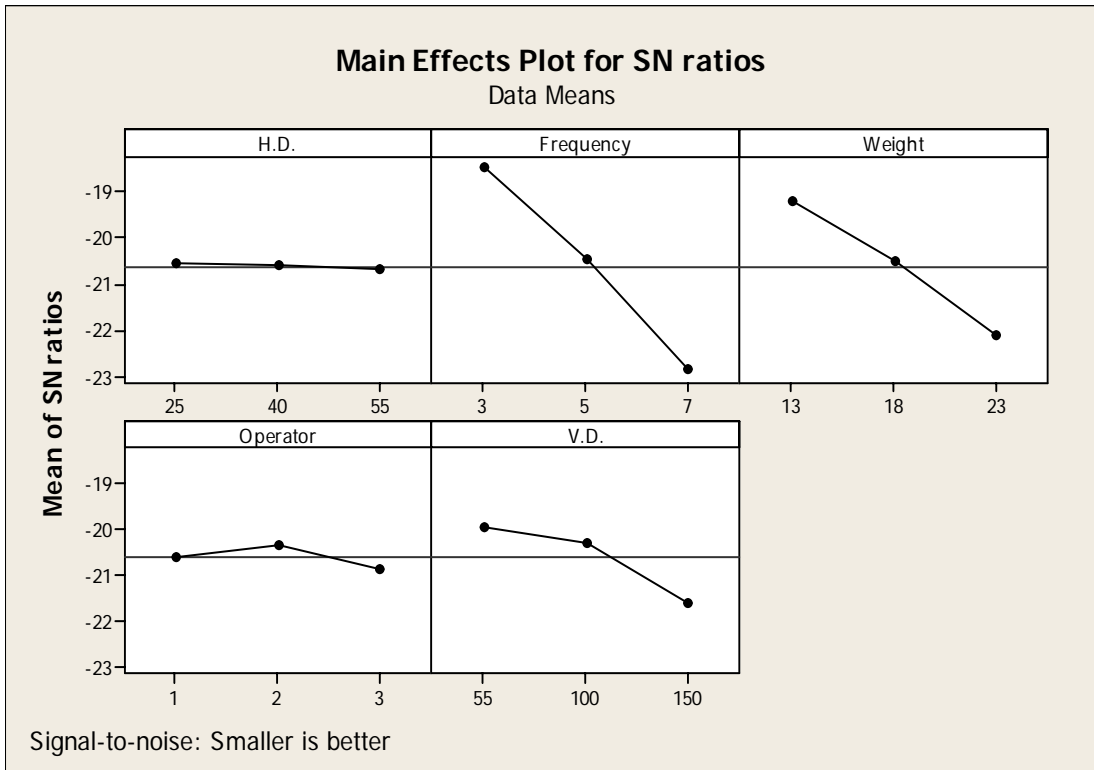


Figure 4.30 Main Effects and Interaction Plot for S/N Ratio

4.5 FURTHER ANALYSIS

The Plots shown in Figure 4.1-Figure 4.27 describes a visual analysis of results obtained from the *Cosmed pulmonary function equipment*. The plots indicate oxygen uptake (ml/kg/min) and heart beat (beats/min) vs. the time span. The *x*-axis indicates the time span and *y*-axis indicates the oxygen uptake (at left) and heart rate (right) of subject. Red curve shows variation in heart rate and the blue curve represents the variation in pulmonary oxygen uptake by the worker. Average of the observation was taken to have a final measurement. While observing the experimental results in Table 4.1, higher oxygen uptake is observed in 3rd, 9th, 12th, 20th, 23rd, and 24th trial run. The common parameter in all of these responses is the higher lift frequency (7lifts/min) and the high vertical distance (150 cm). Low oxygen uptake was observed when lift frequency was set at 3lifts/min (1st, 4th, 10th, 13th, 16th and 25th trial run). While observing the data it has been found that the pulmonary oxygen uptake at high stress tasks (12th trial) is more than double compared to low stress tasks (1st trial run).

4.6 OPTIMAL DESIGN

In experimental analysis, there are three possible categories of the characteristics; a higher average response is better (HB), a nominal value is best (NB) or a lower average response is better (LB). Lower is better is used where the lesser target values are desired. Volume of oxygen uptake by the workers while doing lifting tasks is such a case. The plot of significant factors in Figure 4.28 can be used to estimate the mean oxygen uptake with optimal design conditions. Since there are three significant factors, plots were used to establish their most significant levels, which gives a lower values of oxygen uptake. The lowest oxygen uptake was observed when weight, lift frequency and vertical distance were set at the lower levels i.e., weight 13kg, frequency 3lifts/min and vertical distance 55 cm i.e., at knee level. The estimated average of the oxygen uptake when the three significant factors were considered at their lower level was found to be 5.875 ml/kg/min. Confidence interval explains that probability of oxygen uptake at optimal design conditions lying between 5.875 ± 1.043 is 95%. Table 4.6 shows significant factors and interactions that affect the mean oxygen uptake after completion of ANOVA

and S/N ratio analysis. Load weight, lifting frequency and vertical distance were found to be significant in both ANOVA as well as S/N ratio.

Mean oxygen uptake for low stress levels

$$\mu_{B_1C_1E_1} = \overline{B_1} + \overline{C_1} + \overline{E_1} - 2\overline{T}$$

$$\mu_{B_1C_1E_1} = 9.428 + 8.494 + 10.206 - 2 \times 11.275 = 5.875 \text{ ml/kg/min}$$

Confidence Interval around the estimated oxygen uptake

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} \quad \text{Where } F_{\alpha, v_1, v_2} = F \text{ ratio}$$

$$\alpha = \text{risk (0.05)} \quad \text{confidence} = 1 - \alpha$$

$$v_1 = \text{dof for mean which is always} = 1$$

$$v_2 = \text{dof for error} = v_e$$

n_{eff} = Number of tests under that condition using the participating factors

$$n_{eff} = \frac{N}{1 + \text{dof}_{B,C\&E}} = \frac{27}{1 + 2 + 2 + 2} = 3.857$$

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} = \sqrt{\frac{4.49 \times 0.936}{3.857}} = 1.043$$

So the confidence interval around the estimated pulmonary oxygen uptake is 5.875 ± 1.043

Table 4.6: Significant Factors and Interactions

Factors	Significance status for ANOVA of oxygen uptake	Significance status for S/N ratio of oxygen uptake
Horizontal distance	No	No
Load weight	Yes	Yes
Lifting frequency	Yes	Yes
Operator	No	No
Vertical distance	Yes	Yes
Load weight vs. lifting frequency	No	No
Load weight vs. vertical distance	No	No
Lifting frequency vs. vertical distance	No	No

CHAPTER 5

ANALYSIS OF HEART RATE

5.1 INTRODUCTION

The effects of four lifting parameters (lifting frequency, load weight, horizontal distance from object and the vertical distance of lifting) and operator with their interactions were evaluated using ANOVA and factorial design analysis. In addition, plots of the significant factors and interactions were developed to show significance in the statistical procedure. The purpose of ANOVA and significant factor plot was to identify the important parameters in estimation of heart rate calculations. An alpha level of 0.05 was used for all statistical tests. Two trials for each of all the 27 experiments were completed to be able to measure the signal to noise ratio. All the statistical calculations and the plots were completed using the Minitab15 software.

