

**ERGONOMIC INVESTIGATIONS OF ASYMMETRICAL  
MANUAL LIFTING TASKS ON INDIAN MALE WORKERS**

**A THESIS**

Submitted in fulfillment of the requirements  
for the award of the degree  
of

**DOCTOR OF PHILOSOPHY**  
in  
**MECHANICAL ENGINEERING**

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**JULY, 2014**

## **PREFACE**

This research work was carried out by the author under the guidance of Dr. Ajay Batish, Professor & Head, Department of Mechanical Engineering at Thapar University, Patiala and Dr. Tejinder Pal Singh, Professor & Director, Symbiosis Institute of Technology, Pune, Maharashtra.

The measuring equipment COSMED (Model: Fitmate PRO-C09066-02-99, Make: COSMED, Rome, Italy), other measuring apparatus and facilities available at Department of Mechanical Engineering, Thapar University, Patiala were used for this research work.

The Kistler force platforms and other supporting equipments were available in Defence Institute of Physiology and Applied Sciences (DIPAS) lab at DRDO New Delhi.

Several research papers were published out of this research work.

**The list of Journals/ Conference in which the papers finds places is given below:**

### **Journals:**

1. Singh R., Batish A, Singh T.P., Bhattacharya A. (2014). An experimental study to evaluate the effect of ambient temperature during manual lifting and design of optimal task parameters. Human Factors and Ergonomics in Manufacturing and Service Industry, Volume 24, Issue 1, pp 56-70
2. Singh R., Batish A, Singh T.P. (2014). Determination of safe limits of significant task parameters during manual lifting. Workplace Health and Safety, Volume 62, Issue 4, pp 150-160

### **Conference**

1. Singh R., Batish A., Sharma S. K. (2008), Proposed Method to Modify the Lifting Equation, Proceedings of the 3<sup>rd</sup> National Conference on Recent Advancements in Mechanical Engineering, Nov 14-15, 2008, pp 154-166.
2. Singh R., Batish A., Singh T.P. (2011). Analyzing s/n ratio optimization of physiological stress of Indian male workers in summer & winter during manual lifting tasks. Contemporary Ergonomics and Human Factors: Proceedings of the international conference on Ergonomics & Human Factors 2011, Stoke Rochford, Lincolnshire, 12-14

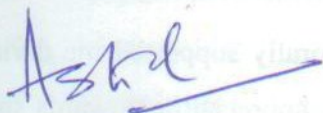
April 2011, pp 270-277. (Book Chapter 37, pp 270-277 Taylor and Francis publisher)

**The list of journals in which the papers are communicated is given below:**

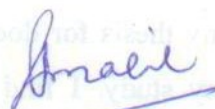
1. “Prediction of ground reaction forces of Indian male workers using neural network during lifting operations” submitted to International journal of Industrial engineering: Theory, Applications and Practices.
2. “Optimization of Physiological Stress and Ground Reaction Forces of Indian Male Workers using AHP during Lifting Operations” submitted to International Journal of Human factor and ergonomics.
3. “An empirical study to assess heart rate during manual lifting tasks” submitted to Occupational Ergonomics.

## CERTIFICATE

Certified that the thesis entitled, '**ERGONOMIC INVESTIGATIONS OF ASYMMETRICAL MANUAL LIFTING TASKS ON INDIAN MALE WORKERS**' being submitted by Ravindra Pratap Singh, to Mechanical Engineering Department, Thapar University, Patiala, in fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY**, is a record of bonafide research work carried out by him under my guidance and supervision. The matter presented in the 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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## ACKNOWLEDGEMENT

It is my humble privilege to thank and express my deepest gratitude towards my work supervisors Dr. Ajay Batish, Professor & Head, Mechanical Engineering Department, Thapar University, Patiala and Dr. Tejinder Pal Singh, Professor & Director, Symbiosis Institute of Technology, Pune, Maharashtra, India, whose concrete and constructive suggestions, keen interest, unfailing and inspiring guidance as well as critical evaluation of entire manuscript made it possible for me to complete my objectives. I am deeply indebted to their outstanding practical and vast research knowledge. I extend my heartfelt thanks to my supervisors forever. I am thankful to almighty God because without His blessings it would be quite difficult to complete this task.

My sincere thanks to Prof. Prakash Gopalan, Director, Thapar University, Patiala and Dr. P. Bajpai, Distinguished Professor and Dean (Research and Sponsored Projects), Thapar University, Patiala for providing me required institutional facilities and constant help.

I devote my thesis for doctorate to my parents who morally supported me during the entire span of my study. I find myself wordless to express appreciation towards my wife Mrs. Ranjana and my sons Master Hritish and Master Chotu who cooperated and encouraged me during my research work with positive attitude.

It would be quite difficult find to express short acknowledgements to my loving friends Mr. Gaurav Sahdev, Mr. Sanjeev Sharma and Mr. Sushil Mittal, and faculty member Mr. Anirban Bhattacharya, Thapar University, Patiala who have not only gave me a continuous and constant encouragement but also had been actively assisted me in this venture.

I would also like to thank to research students at Thapar University Patiala for their support. Last but not the least, I would never forget to thank to all those persons who helped and supported me throughout my PhD journey.

*Ravindra Pratap Singh*  
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# CONTENTS

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| <b><u>TITLE</u></b>                                                      | <b><u>PAGE NO.</u></b> |
|--------------------------------------------------------------------------|------------------------|
| <b>Preface</b>                                                           | <b>ii</b>              |
| <b>Certificate</b>                                                       | <b>iv</b>              |
| <b>Acknowledgement</b>                                                   | <b>v</b>               |
| <b>Contents</b>                                                          | <b>vi</b>              |
| <b>List of Figures</b>                                                   | <b>x</b>               |
| <b>List of Tables</b>                                                    | <b>xv</b>              |
| <b>Abstract</b>                                                          | <b>xix</b>             |
| <br>                                                                     |                        |
| <b>Chapter – 1 INTRODUCTION</b>                                          | <b>1</b>               |
| 1.1 Lifting Tasks and Injuries                                           | 1                      |
| 1.2 Safe Lifting Weights and Parameters                                  | 4                      |
| 1.3 Objectives of the Study                                              | 5                      |
| 1.4 Methodology                                                          | 5                      |
| 1.5 Organization of the Thesis                                           | 7                      |
| <br>                                                                     |                        |
| <b>Chapter – 2 LITERATURE REVIEW</b>                                     | <b>11</b>              |
| 2.1 Categorization of Literature Review                                  |                        |
| 2.1.1 Manual Material Handling                                           | 11                     |
| 2.1.2 Lifting Task                                                       | 17                     |
| 2.1.3 Effect of lifting tasks on ground reaction forces                  | 27                     |
| 2.1.4 Analysis of lifting tasks neural networks                          | 29                     |
| 2.1.5 Lifting and Carrying Tasks                                         | 31                     |
| 2.1.6 Application of NIOSH lifting equation to analysis of lifting tasks | 35                     |
| 2.2 Summary, Limitations and Need of Study                               | 38                     |
| <br>                                                                     |                        |
| <b>Chapter – 3 DESIGN OF STUDY</b>                                       | <b>39</b>              |
| 3.1 Pilot Experimentation                                                | 39                     |
| 3.2 Methodology                                                          | 48                     |
| 3.3 Procedures of Taguchi Method                                         | 48                     |
| 3.3.1 Establishment of objective function                                | 49                     |
| 3.3.2 Determine the measurement methods                                  | 49                     |

|                    |                                                                                                            |           |
|--------------------|------------------------------------------------------------------------------------------------------------|-----------|
| 3.3.3              | Determination of controllable factors and their levels                                                     | 49        |
| 3.3.4              | Identification of uncontrollable factors and test conditions                                               | 50        |
| 3.3.5              | Design of Taguchi crossed array layout                                                                     | 50        |
| 3.3.6              | Execution of experiments according to trial conditions                                                     | 52        |
| 3.3.7              | Analysis of results                                                                                        | 52        |
| 3.4                | Experimental Design                                                                                        | 54        |
| 3.5                | Multiple Regression Model                                                                                  | 54        |
| <b>Chapter – 4</b> | <b>EFFECT OF AMBIENT TEMPERATURE DURING<br/>MANUAL LIFTING</b>                                             | <b>55</b> |
| 4.1                | Experiment Design                                                                                          | 55        |
| 4.2                | Analysis of Oxygen Uptake and Heart Rate                                                                   | 59        |
| 4.3                | Analysis of Perceived Exertion                                                                             | 65        |
| 4.4                | Optimal Design                                                                                             | 66        |
| 4.4.1              | Optimal design for oxygen uptake and heart rate                                                            | 70        |
| 4.5                | Effect of Ambient Temperature                                                                              | 71        |
| 4.5.1              | Analysis for summer (Ambient temperature 35° C)                                                            | 71        |
| 4.5.2              | Analysis for winter (Ambient temperature 5° - 10° C)                                                       | 72        |
| 4.6                | Multi -Response Optimization                                                                               | 74        |
| 4.6.1              | Sample MRSN calculation                                                                                    | 80        |
| 4.6.2              | Maximum MRSN for all trials                                                                                | 83        |
| 4.6.3              | Main Effect and Interaction Plots                                                                          | 84        |
| 4.6.4              | Regression Analysis for MRSN                                                                               | 88        |
| 4.7                | Development of a Multiplicative Equation to Calculate Predicted<br>Heart Rate (PHR)                        | 89        |
| 4.7.1              | Determining the correction coefficients                                                                    | 90        |
| 4.7.2              | Sample PHR calculation for load of 20 kg at a frequency of<br>7 lifts/min up to a height 100 cm for winter | 92        |
| 4.7.3              | PHR Index                                                                                                  | 93        |
| 4.7.4              | Confirmation Experiment                                                                                    | 94        |
| <b>Chapter – 5</b> | <b>PREDICTED OXYGEN UPTAKE (POU)</b>                                                                       | <b>95</b> |
| 5.1                | Experiment Design                                                                                          | 95        |
| 5.2                | Analysis of Oxygen uptake                                                                                  | 96        |
| 5.2.1              | Main Effect and Interaction Plots                                                                          | 100       |

|                    |                                                                                                      |            |
|--------------------|------------------------------------------------------------------------------------------------------|------------|
| 5.3                | Optimal Design for Oxygen Uptake                                                                     | 100        |
| 5.4                | Development of a Multiplicative Equation to Calculate Predicted Oxygen Uptake (POU)                  | 104        |
| 5.4.1              | POU Calculation for Different Combination of Load, Frequency, Vertical Distance (one sample example) | 108        |
| 5.4.2              | POU Index                                                                                            | 109        |
| 5.4.3              | Validation                                                                                           | 109        |
| <b>Chapter – 6</b> | <b>SAFE LIMITS OF MANUAL LIFTING TASK PARAMETERS USING BIOMECHANICS PRINCIPLE</b>                    | <b>111</b> |
| 6.1                | Experiment Design                                                                                    | 111        |
| 6.2                | Ground Reaction force                                                                                | 114        |
| 6.2.1              | Measurement of ground reaction force                                                                 | 114        |
| 6.2.2              | Calculation of Loading Rate from Vertical Reaction Force                                             | 123        |
| 6.3                | Analysis of Ground Reaction Force                                                                    | 123        |
| 6.4                | Optimal Design for Loading Rate                                                                      | 128        |
| <b>Chapter – 7</b> | <b>PREDICTION OF LOADING RATE USING NEURAL NETWORKS</b>                                              | <b>137</b> |
| 7.1                | Experiment Design                                                                                    | 137        |
| 7.2                | Calculation of Loading rate                                                                          | 138        |
| 7.3                | Analysis of Loading rate                                                                             | 140        |
| 7.4                | Artificial Neural Network                                                                            | 142        |
| <b>Chapter – 8</b> | <b>OPTIMIZATION FOR EXPERIMENTAL SETTING FOR SAFE LIFTING</b>                                        | <b>150</b> |
| 8.1                | Experiment Design                                                                                    | 150        |
| 8.2                | Measurement of Responses                                                                             | 152        |
| 8.3                | Analytical Hierarchical Process                                                                      | 155        |
| 8.4                | Implementation of AHP in Lifting Operation                                                           | 158        |
| <b>Chapter – 9</b> | <b>RESULTS, DISCUSSION AND CONCLUSIONS</b>                                                           | <b>169</b> |
| 9.1                | Effect of Environmental Conditions during Manual Lifting                                             | 169        |
| 9.2                | Predicted Oxygen Uptake                                                                              | 175        |
| 9.3                | Safe Limits Of Manual Lifting Task Parameters Using                                                  | 176        |