5.2 ANALYSIS OF VARIANCE FOR HEART RATE

The experimental results for heart rate were analyzed using ANOVA for identifying the significant factors affecting the performance measures. Experimental results for each of the 27 treatment conditions with one repetition and their means are shown in the Table 5.1. ANOVA table for mean heart rate is shown in Table 5.2. Last column of ANOVA table shows the p-value for each variable and the interactions. The principal of p value is those factors are significant, which have p-value less than 0.05 as α level of 0.05(confidence level 95%) was selected. The principle of the F test is that the larger the F value for a particular parameter, the greater the effect on the performance characteristic due to the change in that process parameter. ANOVA results shows that p values for frequency ($p=0.003$) and vertical distance ($p=0.013$) are less than 0.05, and are thus significant affecting the heart rate. Also, F-values for frequency and vertical distance are larger than the other parameters. Weight ($p=0.106$), operator ($p=0.178$), and horizontal distance ($p=0.998$) have higher p-values ($p>0.05$), and are thus found to be non-significant. No interaction was found to be significant at least for this set up of experiments. Frequency with lowest p value and high f-value is the most significant factor as compared to other factors. Table 5.3 shows the mean values for each of the

variables at each level. Rank under each factor shows the level of significance of that factor, as frequency is ranked one, and thus found to be most significant. Horizontal distance from the lift is the least significant factor and is ranked 5, as it shows negligible change of heart rate of each of three levels.

Table 5.1: Results for Heart Rate

Trial no.	H.D (cm)	Weight (kg)	Frequency (lifts/min)	operator	V.D (cm)	Heart rate (beats/min)		Mean heart rate (beats/min)
						Response I	Response II	
1	25	13	3	1	55	97	99	98
2	25	13	5	2	100	95	96	95.5
3	25	13	7	3	150	124	126	125
4	40	18	3	1	100	100	101	100.5
5	40	18	5	2	150	105	103	104
6	40	18	7	3	55	111	110	110.5
7	55	23	3	1	150	107	108	107.5
8	55	23	5	2	55	101	103	102
9	55	23	7	3	100	118	116	117
10	40	23	3	3	55	100	98	99
11	40	23	5	1	100	110	112	111
12	40	23	7	2	150	126	127	126.5
13	55	13	3	3	100	103	105	104
14	55	13	5	1	150	106	106	106
15	55	13	7	2	55	105	106	105.5
16	25	18	3	3	150	105	107	106
17	25	18	5	1	55	100	101	100.5
18	25	18	7	2	100	115	114	114.5
19	55	18	3	2	55	98	101	99.5
20	55	18	5	3	100	102	103	102.5
21	55	18	7	1	150	121	124	122.5
22	25	23	3	2	100	105	106	105.5
23	25	23	5	3	150	115	114	114.5
24	25	23	7	1	55	107	106	106.5
25	40	13	3	2	150	96	97	96.5
26	40	13	5	3	55	105	106	105.5
27	40	13	7	1	100	111	113	112

Table 5.2 ANOVA table for Heart rate

Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
H.d.	2	0.06	0.056	0.028	0.00	0.998
Weight	2	100.72	100.722	50.361	4.14	0.106
Frequency	2	947.39	947.389	473.694	38.98	0.002
Operator	2	66.50	66.500	33.250	2.74	0.178
V.d.	2	371.06	371.056	185.528	15.27	0.013
Weight*Frequency	4	32.89	32.889	8.222	0.68	0.643
Weight*V.d.	4	67.22	67.222	16.806	1.38	0.381
Frequency*V.d.	4	173.56	173.556	43.389	3.57	0.123
Residual Error	4	48.61	48.611	12.153		
Total	26	1808.00				

Table 5.3 Response Table for Means

Level	H.d.	Weight	Frequency	Operator	V.d.
1	107.3	105.3	101.8	107.2	103.0
2	107.3	106.7	104.6	105.5	106.9
3	107.4	109.9	115.6	109.3	112.1
Delta	0.1	4.6	13.7	3.8	9.1
Rank	5	3	1	4	2

5.3 MAIN EFFECT AND INTERACTION PLOTS

The main effect plot and Interaction plot for mean heart rate is shown in Figure 5.1. The main effect plot shows the variation of heart rate with each of the variable i.e., horizontal distance, weight, frequency, vertical distance and operator. X-axis of the plots represents the change in level of factor and y-axis represents the change in resultant response. Mean value of the response is shown by the horizontal line. Main effect plot shows continuous increase of heart rate with increase in frequency and vertical distance. There is a significant increase of heart rate with higher level of weight. While the plot for horizontal distance shows almost straight horizontal line means thereby that there is no response with changing levels. Also, in case of change of operator no change in heart rate is observed, thereby inferring it's no effect on heart rate. Interaction plots show that none of the interaction i.e., weight vs. frequency, weight vs. vertical distance and frequency vs. vertical distance of lifting was found to be significant for this set of experiments. Interaction plots have verified the results obtained from the Table 5.2.

Surface plots of weight, frequency and vertical distance verses mean heart rate are shown in Figure 5.2. *Z-axis* of surface plots represents the change in heart rate of the subject. *X* axis and *y* axis represents the change in level of weight, frequency and vertical distance of lifting. Surface plots helps to visualize the change in response with change in two factors simultaneously.