|                     |                                                          |            |
|---------------------|----------------------------------------------------------|------------|
|                     | Biomechanics Principle                                   |            |
| 9.4                 | Predicted Loading Rate Using Neural Networks             | 182        |
| 9.5                 | Optimization of Experimental Setting<br>for Safe Lifting | 183        |
| 9.6                 | Conclusion                                               | 183        |
| 9.7                 | Future Scope of Study                                    | 184        |
| <b>REFERENCES</b>   |                                                          | <b>186</b> |
| <b>APPENDIX – I</b> | Mat lab code                                             | 203        |

## LIST OF FIGURES

| <b>Figure No.</b> | <b>Title</b>                                                                                                                                                                    | <b>Page No.</b> |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| <b>Figure 3.1</b> | Phases of study                                                                                                                                                                 | 40              |
| <b>Figure 3.2</b> | Flow chart of the study of phase I                                                                                                                                              | 41              |
| <b>Figure 3.3</b> | Flow chart of the study of phase II                                                                                                                                             | 42              |
| <b>Figure 3.4</b> | The effect of lifting frequency on oxygen uptake and heart rate                                                                                                                 | 43              |
| <b>Figure 3.5</b> | The effect of vertical distance on oxygen uptake and heart rate                                                                                                                 | 44              |
| <b>Figure 3.6</b> | The effect of load weight on oxygen uptake and heart rate                                                                                                                       | 44              |
| <b>Figure 3.7</b> | Loading rate plot with vertical distance keeping load and frequency<br>Constant                                                                                                 | 46              |
| <b>Figure 3.8</b> | Loading rate plot with frequency keeping load and vertical distance<br>constant                                                                                                 | 47              |
| <b>Figure 3.9</b> | Loading rate plot with load rate keeping vertical distance and frequency                                                                                                        | 47              |
| <b>Figure 4.1</b> | COSMED ( <i>Fitmate-PRO</i> ) pulmonary function equipment being<br>used for lifting task                                                                                       | 57              |
| <b>Figure 4.2</b> | Level effect for each factor on oxygen uptake during summer<br>and winter                                                                                                       | 63              |
| <b>Figure 4.3</b> | Level effect for each factor on heart rate during summer<br>and winter                                                                                                          | 63              |
| <b>Figure 4.4</b> | Mean responses during each trial at summer and winter                                                                                                                           | 64              |
| <b>Figure 4.5</b> | Sample COSMED output of oxygen uptake and heart rate for trials<br>where high exertion was reported (a) 27 <sup>th</sup> trial (summer),<br>(b) 26 <sup>th</sup> trial (winter) | 68              |
| <b>Figure 4.6</b> | Sample COSMED output of oxygen uptake and heart rate for trials<br>where low exertion was reported (a) 2 <sup>nd</sup> trial (summer)<br>(b) 1 <sup>st</sup> trial (winter)     | 69              |
| <b>Figure 4.7</b> | Sample COSMED output of oxygen uptake and heart rate for trials<br>(a) 23 <sup>rd</sup> trial, (b) 27 <sup>th</sup> trial (summer)                                              | 69              |
| <b>Figure 4.8</b> | Sample COSMED output of oxygen uptake and heart rate for trials<br>(a) 15 <sup>th</sup> trial (summer), (b) 17 <sup>th</sup> trial (winter)                                     | 69              |
| <b>Figure 4.9</b> | Sample COSMED output of oxygen uptake and heart rate for trials                                                                                                                 | 70              |

|                      |                                                                                                                                                      |     |
|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|                      | (a) 26 <sup>th</sup> trial (b) 27 <sup>th</sup> trial (winter)                                                                                       |     |
| <b>Figure 4.10</b>   | Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task in summer and winter                      | 73  |
| <b>Figure 4.11</b>   | Optimum heart rate for different level setting of significant factors for identifying safe lifting task in summer and winter                         | 73  |
| <b>Figure 4.12</b>   | Graphical representation of MRSN (winter)                                                                                                            | 84  |
| <b>Figure 4.13</b>   | Graphical representation of MRSN (summer)                                                                                                            | 84  |
| <b>Figure 4.14</b>   | Main Effects Plot for MRSN (winter)                                                                                                                  | 85  |
| <b>Figure 4.15</b>   | Interaction plot for MRSN (winter)                                                                                                                   | 86  |
| <b>Figure 4.16</b>   | Main Effects Plot for MRSN (summer)                                                                                                                  | 86  |
| <b>Figure 4.17</b>   | Interaction plot for MRSN (summer)                                                                                                                   | 87  |
| <b>Figure 4.18</b>   | Correction coefficients plot for three significant factors over the entire range; (a) for load, (b) for lift frequency and (c) for vertical distance | 92  |
| <b>Figure 4.19</b>   | Assessment chart for determination of safe lifting task using heart rate measurement                                                                 | 94  |
| <b>Figure 5.1</b>    | Worker involved in manual lifting task using COSMED pulmonary equipment                                                                              | 97  |
| <b>Figure 5.2</b>    | Fitmate Pro output for low and high exertion Trial condition (a) for Trial 1 and (b) for Trial 12                                                    | 100 |
| <b>Figure 5.3</b>    | Main effect plot for oxygen uptake                                                                                                                   | 101 |
| <b>Figure 5.4</b>    | Interaction plot for oxygen uptake                                                                                                                   | 101 |
| <b>Figure 5.5</b>    | Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task                                           | 104 |
| <b>Figure 5.6</b>    | Plot of normalized oxygen uptake and correction coefficients for the three significant factors                                                       | 108 |
| <b>Figure 5.7</b>    | Assessment chart for determination of safe lifting task using oxygen Uptake measurement                                                              | 110 |
| <b>Figure 6.1</b>    | Worker involved in lifting task with Kistler force platform (9286AA)                                                                                 | 113 |
| <b>Figure 6.2(a)</b> | Force –time vertical reaction force graph for workers involved in lifting task (Trial no 15, weight 18 kg, frequency 7 lifts in                      | 116 |

60 seconds, vertical distance shoulder height)

|                      |                                                                                                                                                                                                                                                                                |     |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 6.2(b)</b> | Force –time vertical reaction force graph for workers involved in lifting task(Trial no 15, weight 18 kg, frequency 7 lifts/min, vertical distance shoulder height in cm for one lift (7 <sup>th</sup> , in this case) in 8.5sec) Vertical reaction force ( $F_z$ ) in Newton) | 116 |
| <b>Figure 6.3</b>    | Graphical output of vertical ground reaction force of trial no. 3                                                                                                                                                                                                              | 117 |
| <b>Figure 6.4</b>    | Graphical output of vertical ground reaction force of trial no. 6                                                                                                                                                                                                              | 117 |
| <b>Figure 6.5</b>    | Graphical output of vertical ground reaction force of trial no. 9                                                                                                                                                                                                              | 118 |
| <b>Figure 6.6</b>    | Graphical output of vertical ground reaction force of trial no. 13                                                                                                                                                                                                             | 118 |
| <b>Figure 6.7</b>    | Graphical output of vertical ground reaction force of trial no. 18                                                                                                                                                                                                             | 119 |
| <b>Figure 6.8</b>    | Graphical output of vertical ground reaction force of trial no. 21                                                                                                                                                                                                             | 119 |
| <b>Figure 6.9</b>    | Graphical output of vertical ground reaction force of trial no. 24                                                                                                                                                                                                             | 120 |
| <b>Figure 6.10</b>   | Graphical output of vertical ground reaction force of trial no. 27                                                                                                                                                                                                             | 120 |
| <b>Figure 6.11</b>   | Main effects plot for Means (vertical ground reaction force $F_z$ )                                                                                                                                                                                                            | 126 |
| <b>Figure 6.12</b>   | Main effects plot for Means (loading rate, LR)                                                                                                                                                                                                                                 | 127 |
| <b>Figure 6.13</b>   | Mean loading rate plot with variation in weight, frequency and vertical distance                                                                                                                                                                                               | 128 |
| <b>Figure 6.14</b>   | Correlation graph of loading rate and oxygen uptake for workers involved in lifting                                                                                                                                                                                            | 130 |
| <b>Figure 6.15</b>   | Correlation graph of loading rate and heart rate for workers involved in lifting                                                                                                                                                                                               | 131 |
| <b>Figure 6.16</b>   | Correlation graph of loading rate, oxygen uptake and heart rate for workers involved in lifting                                                                                                                                                                                | 131 |
| <b>Figure 6.17</b>   | Safe optimum graph of loading rate for workers involved in lifting task                                                                                                                                                                                                        | 134 |
| <b>Figure 6.18</b>   | Safe optimum graph of oxygen uptake for workers involved in lifting task                                                                                                                                                                                                       | 134 |
| <b>Figure 6.19</b>   | Safe optimum graph of heart rate for workers involved in lifting task                                                                                                                                                                                                          | 135 |
| <b>Figure 7.1</b>    | Experimental Set up with Kistler force platforms                                                                                                                                                                                                                               | 138 |
| <b>Figure 7.2</b>    | Force –time vertical reaction force graph for workers involved in lifting task (Trial no. 10, 5 lifts in 60 seconds)                                                                                                                                                           | 139 |
| <b>Figure 7.3</b>    | Force –time vertical reaction force graph for workers involved in lifting tasks (Trial no. 10, one lift (2 <sup>nd</sup> , in this case) in 10.5 sec)                                                                                                                          | 140 |

|                      |                                                                                                                                                                                                                                                                                         |     |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 7.4</b>    | Schematic diagram of single neuron in a network model, showing how it was connected to other nodes and the each input connections with weight                                                                                                                                           | 143 |
| <b>Figure 7.5</b>    | Comparison of the experimental value and predicted value from ANN model                                                                                                                                                                                                                 | 145 |
| <b>Figure 7.6</b>    | All performances result of ANN predicted model for loading rate                                                                                                                                                                                                                         | 146 |
| <b>Figure 7.7</b>    | The comparison of the experimental results and predicted results obtained by the neural network                                                                                                                                                                                         | 147 |
| <b>Figure 7.8</b>    | Linear regression analysis between the experimental values and predicted values of loading rate for training, validation, testing and overall                                                                                                                                           | 148 |
| <b>Figure 7.9</b>    | Learning behavior of the neural network model                                                                                                                                                                                                                                           | 148 |
| <b>Figure 8.1</b>    | Experimental Set up with Kistler force platforms and and COSMED pulmonary function equipment                                                                                                                                                                                            | 151 |
| <b>Figure 8.2(a)</b> | Vertical reaction force-time graph for workers involved in lifting task (Trial no 19, worker no. 9, weight 13 kg, frequency 9 lifts/min, vertical distance shoulder height in cm for 9 lifts in 60 seconds)                                                                             | 153 |
| <b>Figure 8.2(b)</b> | Vertical reaction force-time graph for workers involved in lifting task (Trial no 19, worker no. 9, weight 13 kg, frequency 9 lifts/min, vertical distance shoulder height in cm for one lift (2 <sup>nd</sup> , in this case) in 6.5sec), Vertical reaction force ( $F_z$ ) in Newton) | 153 |
| <b>Figure 8.3</b>    | Oxygen uptake and heart rate for trials where high exertion were reported 23 <sup>rd</sup> trial, (b) 27 <sup>th</sup> trial                                                                                                                                                            | 156 |
| <b>Figure 8.4</b>    | Oxygen uptake and heart rate for trials where moderate exertion were reported (a) 6 <sup>th</sup> trial, (b) 15 <sup>th</sup> trial (c) 21 <sup>th</sup> trial                                                                                                                          | 156 |
| <b>Figure 8.5</b>    | Hierarchy tree of the studied problem of analytic hierarchy process                                                                                                                                                                                                                     | 159 |
| <b>Figure 8.6</b>    | Correlation in optimal setting parameters for safe lifting using AHP                                                                                                                                                                                                                    | 168 |
| <b>Figure 9.1</b>    | Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task in summer & winter                                                                                                                                                           | 173 |
| <b>Figure 9.2</b>    | Optimum heart rate for different level setting of significant factors                                                                                                                                                                                                                   | 174 |

|                   |                                                                                                                                                      |     |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|                   | for identifying safe lifting task in summer and winter                                                                                               |     |
| <b>Figure 9.3</b> | Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task without the effect of ambient temperature | 176 |
| <b>Figure 9.4</b> | Loading rate plot with load and frequency keeping vertical height constant                                                                           | 177 |
| <b>Figure 9.5</b> | Loading rate plot with load and vertical distance keeping frequency constant                                                                         | 178 |
| <b>Figure 9.6</b> | Loading rate plot with frequency and vertical distance keeping load constant                                                                         | 178 |
| <b>Figure 9.7</b> | Optimum loading rate for different level setting of significant factors for identifying safe lifting task                                            | 181 |
| <b>Figure 9.8</b> | Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task                                           | 181 |
| <b>Figure 9.9</b> | Optimum heart rate for different level setting of significant factors for identifying safe lifting task                                              | 182 |

## LIST OF TABLES

| <b>Table No.</b>  | <b>Title</b>                                                                                                                                         | <b>Page No</b> |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>Table 3.1</b>  | Factors and their levels identified during pilot study                                                                                               | 45             |
| <b>Table 4.1</b>  | Factors and their levels involved in the study                                                                                                       | 55             |
| <b>Table 4.2</b>  | Demographic details of the subjects                                                                                                                  | 56             |
| <b>Table 4.3</b>  | L <sub>27</sub> Experimental design for first part of the study of first phase                                                                       | 58             |
| <b>Table 4.4</b>  | Results for oxygen uptake & heart rate (summer)                                                                                                      | 59             |
| <b>Table 4.5</b>  | Results for oxygen uptake & heart rate (winter)                                                                                                      | 60             |
| <b>Table 4.6</b>  | Pooled ANOVA for oxygen uptake                                                                                                                       | 61             |
| <b>Table 4.7</b>  | Pooled ANOVA for heart rate                                                                                                                          | 62             |
| <b>Table 4.8</b>  | Seasonal percentage change in oxygen uptake, heart rate and perceived exertion                                                                       | 64             |
| <b>Table 4.9</b>  | Response table for mean oxygen uptake                                                                                                                | 67             |
| <b>Table 4.10</b> | Response table for mean heart rate                                                                                                                   | 67             |
| <b>Table 4.11</b> | Decision matrix for identifying safe lifting task                                                                                                    | 71             |
| <b>Table 4.12</b> | Results for oxygen uptake & heart Rate (winter)                                                                                                      | 75             |
| <b>Table 4.13</b> | Results for oxygen uptake & heart Rate (summer)                                                                                                      | 76             |
| <b>Table 4.14</b> | Normalization of Signal to Noise ratio of the responses                                                                                              | 77             |
| <b>Table 4.15</b> | Normalized S/N ratio of responses converted to MRSN using L <sub>9</sub> OA as weight matrix (sample calculations for 3 <sup>rd</sup> trial, winter) | 78             |
| <b>Table 4.16</b> | Normalized S/N ratio of responses converted to MRSN using L <sub>9</sub> OA as weight matrix (sample for 3 <sup>rd</sup> trial, summer)              | 79             |
| <b>Table 4.17</b> | Weight effect of responses at each level (Sample representation of 3 <sup>rd</sup> trial)                                                            | 80             |
| <b>Table 4.18</b> | Final MRSN corresponding to each trial (winter)                                                                                                      | 81             |
| <b>Table 4.19</b> | Response table/ level effect of control factors (winter)                                                                                             | 82             |
| <b>Table 4.20</b> | Response table/ level effect of control factors (summer)                                                                                             | 82             |
| <b>Table 4.21</b> | ANOVA table for MRSN (winter)                                                                                                                        | 82             |
| <b>Table 4.22</b> | ANOVA table for MRSN (summer)                                                                                                                        | 83             |
| <b>Table 4.23</b> | Analysis of Variance for regression analysis for significance of model                                                                               | 89             |
| <b>Table 4.24</b> | Regression analysis for MRSN                                                                                                                         | 89             |

|                   |                                                                                                                                                  |     |
|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Table 4.25</b> | Correction Coefficients (CC) for the different levels of the significant factors and ambient temperature                                         | 93  |
| <b>Table 5.1</b>  | Factors studied with their levels in second part of the study of first phase                                                                     | 95  |
| <b>Table 5.2</b>  | Mean oxygen uptake of workers with L <sub>27</sub> experimental design                                                                           | 98  |
| <b>Table 5.3</b>  | ANOVA table for oxygen uptake                                                                                                                    | 99  |
| <b>Table 5.4</b>  | Response table for means of oxygen uptake                                                                                                        | 99  |
| <b>Table 5.5</b>  | Mean and normalized oxygen uptake for different levels of three significant factors                                                              | 103 |
| <b>Table 5.6</b>  | Response table of mean normalized oxygen uptake                                                                                                  | 106 |
| <b>Table 5.7</b>  | Interpolated and extrapolated values of normalized oxygen uptake                                                                                 | 106 |
| <b>Table 5.8</b>  | Correction coefficients for the different levels of the three significant factors                                                                | 109 |
| <b>Table 6.1</b>  | Factors studied with their levels in first part of study of second phase                                                                         | 112 |
| <b>Table 6.2</b>  | Vertical ground reaction force ( $F_z$ ), lower, mean and peak values                                                                            | 121 |
| <b>Table 6.3</b>  | Mean loading rate (LR) of workers                                                                                                                | 124 |
| <b>Table 6.4</b>  | Lower, peak and mean values of Vertical ground reaction force (GRF) ( $F_z$ ) and mean loading rate of all workers with experiment design trials | 125 |
| <b>Table 6.5</b>  | Pooled ANOVA for Vertical ground reaction forces ( $F_z$ ) and Loading Rate (LR)                                                                 | 126 |
| <b>Table 6.6</b>  | Extra loading rate required with changing levels of significant factors                                                                          | 128 |
| <b>Table 6.7</b>  | Decision matrix for identifying safe lifting task (options for optimal designs)                                                                  | 133 |
| <b>Table 6.8</b>  | Safe Limits for various combinations of weight, lifting frequency and vertical distance                                                          | 135 |
| <b>Table 7.1</b>  | Factors involved with their levels in second part of study of                                                                                    | 137 |

|                   |                                                                                   |     |
|-------------------|-----------------------------------------------------------------------------------|-----|
|                   | second phase                                                                      |     |
| <b>Table 7.2</b>  | Mean loading rate of all workers with experiment design trials                    | 141 |
| <b>Table 7.3</b>  | Pooled ANOVA for loading rate                                                     | 142 |
| <b>Table 7.4</b>  | Comparison of the experimental value and predicted value from ANN model           | 145 |
| <b>Table 7.5</b>  | Mean squared error and Regression error of predicted model results                | 147 |
| <b>Table 7.6</b>  | Correlation between the experimental value and ANN model value                    | 149 |
| <b>Table 7.7</b>  | Paired sample t- test of pair<br>(Experimental value and ANN model value)         | 149 |
| <b>Table 8.1</b>  | Factors studied with their levels                                                 | 151 |
| <b>Table 8.2</b>  | Design of Experiment ( $L_{27}$ ) with output responses                           | 154 |
| <b>Table 8.3</b>  | Analysis of variance for oxygen uptake, heart rate and loading rate               | 155 |
| <b>Table 8.4</b>  | The Saaty Rating scale                                                            | 157 |
| <b>Table 8.5</b>  | Random consistency index                                                          | 158 |
| <b>Table 8.6</b>  | Pair-wise comparison of criteria                                                  | 159 |
| <b>Table 8.7</b>  | Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample I      | 159 |
| <b>Table 8.8</b>  | Pair-wise comparison of heart rate w.r.t. their alternatives for sample I         | 160 |
| <b>Table 8.9</b>  | Pair-wise comparison of loading rate w.r.t. their alternatives for sample I       | 160 |
| <b>Table 8.10</b> | Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample I | 161 |
| <b>Table 8.11</b> | Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample II     | 161 |
| <b>Table 8.12</b> | Pair-wise comparison of heart rate w.r.t. their alternatives for sample II        | 161 |
| <b>Table 8.13</b> | Pair-wise comparison of loading rate w.r.t. their alternatives for sample II      | 162 |

|                   |                                                                                            |     |
|-------------------|--------------------------------------------------------------------------------------------|-----|
| <b>Table 8.14</b> | Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample II         | 162 |
| <b>Table 8.15</b> | Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample III             | 163 |
| <b>Table 8.16</b> | Pair-wise comparison of heart rate w.r.t. their alternatives for sample III                | 163 |
| <b>Table 8.17</b> | Pair-wise comparison of loading rate w.r.t. their alternatives for sample III              | 163 |
| <b>Table 8.18</b> | Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample III        | 164 |
| <b>Table 8.19</b> | Calculation of pair wise comparison of Sample I (110, $T_1 \dots T_9$ ) Oxygen uptake      | 165 |
| <b>Table 8.20</b> | Overall weight matrix of sample I for priority                                             | 165 |
| <b>Table 8.21</b> | Overall weight matrix of sample II for priority                                            | 166 |
| <b>Table 8.22</b> | Overall weight matrix of sample III for priority                                           | 166 |
| <b>Table 8.23</b> | Optimal lifting parameter setting for safe lifting for different sets of frequencies       | 167 |
| <b>Table 9.1</b>  | Percentage change in oxygen uptake, heart rate and perceived exertion in summer and winter | 170 |
| <b>Table 9.2</b>  | Decision with safe limit for identifying safe lifting task in summer & winter              | 172 |
| <b>Table 9.3</b>  | Percentage change in loading rate with changing levels of significant factors              | 179 |
| <b>Table 9.4</b>  | Decision with safe limit for identifying safe/unsafe lifting task                          | 179 |

## ABSTRACT

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In India, manual material handling tasks are very common in manufacturing industry and construction sites. Manual lifting activities involve moving construction materials at sites loading and unloading of jobs on machines or lifting and moving materials from one location to another with varying frequency and sometimes with asymmetrical postures. The incidence, severity and potential disability of musculoskeletal injury are in many cases directly related to the kind of manual material handling jobs entrusted to the workmen in the workplace. There is thus a need for a scientific study to investigate into the effect of performance of such jobs on human health. The present research work was undertaken to carry out experimentation on healthy workmen using different task parameters during manual material handling and determine the safe limits and a parametric combination of lifting tasks. The work was completed in two phases. In the first phase, an experimental study was conducted to evaluate the effect of lifting task parameters and their interactions in different ambient temperature conditions on the heart rate and oxygen uptake of workers involved in manual lifting tasks. Workers were involved in lifting a loaded container from different levels asymmetrically and placing these at target locations at different levels as per the designed experimental conditions. Experiments were conducted in two different ambient temperature conditions. The climate of north western region of India has extreme variation of temperature over the year. The temperature in summer varies between 30 and 45° C while in winters, the minimum temperature goes even below 5° C on some days. Further, high humidity levels cause very harsh work conditions for workers involved in manual material handling tasks. Therefore effect of environmental conditions (heat and cold) should be considered as an integral component of the lifting process.