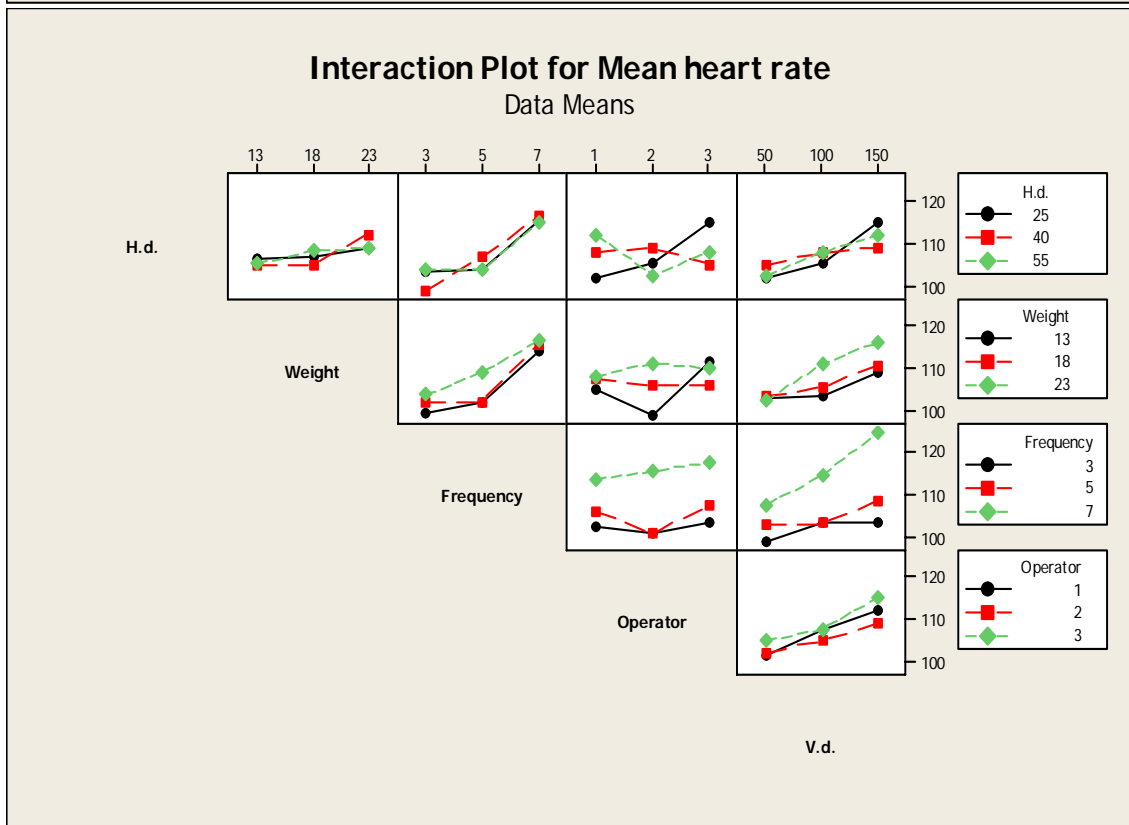
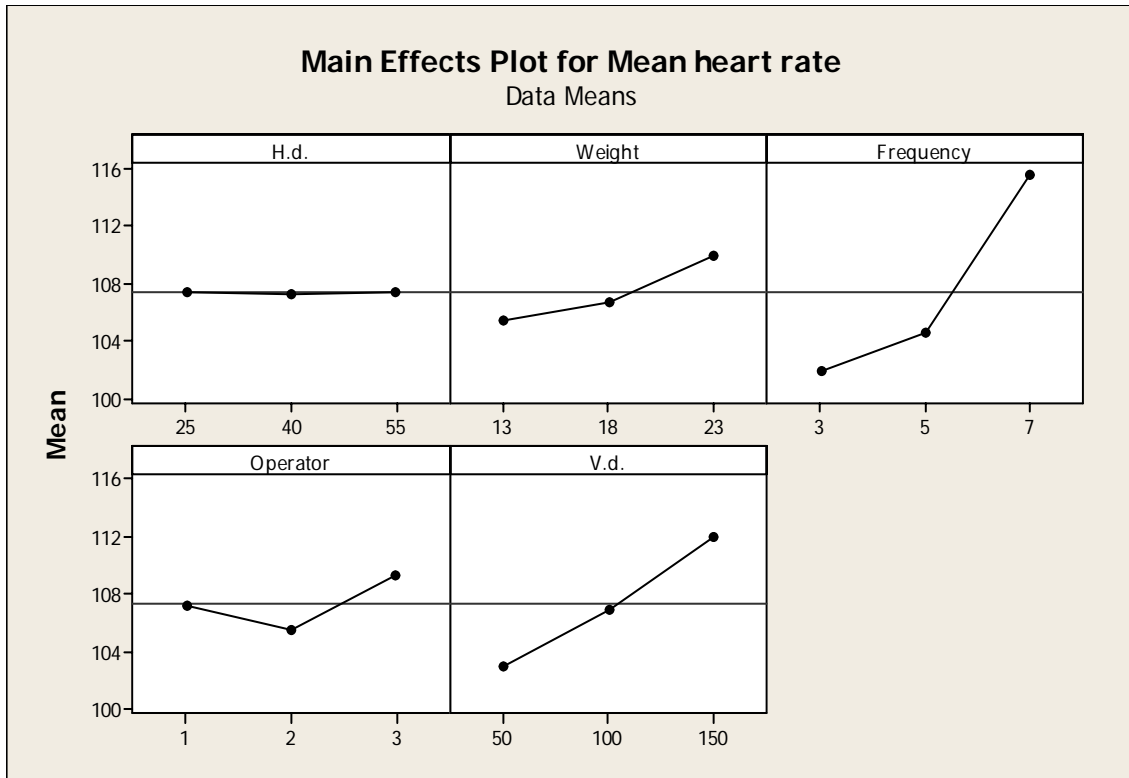
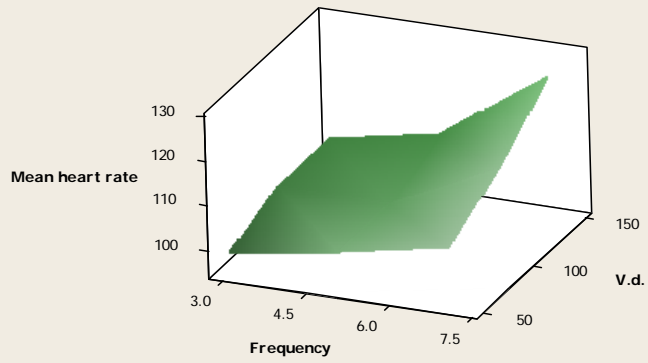
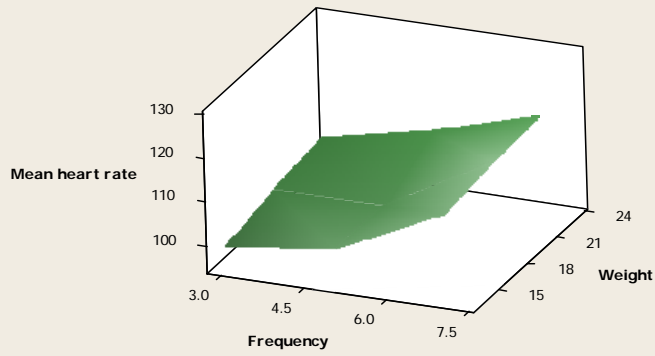


Figure 5.1: Main Effects and Interaction Plots for Heart Rate

Surface Plot of Mean heart rate vs V.d., Frequency



Surface Plot of Mean heart rate vs Weight, Frequency



Surface Plot of Mean heart rate vs Weight, V.d.