The most significant lifting parameters and their ranges for this work were selected on the basis of pilot experimentation. An experiment study was carried out by using Taguchi's  $L_{27}$  orthogonal array. Load weight, lift frequency, coupling (grip), asymmetric angle (posture), vertical distance (lifting height), horizontal distance from the object and travel distance (carrying distance) were the input process parameters (control factors) that constituted the orthogonal array. Temperature, a noise factor has been assigned to the outer array to study its effect. The set of twenty seven experiments were repeated three times for each combination of seven lifting parameters during the first phase. The main aim was to study the effect of variation in ambient temperature condition on the exertion caused to the worker in a lifting

task. The interactions effect of some of these lifting parameters was studied by using a parameterization approach. Analysis of Variance (ANOVA) was used for the significance and percentage contribution of the significant factors. The design matrix was prepared for the identification of safe combinations of significant parameters as compared with the safe limits in different ambient conditions. The mean oxygen uptake and heart rate were calculated for all combinations of contributing factors using the Taguchi's additive model the correction coefficients were then obtained statistically for these factors. The multiplicative equations using the task parameters were developed to calculate Predicted Heart Rate (PHR) and Predicted Oxygen Uptake (POU) for quick assessment of a manual lifting task. Both the responses (oxygen uptake and heart rate) were optimized simultaneously with Multi-Response Signal to Noise (MRSN) ratio obtained by normalization of S/N ratio of responses. MRSN was analyzed using ANOVA to identify the optimal condition. A regression equation was also developed to predict the response values in similar work conditions.

In the second phase of the study, experiments were carried out to analyze the affect of lifting task parameters (lifting weight, frequency, coupling, asymmetric angle, vertical, horizontal and travel distances) on the ground reaction forces of workers using Taguchi's Fractional Factorial Experiments design ( $L_{27}$ ) during lifting tasks. Workers lifted and placed a loaded container as per experimental design. Measuring ground reaction forces (force platform, Kistler 9286AA, 200 Hz) gives a good measure of musculoskeletal stresses of the workers performing such task. Loading rate was calculated from the graphical output of vertical reaction force obtained from the force platform. The results were analyzed using analysis of variance for identification of significant factors. The combinations of all significant factors were used to calculate the optimal loading rate using the Taguchi's additive model. The design matrix has been made to identify the safe combinations of significant parameters for achieving safe limits in lifting tasks.

Loading rate was predicted using an artificial neural network model. The lifting task parameters; lifting frequency, load, vertical distance, horizontal and travel distances were used as inputs to the model. Statistical tests were applied to find out the relation between the experimental and predicted values. The neural network model can be used to predict the exertion in performing the manual lifting task.

Four responses; namely oxygen uptake, heart rate, perceived exertion and the ground reaction forces of workers were optimized collectively using the Analytical Hierarchy Process (AHP). Three samples were prepared according to frequency levels. The safe limits of all the responses were calculated using safe combinations of significant parameters in first and second phase of

the study. The best suitable settings of parameters for safe lifting were evaluated using this method.

It can be concluded from the present research work that ambient temperature affected the oxygen uptake and heart rate significantly during manual material handling tasks. Load weight, lifting frequency and vertical distance were found to be the most significant factors affecting all responses. Some interactions (load and lifting frequency etc) also showed their effect on cardiopulmonary responses. Workers should have some relaxation to overcome the exertion in winters and the limits of significant parameters can be increased without causing higher exertion to the workers under controlled temperature conditions. It was also observed that vertical reaction forces are more when worker lifts the weight from floor to shoulder height with high frequency and instantaneous loading rate increases with increase in weight, vertical distance and frequency. The safe limits of various responses can be used to design manual lifting tasks without any musculoskeletal injury/low back strain.

# CHAPTER 1

## INTRODUCTION

---

Manual material handling (MMH) exposures are complex in nature. Jobs in a variety of sectors (e.g., manufacturing, service, transportation) often require workers to perform multiple types of MMH tasks and in different stress- demanding situations. Despite improved technology and automation, many small and medium scale manufacturing units have manual activities involving lifting of objects from floor level and placing these at a different level. Some of these material handling tasks involve frequent lifting of heavy to very heavy objects with asymmetrical bending. Loading and unloading of parts on machines in mass production units are common operations which involve such lifting tasks. Moving of construction material (bricks, mortar, fine and coarse aggregates etc) at sites pose a huge risk to the workers involved in these activities. Another example of such tasks is to manually pick up trays filled with ingredients of food product from a trolley and placing them in an oven anywhere between shoulder height to floor level with rapid frequency and an asymmetrical posture. Such operations are a potential hazard to health and safety of the workers performing such tasks. Many employers, especially in the developing countries are either ignorant or not sensitive enough to such health hazards leading to health and safety issues for the workers involved. Many others employers want to improve the work environment and task conditions but do not exactly know the safe limits and appropriate actions to be initiated in this regard.

### 1.1 LIFTING TASKS AND INJURIES

The emphasis on ergonomics in manual material handling (MMH) task arises from the potential risk of workplace accidents and injuries. As per Konz [89], more than a quarter of all injuries related to industrial work are directly associated with MMH activities primarily due to improper handling of materials. Statistics show that four out of five of such injuries affect the lower back (FRP Rules [49]).

Snook [156, 158] reported that 79% of the manual handling injuries cause the lower back strain and back muscle injury. According to the U.S. Department of Labor [173] the construction industry has the highest injury rate among major U.S. industry divisions. As per U.K. Government's Health and Safety Executive [67] the illness rate among construction workers was 5600 in 100,000 cases. As per Dempsey and Hashemi [40] MMH is the most frequent (36% of all claims) and costly (35% of total cost) category of compensable loss in the USA.

Musculoskeletal disorders compensation claims contribute a large proportion (63–70%) of all claims for low back disability (Ciriello & Snook [31]; Murphy & Courtney [126]. Singh [153] reported that out of a total 68,484 industrial injuries, 9283 were caused due to material handling of objects. In the annual report [103] Liberty Mutual Research Center for Safety study revealed that overexertion, comprising of injuries due to lifting, pulling, holding or carrying of an object, was the number one cause for workplace injuries in 2002 and ranked among the top five during the preceding years. Two other studies (Snook et al. [155, 157]) indicated that more than half of all compensable low back pain has been related to manual material handling tasks. Lifting has been involved in 37% to 49% of all cases (Fathallah and Paskiewicz [48]. The second main reason for lost workdays is injuries due to overexertion when performing lifting procedures in the workplace (Snook [159]). Industrial injuries related to lifting are the second most common reason cited for back injury (Brooks [19]). Amongst basic manual material handling activities, manual lifting most frequently resulted in lower back pain (LBP) (Snook et al. [157]; Cady et al., [22]; U.S. Bureau of Labor Statistics, [172]). Specifically, lifting of low-lying objects is associated with a high risk of LBP (Straker [161]). Lifting activities accounted for the majority of back disorders (Konz [89]; Straker and Cain [162]). Back injuries contribute majorly to ailments and result in substantial workers' compensation costs (Hsiang [72]). As per Hashemi et al. [65] a small percentage of the most costly claims for low back (10%) are responsible for the major chunk of the total cost of low back claims (86%). About one hundred million workdays are lost each year due to back disability; (Johanning [77].

Musculoskeletal injuries increase significantly when heavy objects are lifted frequently or the object is bulky and is lifted from the floor. Musculoskeletal disorders often involve strains and sprains to the lower back, shoulders, and upper limbs. It is important to reduce the risk of such type of injuries and disorders in a lifting and or carrying manual loads (Snook [156, 157]) and (Wrigley [179]). A combination of lifting, bending and twisting is the most hazardous material handling activity (Garg and Moore [56]; Jin et al. [76]. A number of recent studies revealed that there is a relationship between occupational tasks as in repetitive lifting tasks which require frequent bending and increased risk of low back disorders (National Academy of Sciences [127]).

The studies discussed above clearly indicate that MMH tasks cause majority of the injuries in production units and construction sites and there is a need to scientifically establish safe limits of weight and lifting frequency to prevent such injuries. This study uses the ergonomics and biomechanics principles to establish safe limits for workers involved in MMH tasks

specifically in small and medium size manufacturing units. The result of the study can also be used in similar other tasks such as those performed on a construction sites.

## **1.2 ERGONOMICS ANALYSIS OF MMH TASKS**

Ergonomics is the scientific study of people and their working conditions and promotes good relations between the user, equipment and working environments to maximize productivity and reduce fatigue and discomfort of worker. The objective of ergonomics is to reduce physical exertion and eliminate musculoskeletal injuries and disorders associated with work postures and movements, repetitiveness and forceful motions. Different types of industrial situations involving postures and lifting etc affect different parts of the human body. One of the problems is the Cardio respiratory endurance. It refers to the ability of the lungs, heart, and blood vessels to deliver adequate amounts of oxygen to the cells to accomplish the demands of prolonged physical activity. The cardio respiratory fitness measures the ability of human body to transport oxygen to muscles and the ability of muscles to absorb and use oxygen during physical activity. The oxygen uptake and heart rate are the indicators of this ability.

Oxygen uptake refers to the amount of oxygen consumed by an individual in one minute. It is measured in milliliters per kilogram of body weight per minute (ml/kg/min). The maximum oxygen uptake refers to the maximum amount of oxygen the body is able to use per minute of physical activity. Oxygen consumption is also known as maximum aerobic capacity or power. Oxygen consumption increases as exercise intensity increases. After attaining some level of oxygen consumption during exercise, there is no increase in oxygen consumption however the intensity of exercise is continuously increasing consumption. This attainable level of oxygen consumption is called the  $VO_2$  max. It is commonly accepted indicator of cardio respiratory fitness.

Heart rate refers to the number of heart beats per unit of time and measures as beats per minute. It can vary as per body's physical needs or oxygen demand. Heart rate increases during physical activity (exercise). The resting heart rate is 60-80 beats per minute. The maximum heart rate is the maximum achievable heart rate by a healthy individual during stress/exercise.

Resting metabolic rate is energy expended to perform the vital organ functions of the body when resting. The major part of energy expenditure (about 50-75%) is attributed to resting metabolic rate.

## 1.2 SAFE LIFTING WEIGHTS AND PARAMETERS

The National Institute for Occupational Safety and Health (NIOSH [128]) developed a lifting equation to indicate “safe” occupational lifting limits. The equation uses a series of lifting multipliers (parameters) to calculate corresponding recommended task weight limits. It also provided analytical procedures to calculate recommended weight for specified two-handed, symmetrical lifting tasks in terms of action limit (AL), an approach for controlling the hazards of low back injury from manual lifting. In 1991, this lifting equation was revised, and the revised lifting equation retained all four multiplicative weighting factors used in 1981 (horizontal distance, vertical distance, distance of lift, and frequency) and added two new factors (asymmetry and coupling) for a total of six multipliers (Waters et al. [175]). Later, Hidalgo et al. [68] used more numbers of lifting parameters to develop a comprehensive lifting model. The 1991 NIOSH Lifting equation is applied to calculate recommended weight limit (RWL) based on a multiplicative model that provides a weighting factor for each lifting parameter. These individual multipliers can be used to identify the specific job-related problems. The relative magnitude of each multiplier indicates relative contribution of each task factor of RWL calculation (Waters et al. [176]). The weightings are expressed as coefficients that serve to decrease the load constant, which represents the maximum recommended load weight under ideal conditions. Karwowski [78] 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. Dempsey and Fathallah [39] also suggested that the interactions calculated from 1991 NIOSH equation were unlikely to accommodate the effect of interactions. Lavender et al. [97] showed that peak L5/S1 moment depended upon the interaction effect of lifting speed, initial lifting height and load weight. They also mentioned that NIOSH guidelines could not account the biomechanical spinal loading for low-lying object lifting, which was better fitted with consideration of interaction effects. The authors also emphasized that consideration of interaction effects could explain the co-contraction effects of different muscles that would be happening during lifting at higher frequencies and could provide better prediction. McKean and Potvin [115] mentioned the significant interaction effects of lifting parameters on trunk extensor muscle activity. Maiti and Ray [113] showed that after considering the interaction effect of lifting frequency and load weight on working heart rate provided a better predictive equation. These results suggest the importance of considering interaction effects of factors in the multiplicative equation. Batish et al. [13]

described an assessment tool for analyzing material handling tasks and its application prevalent in engine bearing industry.

### **1.3 OBJECTIVES OF THE STUDY**

This research was undertaken to study the interactions of various lifting parameters involved in manual lifting. The study takes lifting equation developed by NIOSH as the basis and uses the analytical procedures and a lifting equation for calculating the Recommended Weight Limit (RWL) for specified two-handed, asymmetrical lifting tasks, as an approach for controlling the hazards of low back injury (Waters et al. [175]).

The objectives of the study are

1. To evaluate the effect of lifting parameters namely, distance (horizontal, vertical), weight load, posture, frequency or duration of lift, coupling (grip) and other environmental factors in a manual lifting task.
2. To evaluate the significant interactions of the above factors during manual lifting and optimize the task parameters
3. To develop equations for predicting heart rate and oxygen uptake during manual lifting and its validation
4. To recommend Guide Lines for Indian male population engaged in such tasks

### **1.4 METHODOLOGY**

The overall methodology for the study has been divided into following phases:

Phase 1: Detailed review of literature

Phase 2: Pilot experimentation and design of study

Phase 3: Experimentation to evaluate the effect of different task parameters and their interaction on Indian male workers performing lifting and carrying tasks involving the following:

- i. Effect of important lifting task parameters in different environmental condition on cardiopulmonary responses (heart rate and oxygen uptake)
- ii. Effect on cardiopulmonary responses during MMH tasks carried out in extreme environmental conditions

- iii. Multi-Response Signal to Noise (MRSN) ratio using Analysis of Variance (ANOVA) to identify the optimal condition where responses (oxygen uptake and heart rate) are optimized under different environmental conditions
- iv. Develop a multiplicative equation incorporating all the significant factors identified from the experimental study to calculate Predicted Heart Rate (PHR) and Predicted Oxygen Uptake (POU)
- v. Effect of weight, frequency of lift, coupling (grip), posture (asymmetry), vertical distance, horizontal and travel distance on the ground reaction forces (GRF), loading rate (LR) of workers in dynamic lifting human activities under different environmental conditions of heat and humidity and use of Artificial Neural Network (ANN)-based model to predict loading rate during manual lifting activities
- vi. Identify the best experimental setting for optimization of four responses, namely heart rate, oxygen uptake, perceived exertion and loading rate together using Analytical Hierarchy Process (AHP)

Detailed literature review was carried out to find the significance of various lifting input process parameters on the output response parameters such as oxygen uptake, heart rate, perceived exertion and ground reaction forces. Pilot experimentation was conducted for assessing the actual impact of lifting parameters and their levels by varying one-parameter-at-a-time approach. The effect of environmental condition was also included in the pilot experimentation. Pilot experimentation brought out the details of levels of interactions between the parameters and facilitated design of main experimentations using Taguchi's approach of experimental design. The Taguchi methodology involves identification of parameters and the establishment of a series of experiments to find out the optimum combination of the parameters which has the greatest influence on the performance and the least variation from the target of the design.

After considering all the variables, Taguchi's  $L_{27}$  Orthogonal Array was adopted for conducting the trials. The factors included in the array were load, lifting frequency, coupling (grip), asymmetric angle, vertical distance, horizontal distance and travel distance. COSMED pulmonary function equipment was used to measure oxygen consumption and heart rate after each trial. Each worker was asked to perform asymmetrical free style lifting of load as per the experimental trial conditions for 20 minutes. Three repetitions for each of the 27 trial conditions were completed to measure oxygen uptake and heart rate in different environmental

conditions. The perceived exertion was measured using the Borg RPE scale [17]. The responses (heart rate and oxygen uptake) were optimized simultaneously to generate optimal level setting using the multi-response optimization method (MRSN) developed by Chen [28] for a manual lifting task. Multiplicative equations were developed to calculate Predicted Heart Rate (PHR) during lifting tasks.

The next phase was completed using two force platforms for measuring ground reaction forces and their effects in manual lifting. For this phase of study,  $L_{27}$  orthogonal array was used with three repetitions for each worker. Analysis of the experimental data established the significance and relative contribution of the process parameters.

To predict the loading rate during manual lifting, a multilayer, fully connected, feed-forward network (Artificial Neural Network, ANN) was used. The multilayer, feed forward networks are capable of generating arbitrarily close approximations to any continuous nonlinear mapping (Cybenko; Hush [33, 74]).

Analytical Hierarchy Process (AHP) was used to optimize all the output responses collectively. AHP is a one of the most successful techniques to solve decision making problems involving the decision goal, the alternatives for reaching it and the criteria for evaluating the alternatives. A number of pair wise comparison matrices are formed according to their relative importance with respect to the parent element in the adjacent upper level to derive weights of the criteria and the local weights of the alternatives using simple mathematical theory of Eigen vector and priority. The alternative with the highest global weight is selected as the best alternative. The advantage of this tool is that it combines both qualitative and quantitative parameters.

## **1.5 ORGANIZATION OF THE THESIS**

The thesis has been divided into nine chapters. Brief description of the contents of each chapter is given below:

### **Chapter – I Introduction**

This chapter introduces manual material handling tasks and highlights the effect of lifting parameters at appropriate levels and their interactions on various responses under different environmental conditions during manual material lifting tasks. The chapter also presents objectives of the research and an outline of the methodology adopted for carrying out the work.

### **Chapter – II Literature Review**

This chapter presents a review of the available literature in context of the effect of lifting parameters on the physiological stress caused to the subjects during manual material lifting and carrying tasks. The chapter also addresses the application of force platform to measure ground reaction forces during manual lifting tasks.

### **Chapter – III Design of Study**

This chapter gives a detailed account of the design of study, process parameters and the pilot experimentation carried out for determining the desirable levels of various parameters. Taguchi approach to design of experiments in the context of this work has also been briefly described.

### **Chapter – IV Effect of Ambient Temperature during Manual Lifting**

This chapter discusses the experimental study to evaluate the effect of lifting task parameters in different environmental conditions on the heart rate and oxygen uptake of workers involved in manual lifting tasks. The safe combinations of the significant factors can be used to design lifting tasks in varied ambient conditions. In order to optimize both the responses simultaneously, the MRSN was analyzed using Analysis of Variance (ANOVA) to identify the optimal conditions. This chapter also explains the experimentation carried out to evaluate the effect of various lifting task parameters on the heart rate and oxygen uptake of the workmen and to develop a multiplicative equation incorporating all the significant factors identified from the experimental study to calculate Predicted Heart Rate (PHR) during lifting tasks. Further, correction coefficients of the significant factors have been developed so as to calculate heart rate for any given task.

Temperature was induced into the experimental study as an additional factor to study its effect. Taguchi's Fractional Factorial Experiments  $L_{27}$  Orthogonal Array was adopted for conducting the trials. Output from COSMED pulmonary function equipment was collected for each trial to measure oxygen uptake and heart rate. Three factors load, lifting frequency and vertical distance were found to significantly affect the two responses. The experiments were conducted in two different environment conditions. Various combinations of the three significant factors were used to calculate the oxygen uptake and heart rate which were then compared to the safe limits as per the maximum aerobic capacity of the workers. Based on these comparisons, the safe combinations of the three factors were identified which can be used to design lifting tasks in varied environmental conditions.

For MRSN, the two responses (oxygen uptake and heart rate) were converted to S/N ratio which was subsequently normalized to obtain a Multi-Response Signal to Noise (MRSN) ratio

for each trial. The MRSN was analyzed using Analysis of Variance (ANOVA) to identify the optimal conditions where both are optimized simultaneously in different climatic conditions.

In similar work conditions, the empirical modeling equation for predicted heart rate was developed by using correction coefficients of significant factors (i) load, (ii) lifting frequency (iii) vertical distance and (iv) ambient temperature to calculate PHR index for identification of safe and unsafe task in industrial applications.

## **Chapter – V Predicted Oxygen Uptake (POU)**

This chapter explains the study to evaluate the effect of various lifting task parameters on the oxygen uptake of the workmen without considering the effect of ambient temperature and to develop a multiplicative equation incorporating all the significant factors identified from the experimental study to calculate predicted oxygen uptake (POU) during lifting tasks. Further, correction coefficients of the significant factors have been developed so as to calculate oxygen uptake for any given task.

The physiological characteristics and body metabolism of Indian male workers are different as compared to other countries. The interaction effect of various lifting parameters has been studied by using a parameterization approach developed by Taguchi. For finding the optimal task parameters, a combination of all significant factors have been used to calculate the oxygen uptake using the Taguchi's additive model. In this experimental situation with three levels for each factor,  $L_{27}$  design matrix was used.

The results were analyzed using Analysis of Variance (ANOVA) for identifying the significant factors and interactions affecting the response and used to find optimal combinations of levels of the contributing factors to quickly analyze various lifting tasks.

## **Chapter – VI Safe Limits Of Manual Lifting Task Parameters Using Biomechanics Principle**

This chapter explains experimental study to analyze the affect of lifting task parameters (lifting weight, frequency, coupling, asymmetric angle, vertical, horizontal and travel distances) in different dynamic manual lifting activities on the ground reaction forces of workers. Safe limits of significant factors were determined for optimality of performance of the manual lifting task.