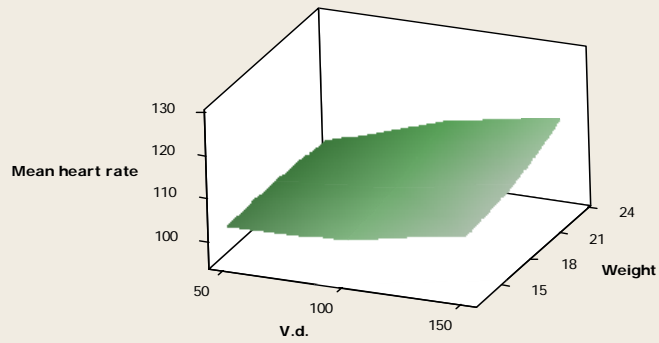


Figure 5.2: Surface plots of Heart Rate

5.4 RESULTS FOR SIGNAL-TO-NOISE RATIO OF HEART RATE

The S/N ratio consolidates repetitions into one value which reflects the amount of variation present. The values of all the results according to Taguchi array parameter design layout are presented in this section. The S/N ratios have been calculated to identify the major contributing factors and interactions to variation in the heart rate values. In this design situation, heart rate is the type of ‘lower is better’, which is a logarithmic function based on the mean square deviation (MSD), given by

$$S / N_{LB} = -10 \log(MSD) = -10 \log\left[\left(\frac{1}{r} \sum_{i=1}^r y^2_i\right)\right]$$

Table 5.4 shows the ANOVA calculations for the S/N ratio. Again the analysis was carried out for a significant level of $\alpha=0.05$. The main effect and interaction plots are shown in Figure.5.3. The results for S/N ratio for all the 27 treatment conditions are given in Table 5.5. ANOVA table shows that lifting frequency ($p=0.005$) and vertical distance ($p=0.019$) are the significant factors. Like in previous calculations horizontal distance, operator and weight do not contribute significantly in the variation of heart rate. Since larger the S/N ratio, better is the response, for reducing the values of heart rate, frequency, weight and vertical distance should be set at lower level i.e., 3lifts/min, 13 kg and 55 cm respectively. None of the interaction was found to be significant between any factors, which mean interactions between the factors do not cause variation in the results.

Table 5.4 ANOVA for Signal to Noise Ratio

Analysis of Variance for SN ratios						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
H.d.	2	0.0016	0.00162	0.00081	0.01	0.991
Weight	2	0.6685	0.66853	0.33427	3.70	0.123
Frequency	2	5.9059	5.90589	2.95295	32.68	0.003
Operator	2	0.4604	0.46037	0.23019	2.55	0.193
V.d.	2	2.2385	2.23853	1.11927	12.39	0.019
Weight*Frequency	4	0.2304	0.23037	0.05759	0.64	0.663
Weight*V.d.	4	0.4418	0.44177	0.11044	1.22	0.425
Frequency*V.d.	4	0.9470	0.94695	0.23674	2.62	0.187
Residual Error	4	0.3614	0.36141	0.09035		
Total	26	11.2554				

Table 5.5: Results for S/N Ratio

Sr. no.	H.D (cm)	Weight (cm)	Frequency (lifts/min)	Operator	V.D (cm)	S/N ratio for heart rate
1	25	13	3	1	55	-39.8250
2	25	13	5	2	100	-39.6002
3	25	13	7	3	150	-41.9385
4	40	18	3	1	100	-40.0434
5	40	18	5	2	150	-40.3411
6	40	18	7	3	55	-40.8673
7	55	23	3	1	150	-40.6283
8	55	23	5	2	55	-40.1724
9	55	23	7	3	100	-41.3640
10	40	23	3	3	55	-39.9131
11	40	23	5	1	100	-40.9068
12	40	23	7	2	150	-42.0419
13	55	13	3	3	100	-40.3411
14	55	13	5	1	150	-40.5061
15	55	13	7	2	55	-40.4651
16	25	18	3	3	150	-40.5065
17	25	18	5	1	55	-40.0434
18	25	18	7	2	100	-41.1762
19	55	18	3	2	55	-39.9574
20	55	18	5	3	100	-40.2146
21	55	18	7	1	150	-41.7634
22	25	23	3	2	100	-40.4651
23	25	23	5	3	150	-41.1762
24	25	23	7	1	55	-40.5471
25	40	13	3	2	150	-39.6907
26	40	13	5	3	55	-40.4651
27	40	13	7	1	100	-40.9847