Two force platforms were used to measure the vertical ground reaction forces produced during lifting. The data was extracted from a graphical output for ground reaction force plotted against a time scale to calculate the loading rate. Using Taguchi's  $L_{27}$  array trial conditions, ANOVA was used to identify the significant factors. For finding the optimal task parameters, the

combinations of all significant factors have been used to calculate the ground reaction force and loading rate using the Taguchi's additive model.

### **Chapter – VII Predicted Loading Rate Using Neural Networks**

The chapter presents an experimental study to develop an artificial neural network model to estimate the ground reaction forces that cause exertion to workers during a manual lifting task. The artificial neural network (ANN) model accurately predicts the loading rate in a lifting task and is a reliable tool for predicting exertion caused to workers during a lifting task.

The lifting task parameters; lifting frequency, load, vertical distance, horizontal and travel distances were used as inputs to predict the neural network model. The loading rate from the ground reaction force was calculated after the completion of the experimental study. A mixed level  $L_{18}$  orthogonal array was selected for experimentation. The relation between the experimental value and the predicted value obtained from the network was established. Other statistical tools such as paired-sample t-test and correlation were also employed.

### **Chapter – VIII Optimization of Experimental Setting for Safe Lifting**

This chapter presents the results of global optimization of all responses namely oxygen uptake, heart rate, perceived exertion and ground reaction forces of workers. In order to optimize all four responses simultaneously, Analytical Hierarchy Process was used for different lifting frequencies during manual lifting. Using this method, most suitable experimental settings for safe lifting were identified.

### **Chapter – IX Results, Discussion and Conclusions**

This chapter presents a collective view of the results of the experimental work discussed in details in the previous chapters and conclusions of the study.

This chapter is followed by references.

## CHAPTER 2

### LITERATURE REVIEW

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Industrial ergonomics deals with physical aspects of work in industry and human aspects capabilities such as force, posture and repetition. Manual materials handling (MMH) involves movement of objects, vertically or horizontally, from one location to another through lifting, lifting and carrying, holding or pushing and pulling objects with hands.

Studies on various aspects of industrial ergonomics have dealt with manual materials handling in three distinct categories. Literature on biomechanical aspects highlights injuries caused by the lifting and carrying tasks with loads placed on the lower spine. Physiological literature involves understanding the fatigue associated with the energy cost of lifting and carrying tasks. Psychophysical techniques discuss understanding the perception of fatigue as well as the load someone would chose to handle during a work day given a work rate.

#### 2.1 CATEGORIZATION OF LITERATURE REVIEW

The review of literature has been categorized into following areas:

1. Manual material handling
2. Lifting task
  - Effect of lifting task on ground reaction forces
  - Analysis of lifting task neural networks
3. Lifting and carrying task
4. Application of NIOSH lifting equation to analysis of lifting tasks

##### 2.1.1 Manual Material Handling

Manual material handling (MMH) tasks, the most common cause of low back disorders, are extensively used in industrial jobs. The tasks share a large percentage of musculoskeletal disorders cases reported annually in the world. Potentially injurious tasks may involve lifting or carrying heavy loads, repetitive motions, bending and twisting.

**Ayoub et al. [9]** proposed the use of the Job Severity Index (JSI) as a tool for job design and employee placement and evaluated the relationship between the JSI and the frequency, severity, and cost of MMH injuries. The JSI is defined as the time- and frequency- weighted average of the maximum weight required by each task divided by the selected lifting capacity

given the lifting task conditions. Procedures for job design, employee placement and applications in industry were discussed.

**Micheline [119]** evaluated two tasks (lifting and lowering) performed at different heights and loads. Cinematography techniques and two AMTI force platforms were used to collect the data. Muscular moments at the joints and work with the help of integration of muscle power were calculated. It has been observed that handling from the waist height was found most significant factor. Handling at lower heights, work was shared mainly by the hips and lower back and handling above the waist, the work efforts were concentrated on the upper limbs.

**Andres [1]** developed a sagittal plane dynamic model to predict L5/S1 compressive force and required coefficients of friction during dynamic cart pushing and pulling. Predicted ground reaction forces were compared with those measured by a force platform, with correlations up to 0.67. Predicted erector spine and rectus abdominis muscle forces were compared with muscle forces derived from root mean square-EMGs of the respective muscle groups. Although correlations were low, this was attributed in part to the use of surface EMG on subjects of widely varied body mass. The biodynamic model can be used as a tool for analysis of actual industrial pushing and pulling tasks.

**Plamondon et al. [138]** determined whether experts differ from novices in their handling strategies and the effects of these differences in joint motions and net reaction moments at the trunk (L5/S1) and knees using AMTI force platforms, and Lo cam cameras coupled with two mirrors. Results showed that both groups minimized trunk asymmetries of posture and efforts; however, the experts' strategies appeared safer overall because they reduced trunk asymmetry, asymmetrical efforts on the knee and stress on the femoropatellar joint.

**Carayon et al. [23]** studied a theoretical relationship between job stress and work-related musculoskeletal disorders (WRMDs) in work organization and highlighted the physiological, psychological, and behavioral reactions to stress that can affect WRMDs directly and indirectly. Also, it is important to examine both physical ergonomic and psychosocial work factors simultaneously to understand the etiology of WRMDs.

**St-Vincent [165]** conducted an ergonomic analysis of the job of warehouse stocker performing an average of 200 manual materials handling operations with cumulative weight of 2000 kg during a shift . Generally, handling activities by stocker were shared an average of 74% of the work shift duration. The merchandise handled was often fragile and unstable. The stockers' pallet jack incompatibility with some of the pallets used increases effort and time pressure.

Stockers' work involved significant planning related to stock movements and arriving shipments. In this regard, four problem situations were identified which add additional handling operations and time pressure. The results indicated that the inherent characteristics of warehouse superstores and their marketing strategies impact on the handling activity and the resulting risks.

**D'Errico et al. [34]** interviewed a cohort of automobile manufacturing employees at baseline, one and six years later about work history, physical and psychosocial exposures at work, upper limb symptoms, injury and medical history, and demographics. Differences in exposure between 1- and 6-year follow-up were analyzed and results showed that large and significant decreases in work pace and physical effort were observed from baseline, although an upper extremity composite index was quite stable in the total population.

**Denis et al. [41]** carried out an ergonomic study in two warehouse superstores of a leading company. The results showed 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 like loss of balance and falls from heights; and (3) Impacts on productivity and quality of service offered to customers in the form of time wasted, stock losses and customer dissatisfaction.

**David et al. [37]** developed the Quick Exposure Check (QEC, an observational tool) to assess exposure to risks for work-related musculoskeletal disorders and provided a basis for ergonomic interventions. The QEC allows the four main body areas to be assessed and involves practitioners and workers in the assessment. The tool is based on epidemiological evidence and investigations of OSH practitioners' aptitudes for undertaking assessments. It has been tested, modified and validated using simulated and workplace tasks, in two phases of development, with participation of practitioners.

**Escorpizo et al. [45]** presented a conceptual model of work productivity-within the area of paid work and within the context of work-related musculoskeletal disorders (WMSD) and discussed the two sub components of work productivity (absenteeism and presenteeism). An accurate measurement of work productivity was crucial to initiating, evaluating, and monitoring work disability management like employee wellness and ergonomics programs, and clinical interventions in WMSD.

**Cooper et al. [32]** measured the forces required of the ambulance workers when loading/unloading ambulance stretchers and performed the kinetic analysis of each stretcher

loading system using a load cell in a force handle arrangement. The postures and forces exerted by the ambulance workers were analyzed using biomechanical assessment software. 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. The critical tasks of each ambulance worker were identified during the loading and unloading operations for each system and design recommendations were given to reduce the forces exerted based on loading requirements from the kinetic analysis.

**Fathallah et al. [48]** developed the belt system, (GRIPSystem™) to assist movers who operate in pairs during lifting heavy and awkward furniture and evaluated the effectiveness of this manual device in reducing key low back disorders risk factors. The participants lifted household furniture items, at varied weights, with and without the lifting device, while trunk kinematics and 10 muscle EMG signals were recorded. The results showed that the device significantly lowered the kinematics and muscle activity of the lower back, as well as the risk of LBDs.

**Kingma et al. [87]** investigated lifting behaviour as well as low back moments with the help of ergonomic interventions involving a reduction of the mass and an increase in the initial lifting height of building blocks in a mock-up of an industrial depalletizing task. When initial lifting height was increased, subjects chose to shift the building blocks less before actually lifting them. The net total low back moment reduced when block mass was decreased.

**Grasmueck et al. [62]** studied an assembly line of work stations of cars manufactured to solve the problem of steadily increasing age of workers performing assembly jobs which frequently involve highly repetitive, short-cycle operations. Two solutions were applied to overcome this problem (1) early retirement schemes for older workers and preference was given to younger workers, on contractual basis (2) ergonomically weak and medical danger points in assembly processes were identified and eliminated by modification of the work model, irrespective of whether older or younger workers were involved. The following results were reported that the age of the assembly workers influences the choice of workplace and older worker found to be in jobs with a 'very favorable' expert rating, younger workers in jobs with '(very) unfavorable' ratings. Age and job strain parameters were not independent variables. Older workers still complained of lumbar spine symptoms despite low demands imposed by their present jobs. This may be indicated long-term cumulative effects.

**Faber et al. [47]** investigated the effects of ship motion on peak spinal loading during lifting. Ship motion, whole body kinematics, ground reaction forces and electromyography were measured. The results showed that with increase of the vertical ship acceleration, moments and compression forces increase.

**Hoozemans et al. [69]** evaluated the effect of lifting height and mass lifted on the peak low back load in terms of net moments, compression forces and anterior–posterior shear forces. The effects of lifting height and lifting mass were quantified using a regression technique (GEE) for correlated data. Lifting height and load mass are important determinants of low back load during manual materials handling. Results indicate that an increase in lifting height and a decrease in lifting mass were related to a decrease in low back load.

**Das et al. [36]** studied the effects of asymmetry on load lifting and moving asymmetric load from knuckle to target shelves by employing electromyography in a simulated MMH task situation. The results showed that the muscle activity for the knuckle lift was significantly lower than the floor lift. The average decrease in muscle activity was approximately 68%. Consequently, asymmetric lifting and moving tasks should be performed from a knuckle height to sternum height.

**David et al. [38]** studied the effects of lifting task conditions and anthropometric variables on foot placements in relation to hand relations for prospective biomechanical analysis in a laboratory experiment. A new parametric system for describing foot placements, the Quantitative Transition Classification System, was developed to facilitate the parameterization of foot placement data. Foot placements chosen by the subjects during the transfer tasks appeared to facilitate a change in the whole-body direction of progression, in addition to aiding in performing the lift.

**Dai et al. [35]** studied lifting loads having horizontal velocity. Trunk motions and trunk muscle activation levels of participants were monitored during lifting task under different conditions of horizontal load speeds and lifting frequencies. It has been observed that with increase of horizontal load speed, peak sagittal angle increases but peak sagittal plane and peak transverse plane angular acceleration decreases and a consistent increase in trunk muscle co-activation.

**Lamberg et al. [94]** examined natural breath control while lifting a loaded crate with different weights from the floor to a table and collected respiratory flow data. Uniform and consistent breath holding during lifting of a maximum load did not occur. All three loads, frequency of

inspiration was highest just before to lift immediately lifting. Holding the breath does not appear to be related to lifting of a maximally prior to lift-off and significantly higher inspired volume occurred at lift-off of the load compared with preparation for tolerated load from floor to table.

**Chang et al. [27]** proposed a method to estimate the dynamic L5/S1 joint loading for asymmetrical lifting task using interpolation of joint angles. The results showed that the four point cubic spline interpolation of segment Euler angles combined with a biomechanical model can provide a good estimation of 3-D peak L5/S1 joint moments. These results greatly helped in developing applied ergonomic field survey tools such as video based systems for estimating L5/S1 moments of manual material handling tasks.

**Plamondon et al. [136]** measured the effect size of important factors in manual material handling; expertise, lifting height and weight lifted. The task consisted of transferring a series of boxes from a conveyor to a hand trolley. The results showed that lifting height and weight had more effect than expertise on external back loading variables (moments) but expertise showed a significant effect of posture variables on the lumbar spine and knees.

**Kuijer et al. [92]** studied different lifting techniques– free style, stoop and squat lifting from knee to waist level using the same dynamic functional capacity evaluation lifting test to assess maximum acceptable weight of lift (MAWL) and to calculate low back and knee kinetics. The results showed that MAWL was significantly different between techniques.

**Bhardwaj et al. [117]** studied the occupational risk factor of workers in the handicraft industry and suggested that if ergonomic principles can be integrated into existing handicraft industry tools, methods and work environments then efficiencies can be realized and the risk of occupational injuries will be reduced.

**Xu X et al. [183]** proposed two regression models predicting cumulative dynamic L5/S1 joint moment based on the static L5/S1 joint moment of a lifting task at varying lifting ranges and asymmetric angles in a laboratory environment. The static L5/S1 joint moments from continuous dynamic L5/S1 moments at lift-off and set-down were measured for the two regression models. The prediction error of the cumulative L5/S1 joint moment was 12% and 8% of the measured cumulative L5/S1 joint moment for the first and the second models, respectively.

**Mohammadi et al. [122]** conducted a study to determine the prevalence of work-related musculoskeletal disorders (WMSDs) and compared manual material handling (MMH) loads

with the acceptable weight and force limits among Iranian casting workers. Workers performance data were recorded in casting workshops using Nordic Musculoskeletal Disorders Questionnaire and the Snook Tables. It was observed that hand/wrist symptoms were the most prevalent problems among the workers (84%). The loads in lifting (84%), lowering (86%), carrying (66%), pushing with initial (43%) and sustained force (59%), and pulling tasks with initial (48%) and sustained force (93%) exceeded recommended limits.

### **2.1.2 Lifting Task**

Work place accidents, injuries and work related low back pain may cause gradual and cumulative deterioration of the musculoskeletal system during continuous lifting or handling activities. Lifting the load can strain the lumbar vertebrae when done improperly. The NIOSH WPG [126] contained a summary of the lifting related literature before 1981; analytical procedures and a lifting equation for calculating a recommend weight for specified two handed, symmetrical lifting and an approach for controlling the hazards of low back injury from manual lifting. Many studies have used different approaches to determine the lifting capacity of individuals engaged in lifting various types and sizes of objects, to and from different heights, at varying frequencies (Chaffin et al. [26]; Ayoub et al. [6]; Mital and Ayoub [121]; Pytel and Kamon [140]; Kroemer [91]; Karwowski and Ayoub [79].

**Ayoub [8]** proposed a job safety index (JSI) to predict LBD risk using a mathematical model between work demands and worker capacity. As JSI increases, the risk of back injury also increases. A job is classified as lower risk if its JSI value is between 0 and 1.5 and high risk if it is higher than 1.5.

**Ayoub [5]** reviewed the literature which offers three solution approaches that can be used separately or collectively for controlling lifting hazards: (a) hazard control through training in safe lifting, (b) control of employee exposure through pre-employment strength testing, and (c) control of job demands through the adoption of workloads acceptable for the industrial population

**Liles et al. [104]** conducted studies to test the validity of the Job Severity Index (JSI) as an engineering tool for the control of manual materials-handling injury. JSI was calculated for individuals working in different jobs and compared it to the injuries sustained by the same individuals over a period of 1057881 exposure hours. It was observed the existence of a job severity threshold above which the incidence, severity, and cost of injury increased. It was

concluded that the JSI method can effectively be used to control injuries caused by the manual lifting of loads.

**Freivalds [53]** developed a biomechanical model consisting of seven rigid links joined at six articulations to evaluate the job-related stresses imposed upon a worker to reduce the high incidence rates of manual material handling injuries in industry. Body position from joint angles, angular velocities & acceleration, inertial moments & forces, and reactive moments & forces at each joint were calculated using data from cinematographic analysis of lifting motions. The results showed the effects of the common task variables; larger load and box sizes increased the rise times and peak values of both vertical ground reaction forces and predicted L<sub>5</sub>/S<sub>1</sub> compressive forces.

**Karwowski and Mital [80]** developed the safety index (SI) using fuzzy sets for risk assessment depending on the effects of biomechanical and physiological stresses.

**Svensson et al. [163]** evaluated the muscular load on the ankle and knee in different packing work postures using the principle of a Muscular Strength Utilization Ratio (MUR) and studied different combinations of box size, box angle, edge height and weight of object handled. It was observed that the lowest MUR for both the ankle and the knee were obtained in postures with the smallest box angled at 90° to the horizontal, with the upper edge at elbow height or higher. The highest MUR values were obtained with the largest box angled at 0° or 30° with the upper edge at elbow height or lower.

**Genaidy et al. [57]** developed a microcomputer-based model for the design and evaluation of frequent manual lifting tasks built upon the concept of job severity index. This model can be used by non-experts in the field of manual materials handling. The software involves possible engineering and administrative controls if human lifting abilities are exceeded.

**Garg and Banaag [55]** conducted a laboratory study to determine the effects of repetitive asymmetric lifting on psychophysically determined maximum acceptable weights and resulting HR and rating of perceived exertion (RPE).

**Karwowski [78]** determined the different cognitive strategies adopted by workers in assessing the effects of lifting-task parameters on effort, validated workers' assessments. Questionnaires were administered to workers with varied levels of experience in manual handling. Workers assessed on-the-job effort, perceived risk of injury and work dissatisfaction, and musculoskeletal outcomes in a cross-sectional design. The results showed that perceived physical effort was significantly associated with lifting variables.

**Granata et al. [60]** demonstrated the influence of different types of lifting belts on trunk motion, muscle activity and spine loading during symmetric and asymmetric lifting exertions. He also examined dynamic trunk motions, lifting moments, myoelectric activity and modelled spinal loads as a function of three belt styles (elastic, leather, and orthotic) and compared with results from a no-belt condition. Dynamic spinal loads were determined from a validated biomechanical model of lifting. It was observed that lifting belts reduced peak trunk angles, velocities and accelerations in the sagittal, lateral and transverse planes and the elastic belt reduced trunk motions in all three dimensions.

**Ayoub [7]** presented a two dimensional whole-body lifting simulation model with dynamic human motions using computerized human motion simulation 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.

**Chad and Brown [24]** conducted a study to determine the differences in thermoregulatory responses and the levels of muscle fatigue in the seated worker, performing a task involving a light metabolic load, versus the standing worker, undertaking a task of a heavier metabolic load (lifting), in different climatic conditions. The results showed that environmental heat significantly influenced the cardiovascular and thermoregulatory systems in workers performing both light and heavy work tasks.

**Larivière [96]** evaluated the validity of two biomechanical dynamic three-dimensional (3D) multi segment models using cameras and force platforms for collection of static and dynamic data. On comparison of the tri axial net moments at L5/S1, good agreement was observed between the two models for the moments of the static tasks but great disparity was observed for the moments of the dynamic tasks (up to 78 Nm in extension). Both models were sensitive to different task parameters (movement or load asymmetry, movement rate, load magnitude).

**Wang [174]** developed an automated system of evaluating the possible risk of low back injury in manual material handling (MMH) task. The system applied computer vision technique to identify the working posture, then incorporating biomechanical model and anthropometric data to calculate the low back compression force. By comparing with the specified standard limits, the system can indicate the risk level of the task.

**Hidalgo [68]** developed a comprehensive lifting model (CLM) for the evaluation and design of manual tasks. The model was built using the psychophysical data. Two lifting indices are

proposed to evaluate lifting tasks for a group of workers (relative lifting safety index or RLSI) and for an individual worker (personal lifting safety index or PLSI).

**Nielsen et al. [129]** investigated the muscular load on the lower back and shoulders and the circulatory load on employees with different combinations of lifting height and frequency at a post center during repetitive lifting of mail transport boxes. The circulatory load was evaluated by measuring the heart rate. It was observed a tradeoff between the low back and shoulders.

**Zhang [186]** proposed an index that quantitatively characterizes different dynamic postural strategies employed during sagittal plane lifting and modeled dynamic lifting strategies in the velocity domain as different schemes of partitioning postural changes between the torso and leg segments. The index consists of two parameters, assigned to two leg segments, quantifying their contributions relative to the torso. The index is applied to different lifting movements performed by subjects. The results indicated that a lifting strategy can be differentiated and visualized using this simple two-parameter index.

**Wu [180]** determined the effects of asymmetric lifting on psychophysically determined maximum acceptable weight of lift (MAWL) and the resulting heart rate, oxygen uptake and rating of perceived exertion. Participants performed lifting tasks with varied lifting frequencies and twisting angles for one hour's work shift using a free-style lifting technique. It was observed that MAWLs were significantly lower for asymmetric lifting than for symmetric lifting and heart rate, oxygen uptake and rating of perceived exertion increased with an increase in lifting frequency though maximum acceptable weight of lift decreased.

**Elfeituri [44]** evaluated the biomechanical effects of working in a restricted environment on manual lifting tasks to estimate the biomechanical loading on the lumbar spine for the selected combinations of limited headroom heights and twisting angles. The results showed that the greater the twisting angle, the higher the compression and shear forces.

**Larivière [95]** evaluated chronic low back pain among patients who performed manual material handling tasks differently from control subjects. Subjects lifted a box from the floor to the hips and lowered back to the floor with symmetric and asymmetric task. A 3D biomechanical analysis involving the assessment of L5/S1 loading, posture of segments, inertial parameters, and EMG was performed. It was observed that 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.

**Kollmitzer [88]** investigated effects of stance condition on postural control during lifting and measured ground reaction force and segmental kinematics. Any voluntary motion of the body causes an internal perturbation of balance. Subjects were involved in repeatedly lifting and lowering a load between a desk and a shelf. The base of support was varied between stances. It was observed that lifting in parallel stance consisted of axial movements in the sagittal plane and lifting in step stance provided extended support in anterior/posterior direction. The postural control mechanisms in the sagittal plane were found to be 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 exhibited positive and negative aspects and cannot be recommended either one as being better in terms of postural control.

**Lin et al. [105]** investigated the association between the task variables of a lifting job and low-back pain. An interview questionnaire was prepared to collect information regarding work activities involving manual lifting. The characteristics of the manual lifting that were significant in patients with low-back pain were determined to be experience, object weight, carrying distance, lifting height, frequency, and activities with pulling or pushing.