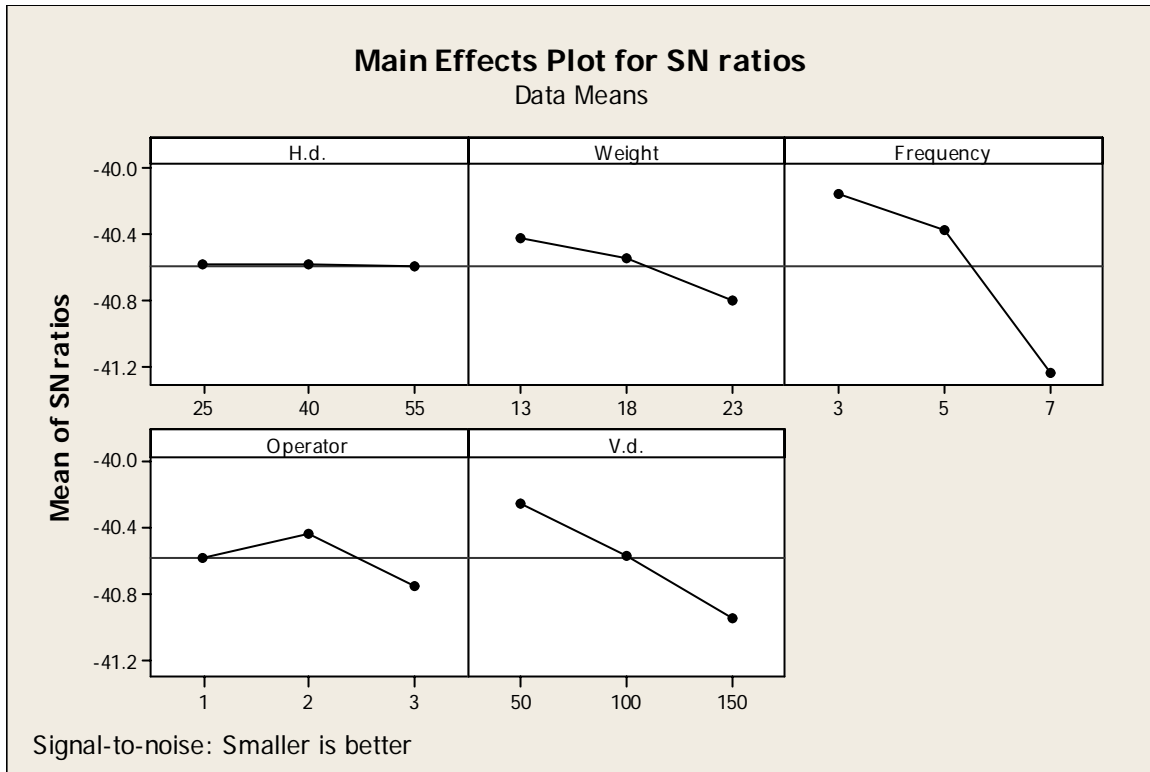


Figure 5.3: Main Effect and Interaction plot of Heart Rate for S/N Ratio

5.5 OPTIMAL DESIGN

In experimental analysis, there are three possible categories of the characteristics; a higher average response is better (HB), a nominal value is best (NB) or a lower average response is better (LB). Lower is better is used where the lesser target values are desired. Heart rate (beats/min) while doing lifting tasks is such a case. The plot of significant factors in Figure 5.1 can be used to estimate the mean heart rate with optimal design conditions. Since there are two significant factors, plots were used to establish their most significant levels, which gives a lower values of heart rate. The lowest heart rate was observed when lift frequency and vertical distance were set at the lower levels i.e., frequency 3lifts/min and vertical distance 55 cm i.e., at knee level. An estimated average of the heart rate when the two significant factors were considered at their better level was found to be 97.5 beats/min. Confidence interval predict with 95% confidence that value of heart rate at optimal design conditions would be 97.5 ± 4.47 Table 4.6 shows significant factors and interactions that affect the mean heart rate after completion of ANOVA and S/N ratio analysis. Lifting frequency and vertical distance were found to be significant in both ANOVA as well as S/N ratio.

Mean heart rate for low stress levels

$$\mu_{C_1E_1} = \bar{C}_1 + \bar{E}_1 - \bar{T}$$

$$\mu_{C_1E_1} = 101.8 + 103.0 - 107.3 = 97.5 \text{ beats/min}$$

Confidence Interval around the estimated heart rate

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} \text{ Where } F_{\alpha v_1 v_2} = F \text{ ratio}$$

$$\alpha = \text{risk (0.05)} \quad \text{confidence} = 1 - \alpha$$

$$v_1 = \text{dof for mean which is always} = 1$$

$$v_2 = \text{dof for error} = v_e$$

n_{eff} = Number of tests under that condition using the participating factors

$$n_{eff} = \frac{N}{1 + dof_{C\&E}} = \frac{27}{1 + 2 + 2} = 5.4$$

$$CI = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} = \sqrt{\frac{4.41 \times 24.497}{5.4}} = 4.47$$

So the confidence interval around the estimated heart rate is 97.5 ± 4.47

Table 5.6: Significant Factors and Interactions

Factors	Significance status for ANOVA of heart rate	Significance status for S/N ratio of heart rate
Horizontal distance	No	No
Load weight	No	No
Lifting frequency	Yes	Yes
Operator	No	No
Vertical distance	Yes	Yes
Load weight vs. lifting frequency	No	No
Load weight vs. vertical distance	No	No
Lifting frequency vs. vertical distance	No	No

6.1 REGRESSION ANALYSIS

Regression analysis is a statistical technique which is used to establish relationship between two variables. An objective of regression analysis is to develop a regression model, relating y to x that can be used to predict values of the response variable. Regression analysis for heart rate and oxygen uptake were completed using the Minitab15 Software. Significant predictors have been predicted by removing the non-significant predictors (variables). A least squares regression equation was obtained for all the responses. Residual analysis is being done to ensure the absence of any non-random pattern in the residuals. An alpha level of 0.05 was used for all statistical tests.

6.2 REGRESSION ANALYSIS FOR OXYGEN UPTAKE

From the ANOVA analysis of oxygen uptake it has been found out that no interaction is having significant effect on oxygen uptake. So a general linear model is applied excluding the interaction effect of the variables. The regression analysis has been done using MINITAB software and the equation obtained is shown in Equation 6.1. ANOVA table for regression analysis is shown in Table 6.1.

The regression equation is

$$\begin{aligned} \text{Mean Oxygen uptake} = & - 5.10 + 0.0013 \text{ H.D.} + 0.365 \text{ Wt.} \\ & +1.39 \text{ Freq.} + 0.153 \text{ Opr} + 0.0233 \text{ V.D.} \\ & \dots\dots\dots \text{Equation 6.1} \end{aligned}$$

Table 6.1 ANOVA for Regression Equation.

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	221.005	44.201	46.29	0.000
Residual Error	21	20.052	0.955		
Total	26	241.057			

Predictor	Coef	SE Coef	T	P
Constant	-5.103	1.374	-3.72	0.001
H.D.	0.00130	0.01535	0.08	0.934
Weight	0.36500	0.04606	7.92	0.000
Frequency	1.3875	0.1152	12.05	0.000
Operator	0.1528	0.2303	0.66	0.514
V.D.	0.023272	0.004847	4.80	0.000

S = 0.977170 R-Sq = 91.7% R-Sq(adj) = 89.7%

6.2.1 Testing the Usefulness of the Model

Some hypothesis tests have been done to determine whether the model is useful in predicting oxygen uptake or not. To test whether the overall model is useful, the null and alternative hypotheses are:

$$H_o: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$$

H_a : At least one parameter differs from zero

The test statistic $F=46.29$ and the p value $=0.000$ are given in the analysis of variance table. Since the p value is zero, H_o is rejected for any α level. So there is strong evidence to conclude the model is useful for predicting the oxygen uptake while doing lifting tasks.

Estimated Standard Error

An estimate of the error variance σ^2 is $s^2 = 0.955$, located in the analysis of variance table at the intersection of Error and MS. An estimate of σ , the standard deviation of the random error, is $s = 0.977170$

Coefficient of Determination

The coefficient of determination is $R^2 = 91.7\%$

$S = 0.977170$ $R\text{-Sq} = 91.7\%$ $R\text{-Sq (adj)} = 89.7\%$

The value of R^2 suggests that approximately 91.7% of total variation in oxygen uptake is explained by the regression model; 8.3% is not explained by the regression model.

6.2.2 Testing the Usefulness of the Predictors

The usefulness of the predictors is tested applying the hypothesis test. The least useful predictors are those with high p ($p > 0.05$) values. To test whether the h.d (horizontal distance), weight and operator, contribute significant information to predict y , the null and alternative hypotheses are.

$$H_o: \beta_2 = \beta_4 = 0$$

$$H_a: \beta_2 \neq \beta_4 \neq 0$$

Null hypothesis is not rejected because of higher value of p ($p > 0.05$). There is not sufficient evidence that h.d (horizontal distance) and operator are useful predictors.

6.2.3 The New Model

Since it has been found that h.d. (horizontal distance) and operator are not useful predictors, hence they are removed from the model. So the regression analysis was done again using weight, frequency and v.d. (vertical distance) as predictors. The regression equation obtained is shown in Equation.6.2.

The regression equation is

$$\begin{aligned} \text{Mean Oxygen uptake} = & - 4.75 + 0.365 \text{ Wt.} + 1.39 \text{ Freq.} \\ & + 0.0233 \text{ V.D.} \quad \text{..... Equation 6.2} \end{aligned}$$

Table 6.2 ANOVA for Regression Equation

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	220.578	73.526	82.58	0.000
Residual Error	23	20.479	0.890		
Total	26	241.057			

Predictor	Coef	SE Coef	T	P
Constant	-4.746	1.100	-4.31	0.000
Weight	0.36500	0.04448	8.21	0.000
Frequency	1.3875	0.1112	12.48	0.000
V.D.	0.023272	0.004680	4.97	0.000

S = 0.943606 R-Sq = 91.5% R-Sq (adj) = 90.4%

The first-order linear model is fitted to predict the oxygen uptake while doing lifting tasks.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

Where x_1 = weight x_2 = frequency and x_3 = v.d. (vertical distance)

The model is tested for its usefulness for predicting the volume of pulmonary oxygen uptake. The null and alternative hypotheses are:

$$H_o: \beta_1 = \beta_2 = \beta_3 = 0$$

H_a : At least one parameter differs from zero

The test statistic $F=82.58$ and the $p=0.000$ are given in the analysis of variance table. Since the p value is zero, H_o for any values α level is rejected. There is strong evidence to conclude that model is useful for predicting the variation of oxygen uptake by the worker for doing lifting tasks. Moreover, p-values of all the three predictors are less than $\alpha = 0.05$, which shows that load weight, frequency and vertical distance are useful

predictors. The least squares regression equation is given in Equation 6.2. The y -intercept $\beta_0 = -4.75$ ml/kg/min is the estimated oxygen uptake when all other variables are kept at zero level. $\beta_1 = 0.365$, $\beta_2 = 1.39$ and $\beta_3 = 0.0233$ are the coefficients of weight, frequency and vertical distance of lifting respectively. Coefficient of frequency is 1.39 which means oxygen uptake is increased by 1.39 ml/kg/min for increase of one level of frequency provided all other variables are kept constant. Higher the coefficient more is the impact of that factor on final values.

6.3 RESIDUAL ANALYSIS

The residual is the difference between the observed and fitted value of the response. Normal probability plot and histogram plots of the residual analysis for all oxygen uptakes are shown in the Figure 6.1. In residual plot of histogram x -axis of plot indicates the residuals and y -axis represents the frequency of occurrence of that residual. The normal probability plot and histogram indicate approximate normal distribution of residuals, which shows the absence of any particular variation affecting the readings that is not included in the model. In residual plot of fits, x -axis represents the oxygen uptake response and y -axis the residuals. A straight horizontal line shows the zero residual or the fitted model line. Which means all the points would have been lying on that if there is zero residual or no residual. The residuals are shown as dots in the graph. Absence of any particular trend of residuals in residual verses fitted value plot shows the good fit of the model. The residual vs. observation order plot shows residuals for all the 27 experiments.

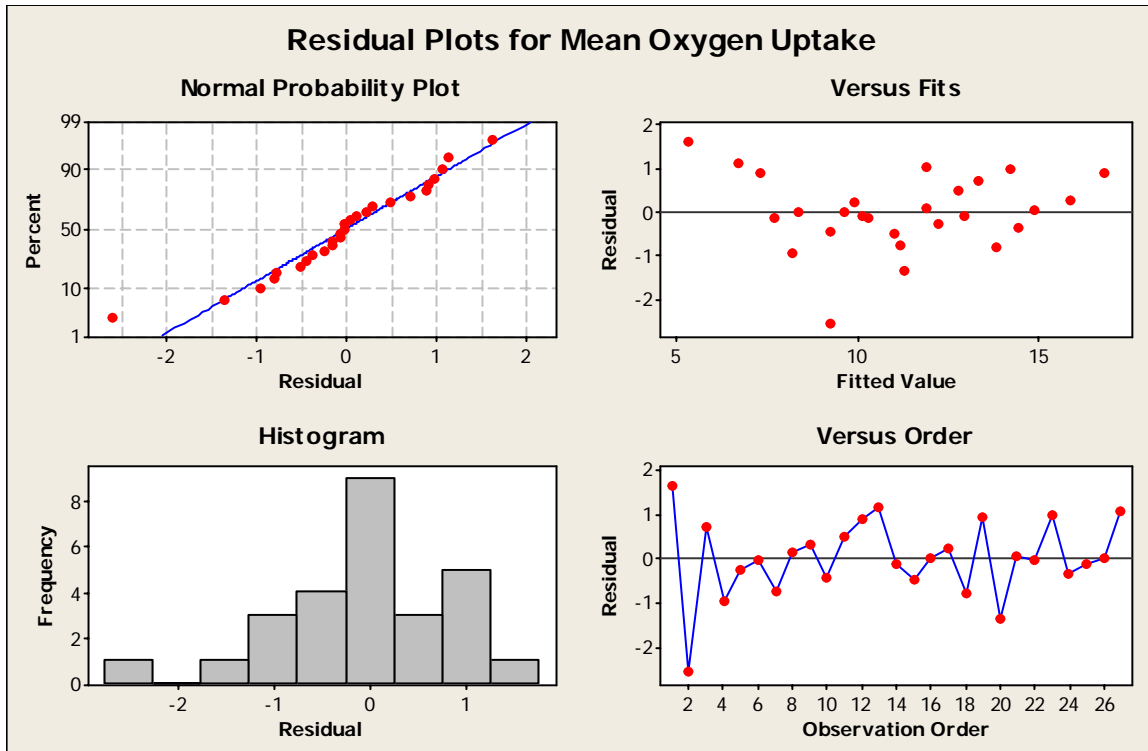


Figure 6.1: Residual plots for Oxygen Uptake

6.4 REGRESSION ANALYSIS FOR HEART RATE

From the ANOVA analysis of heart rate no interaction was found to be significant. So a general linear model is applied which excludes the interaction effect of the variables. The regression analysis has been done using MINITAB software and the equation obtained is shown in Equation. 6.3. ANOVA table for regression analysis is shown in Table 6.4.

$$\text{Mean heart rate} = 70.6 + 0.0019\text{H.d.} + 0.461\text{Wt.} + 3.43\text{Freq} + 1.08\text{Opr} + 0.0906\text{V.d.} \dots \dots \dots \text{Equation 6.3}$$

The coefficients of weight (0.461), H.d (0.0019), Frequency (3.43), Operator (1.08) and V.d. (.0906) in the equation represent the change in value of heart rate for a unit change in the value of that independent variable provided all other variables are kept constant.

Table 6.3 ANOVA for Regression Equation

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	1333.18	266.64	11.79	0.000
Residual Error	21	474.82	22.61		
Total	26	1808.00			

Predictor	Coef	SE Coef	T	P
Constant	70.584	6.629	10.65	0.000
H.d.	0.00185	0.07472	0.02	0.980
Weight	0.4611	0.2242	2.06	0.052
Frequency	3.4306	0.5604	6.12	0.000
Operator	1.083	1.121	0.97	0.345
V.d.	0.09056	0.02242	4.04	0.001

S = 4.75504 R-Sq = 73.7% R-Sq(adj) = 67.5%

6.4.1 Testing the Usefulness of the Model

Some hypothesis tests have been done to determine whether the model is useful in predicting heart rate. To test whether the overall model is useful, the null and alternative hypotheses are:

$$H_o: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$$

H_a : At least one parameter differs from zero

The test statistic $F=11.79$ and the $p=0.000$ are shown in the analysis of variance table. Since the p value is zero, H_o is rejected for any level. So there is strong evidence to conclude the model is useful for predicting the heart rate.

Estimated Standard Error

An estimate of the error variance σ^2 is $s^2=22.61$, located in the analysis of variance table at the intersection of Error and MS. An estimate of σ , the standard deviation of the random error, is $s = 4.75504$.

Coefficient of Determination

The coefficient of determination is $R^2 = 73.7\%$

$$S = 4.75504 \quad R\text{-Sq} = 73.7\% \quad R\text{-Sq (adj)} = 67.5\%$$

The value of R^2 suggests that approximately 73.7% of total variation in heart rate is explained by the regression model; 26.3% is not explained by the regression model.

6.4.2 Testing the Usefulness of the Predictors

The test for usefulness of the predictors is done by applying hypothesis. The least useful predictors are those with high p ($p>0.05$) values. To test whether the h.d (horizontal distance) weight and operator, contribute significant information to predict y, the null and alternative hypotheses are.

$$H_o: \beta_2 = \beta_3 = \beta_5 = 0$$

$$H_a: \beta_2 \neq \beta_3 \neq \beta_5 \neq 0$$

Null hypothesis is rejected because of higher value of p ($p>0.05$) in Table 6.3. There is not sufficient evidence that h.d and operator are useful predictors. As the p value for weight is close to 0.05, it is not excluded from the model.

6.4.3 The New Model

It has been found that h.d. and operator are not useful predictors; they are removed from new model. So the regression analysis was done again using weight, frequency and v.d. (vertical distance) as predictors. The regression equation obtained is shown in Equation 6.4 and Table of Analysis of Variance is shown in Table 6.4.

$$\text{Mean heart rate} = 72.8 + 3.43\text{Freq.} + 0.0906\text{V.d.} + 0.461 \text{Wt.}$$

..... **Equation 6.4**

Table 6.4 ANOVA for Regression Equation

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	1312.04	437.35	20.28	0.000
Residual Error	23	495.96	21.56		
Total	26	1808.00			

Predictor	Coef	SE Coef	T	P
Constant	72.825	5.348	13.62	0.000
Frequency	3.4306	0.5473	6.27	0.000
V.d.	0.09056	0.02189	4.14	0.000
Weight	0.4611	0.2189	2.11	0.046

S = 4.64364 R-Sq = 72.6% R-Sq(adj) = 69.0%

The first-order linear model is fitted to predict the heart rate while doing lifting tasks.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

Where x_1 = frequency x_2 = v.d. and x_3 = weight

The model is tested for its usefulness for predicting heart rate. The hypotheses are:

$$H_o: \beta_1 = \beta_2 = \beta_3 = 0$$

H_a : At least one parameter differs from zero

The test statistic $F=20.28$ and the $p\text{-value}=0.000$ are given in the analysis of variance table. Since the p value is zero H_o for any values of α is rejected. There is strong evidence to conclude that model is useful for predicting the values of heart rate for doing

lifting tasks. Moreover, p-values of all the three predictors are less than $\alpha = 0.05$, thus load weight, lift frequency and vertical distance are useful predictors.

6.5 RESIDUAL ANALYSIS

The residual is the difference between the observed and fitted value of the response. Normal probability plot and histogram plots of the residual analysis for heart rate is shown in the Figure 6.2. In residual plot of histogram x-axis of plot indicates the residuals and y-axis is indicating frequency of occurrence of that residual. The normal probability plot and histogram indicate approximate normal distribution of residuals, which shows the absence of any particular variation affecting the readings that is not included in the model. In residual plot of fits, x-axis represents the heart rate response and y-axis the residuals. A straight horizontal line shows the zero residual or the fitted model line. Which means all the points would have been lying on that line if there is zero residual or no residual. The residuals are shown as dots in the graph. Absence of any particular trend of residuals in residual verses fitted value plot shows the good fit of the model and ensures none of the considerable variation of errors is not absent in the model.

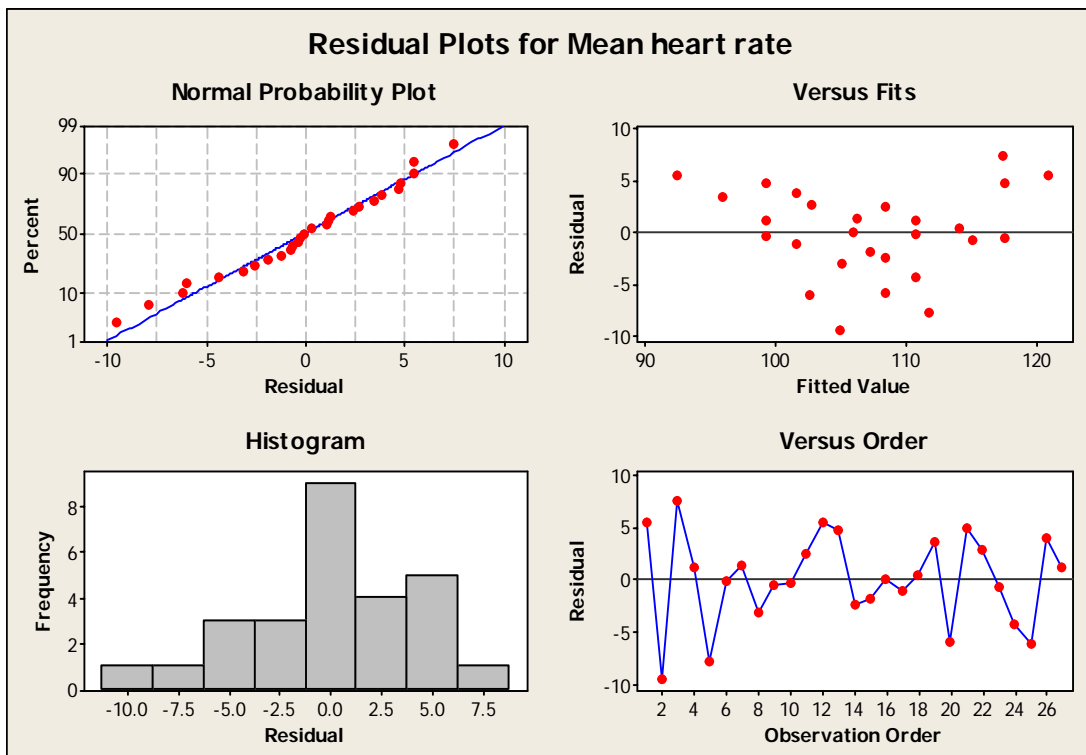


Figure 6.2: Residual plots for Heart Rate

CHAPTER 7

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

7.1 RESULTS

The effects of the five independent variables (namely lift frequency, load weight, horizontal distance from the object, operator and the vertical distance) and their interactions were evaluated using ANOVA and factorial design analysis. In addition, plots of the significant factors and interactions were developed to show significance. Regression analysis for heart rate and pulmonary oxygen uptake was completed. A predictor Regression Equation defined the empirical model that shows the significance of each factor and its relative contribution. The purpose of the ANOVA and significant factors plot was to identify the important parameters in prediction of heart rate and oxygen uptake. The regression analysis and ANOVA was done using the MINITAB15 software. Some results consolidated from ANOVA and plots are given below:

- Load weight ($p=0.000$), lift frequency ($p=0.001$) and vertical distance ($p=0.008$) were the three factors found significant in ANOVA of oxygen uptake.
- The horizontal distance and operator had no effect on oxygen uptake during lifting tasks described in the experimental study.
- Lift frequency was found to be most significant factor for oxygen uptake and the horizontal distance from the lift was found to be least significant as it shows negligible change of response for each of its three levels.
- The pulmonary oxygen uptake at extreme conditions (weight = 23 kg, v.d. = 150 cm and lift frequency = 7 lifts/min) was doubled as compared to relatively easier work conditions (weight = 13 kg, v.d. = 55cm and lifting frequency = 3 lifts/min).
- Since S/N ratio is higher the better response, lift frequency, load weight and vertical distance should be set at lower level i.e., 3 lifts/min, 13 kg and 55 cm respectively for reducing the variation in oxygen uptake.
- The estimated mean value of the pulmonary oxygen uptake when three significant factors were considered at their lower level i.e., weight 13 kg, frequency 3 lifts/min

and vertical distance 55 cm i.e., at knee level with 95% probability was found to be varying between 4.832 ml/kg/min and 6.918 ml/kg/min.

- The least squares regression equation for oxygen uptake was found to be: mean oxygen uptake = - 4.75 + 0.365 Wt. + 1.39 Freq. + 0.0233 V.D, where 0.365, 1.39, 0.0233 are the coefficients for load weight, lift frequency and vertical distance.
- Lift Frequency (p=0.003) and vertical distance (p=0.013) were the most significant factors affecting the heart rate. Also lift frequency (p=0.005) and vertical distance (p=0.019) were the significant factors in S/N ratio calculations.
- Frequency was found to be the most contributing factor and the horizontal distance was found to be the least significant factor for heart rate calculations.
- The worker stress level did not vary significantly from one individual to another.
- Since S/N ratio is higher the better response, heart rate, frequency, weight and vertical distance should be set at lower level i.e., 3lifts/min, 13 kg and 55 cm respectively for reducing the variation in heart rate.
- The estimated mean of the heart rate when the two significant factors were considered at their lower level i.e., frequency 3lifts/min and vertical distance 55cm i.e., at knee level with 95% probability was found to be varying between 93.03 beats/min and 101.97 beats/min.
- The least squares regression equation for heart rate was found to be mean heart rate = 72.8 + 3.43Freq. + 0.0906V.d. + 0.461 Wt, where 3.43, 0.906 and 0.461 are the coefficients for lift frequency, vertical distance and load weight respectively

7.2 CONCLUSIONS AND RECOMMENDATIONS

The manual lifting tasks typically undertaken by Indian operators at their workplaces were evaluated with a focus on the physiological effects of load weight, lift frequency, horizontal distance and vertical distance on the operator. The results of the experiment showed that lifting loads and higher lifting frequencies increases the physiological workloads. The tasks become even more stressful when the vertical distance of the lift is above the shoulder level. The effect of the load weight and frequency of lift was found to

be most significant factors leading to the increased oxygen uptake and heart rate when carrying heavier loads such as 23 kilogram at high lifting frequency (7 lifts per minute).

Mechanized lifting either fully or partially is must to ease the task for the operators and if not possible the task must be followed by substantial rest periods varying from 30 minutes to one hour after continuous lifting of more than one hour. It is important to design appropriate work rest cycles and incorporated into such tasks. Empirical model generated for heart rate and oxygen uptake calculations could be used to optimize the output parameters. The equation generated generalizes the task conditions and could be used to describe job designs of manual lifting tasks. The recommendation of this thesis coupled with appropriate training could ease the task of large number of Indian workers engaged in manual lifting tasks.

7.3 SCOPE FOR FURTHER WORK

Further investigations are necessary to identify the strenuous levels of lifting parameters which stresses the cardiovascular system of the workers. A detailed work guide should be created fixing the higher levels of lifting parameters to lower the cardiovascular risks and metabolic energy expenditure of the workers. Moreover, a rigorous study of the interaction affect is needed to have a better understanding of the physiological risks involved in lifting operations.

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