**Wu [181]** evaluated psychophysically the effects of asymmetric lifting on the maximum acceptable weight of lift (MAWL) and the resulting heart rate, oxygen uptake and rating of perceived exertion (RPE). Subjects performed the lifting task with different heights, asymmetric angles and frequencies for a 1-h work period using a free-style lifting technique. The MAWLs for asymmetric lifting were significantly lower than those for symmetric lifting in the sagittal plane. The MAWL decreased with the increase in the angle of asymmetry. However, the heart rate, oxygen uptake and RPE remained unchanged. Though, the MAWL decreased significantly with increase in lifting frequency, both the physiological costs (heart rate and oxygen uptake) and rating of perceived exertion increased with the increase in lift frequency.

**Wrigley [179]** evaluated the differences in lifting technique using principal component analysis. The two-dimensional motion of the trunk and load in kinematic and kinetic waveforms were measured for principal component scores. The scores were used in ANOVA for identifying the significant factors. Principal component analysis was able to identify important biomechanical differences where traditional analyses failed.

**Maiti & Ray [113]** conducted a study on maximum acceptable weight limit (MAWL) on adult Indian female building construction and household workers, using the psychophysical methodology and developed an equation based on the effects of the following three lifting parameters on working heart rate: vertical height (knee, waist, shoulder and maximum reach height), lifting frequency and load weight. The variations of the specific lifting parameter values were selected from field observations. The MAWL working heart rates were obtained for both the groups and psychophysically rated the work in moderate to heavy category. It was observed that with increase of work duration, the heart rate increased for both the groups of workers.

**Maduri et al. [111]** 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 inter vertebral 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. They also examined the range of lumbar curvature rotation of workers 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.

**Bagchi et al. [10]** examined the effect of lifting parameters of lifting frequency, vertical lifting distance from floor, and lifting weight and their interactions in a laboratory experiment. Multipliers of lifting parameters were used to calculate recommended weight limits (RWL) in revised NIOSH equation 1991. The corresponding weight limit may not be valid due to the nature of risk factor interaction. Female subjects performed lifting task adopting free-style lifting technique with combination of lifting weights, frequency, and vertical height from floor. The working heart rates were measured and converted to normalized working heart rate using the maximum heart rate obtained during maximum aerobic power measurement. The results showed that the main effects were significantly related with normalized working heart rate and the interaction effects of different lifting parameters shared small part of total variance. The study concluded that the interaction effects between different lifting parameters must be considered in addition to the effects of individual lifting parameters.

**Maines et al. [112]** determined the asymmetries during lifting a milk crate in the sagittal plane from floor to knuckle height ten times using a symmetric stance. Mean ground reaction forces under each foot were compared over the entire lift. Paired *t*-tests were used to determine

individual asymmetries in vertical, anterior/posterior, and medial/lateral forces. It was observed that there were no significant differences between genders; subjects were grouped to determine if kicking leg was related to the asymmetry. Over the entire lift, 75.0% of the subjects were statistically asymmetric in the vertical direction, 7.1% in the anterior/posterior, and 96.4% in the medial/lateral. It was concluded that even in subjects with no reason to be asymmetric, asymmetries in the ground reaction forces are more likely the norm rather than the exception. However, assessing based on kicking leg alone will most likely not predict the side with greater forces.

**Cooper [32]** carried out a detailed analysis of the loads applied by the ambulance workers when loading/unloading ambulance stretchers. The postures and forces exerted by the ambulance workers are analyzed using biomechanical assessment software to examine if the workloads at any stage of the process are harmful. Kinetic analysis of each stretcher loading system was performed. Comparison of the kinetic analysis and measurements showed very close agreement for most of the cases. The force analysis results were evaluated against derived failure criteria.

**Ciriello [30]** studied the effects of frequency on maximum acceptable weights (MAWs) of lifting with a large box and a small box with female industrial workers and also, studied the effects of high frequency (20 lifts/ min) on MAWs 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 and the effects of the 20 lifts/min frequency resulted in a MAW that was 47% of a 1 lift/min MAW. The study concluded that the design of MMH tasks for female workers may be improved incorporating these results in future guidelines.

**Reisera [141]** determined the effects of lifting from a sloped floor surface (both facing up and down) on the lumbar region and compared with the level surface. A top-down inverse-dynamics model was used to calculate the net moment at L5/S1. As the slope changed from down to up, the crate loaded subject foot placement was significantly affected by lifting condition. Maximum L5/S1 moments were not affected by lifting condition. However, the static contribution from mass location significantly increased when facing up hill.

**Batish et al. [13]** described an assessment tool for analyzing material handling tasks and its application prevalent in engine bearing industry. 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. Material handling assessment chart (MHAC) was prepared using the data of categories and different variables and parameters.

**Kwon et al. [93]** examined the maximum acceptable frequencies (motions/min) of upper extremity motions in the sagittal plane at different forces.

**Banks et al. [12]** evaluated the effect of progressive fatigue on factors that previously have been associated with increased risk of low back pain in various occupational settings, during a repetitive lifting task. Electromyography amplitude, kinematic, and kinetic parameters of repetitive freestyle lifting were evaluated. The results showed that subjective fatigue rating increased over time and static composite strength decreased as the experiment progressed.

**Hattoria et al. [66]** evaluated the effects of box load weight, vertical location and symmetry on the lifting capacities and subjective burden in Japanese female workers with manual material handling tasks. A remarkable increase was observed in heart rate and it was also suggested that lifting the 15-kg weight from the elbow to the shoulder level was difficult for female workers. Not only peak force, but also the average upward acceleration and peak velocity were lower in asymmetric liftings than those in symmetric liftings.

**Balderrama et al. [11]** studied the importance of the metabolism to establish the appropriate limits of loads at work and compared the aerobic capacity of people of young to old age in different groups.  $VO_2$  was measured using a portable breath by breath metabolic system and a telemetric heart rate monitor. Comparison was made in three methods to estimate the  $VO_{2max}$ , first, a direct measurement of  $VO_2$ , second, estimation by heart rate, and third, a step test method using predetermined charts. The results showed that the significant difference was observed among the estimation methods as well as among the age ranges. The method of predetermined charts is better suited for males and people younger than 30 years.

**Batish et al. [14]** investigated the effect of different independent lifting parameters on physiological stress of the workers and optimized the responses simultaneously using MRSN (Multi Response Signal to Ratio) to find the optimum condition.

**Lee et al. [101]** examined human 4-h maximum acceptable weight of lifting (MAWL) and maximum weight of lifting (MWL) for different modes of asymmetric lifting and containers. The results showed that asymmetric lifting with trunk rotation decreased MAWL and MWL by 9.1 and 17.3%, respectively, and asymmetric lifting with body turn decreased MAWL and MWL by 6.1%, when compared with the symmetric lifting.

**Sorensen et al. [164]** explored the effect of lifting stance width into the occupational setting under different load level conditions during sagittally symmetric lifting and lowering task. The results showed that both the ranges of motion and peak acceleration were significantly affected with the stance width and no effect was observed on muscle activation levels. It was concluded that the stance width effects can be seen in power lifting activities but do not show any significant changes into the occupational environment.

**Shamsul and Tan [150]** evaluated the maximum static lifting strengths for one-handed (left hand or right hand) and two-handed exertions in four lifting types (back lifting, upper-body lifting, arm lifting, and shoulder lifting) and the results recommended two-handed lifting due to higher lifting strength and less strain.

**Brown et al. [20]** evaluated the effects of straddle and symmetric stance on the lower limb load distribution when lifting a crate from the floor to standing hip height. Three separate stances: dominant foot forward (DFF), non-dominant foot forward (NDFF) and a symmetric (SYM) were used. It was observed that placing the non dominant limb forward reduced the loading asymmetry and to ensure equal limb loading, alternate lead limb during a straddle lift is required.

**Yoon et al. [184]** compared the effect on the trunk and upper extremity muscle recruitment when controlling the lifting pace and the lifting weight from waist height to shoulder height. Heavier lifting weight evenly increased the muscle recruitment throughout the lifting period without changing their temporal pattern. In contrary, lifting pace affected the temporal recruitment pattern in most of muscles. The faster lifting pace increased the muscle recruitment at the beginning phase but decreased at the terminal phase of lifting. These results may be helpful to educate the workers about the effect of lifting pace and weight on the biomechanical load to control the mechanical load on the muscles and spine.

**Kalra et al. [154]** evaluated the effect of psychophysical approach on maximum accepted weight limit (MAWL) for underweight, normal weight and overweight male workers. Workers with different body mass index (BMI) lifted weights at different heights and frequencies using free style lifting technique. The results showed that MAWL is affected by lifting in box size, BMI of the worker, lifting frequency and vertical distance.

**Widanako et al. [178]** interviewed the randomly selected persons by telephone about self reported physical, psychosocial, organizational, environmental factors and the consequences of low back symptoms (LBS). It was observed that the prevalence of reduced activities and

absenteeism due to LBS were 18% and 9%, respectively. Lifting increased the risk of reduced activities. Working in awkward/tiring positions and a cold/damp environment increased the risk of absenteeism. In conclusion: awkward/tiring positions, lifting, and work in a cold/damp environment should be reduced.

**Singh [151]** conducted a study to analyze the association between the low back injury risk and lifting task factors in small scale casting units and evaluated the safe limits of lifting index for no low back injury in workers. The results revealed that Lifting Index (LI), frequency of lifts, vertical and other distances were found most significant.

**Seay et al. [149]** compared three-dimensional trunk and pelvis range of motion (ROM) during a sustained asymmetric box lift/lower task between groups with a history of low back pain and no low back pain. Two way analysis of variance for all variables was performed and it was observed that initially pelvis and trunk transverse ROM were similar. It was concluded that despite no current pain, the HBP group demonstrated protective lifting mechanics compared to controls.

**Toosizadeh et al. [170]** investigated the effects of flexion angle and lift rate on trunk mechanical and neuromuscular behaviors during repetitive lifting which is associated with an increased risk of occupational low back disorders. The results indicated that increasing flexion angle had adverse effects on these outcomes, although lift rate had inconsistent effects and recovery time was more than 20 minutes.

**Pinto et al. [135]** focused on the effect of engineering controls on trunk muscle activity. Engineering controls were designed to control the instability of a liquid load. Subjects manually performed lifting asymmetrically in the transverse direction with stable loads, unstable loads, and unstable loads with engineering controls. Trunk and load kinematic and trunk muscle electromyography data were measured during lifting. It has been observed that unstable loads with engineering controls significantly reduced trunk muscle activity compared to unstable loads.

**Beek et al. [15]** explored whether routinely collected company data based on manual materials handling during scaffolding could be used to estimate exposure to manual lifting. It was observed that company data might provide an easy, cost-efficient way of assessing manual lifting.

**Whitfield et al. [177]** determined the effect of an on-body personal lift assistive device (PLAD) on oxygen consumption and investigated any difference in muscle activity or lifting

technique during a continuous lifting task. The results showed that there was no effect on oxygen consumption using PLAD. Participants used a variety of lifting styles; No changes were observed.

**Pinder et al. [134]** developed models for predicting the mean maximum acceptable weight of lift (MAWLs) for males and females from frequency of lifting and quantified the relationship between lifting frequency and the MAWL. The best fitting models were logarithmic with less than 50% of the variance. Normalising to MAWL at one lift per minute resulted in more accurate models.

**Fox et al. [51]** focused on the light weight lifting with maximum acceptable frequency of lifts of subjects for a two handed lifting task. Lifting height was varied from knuckle height to shoulder height similar to loading and unloading operation in industry. Oxygen consumption and heart rate were measured with psychophysical measure of lift frequency. The results reported that much higher frequencies were obtained in psychophysical studies in comparison of typical studies. Small changes in lift weight (4kg) had a significant impact on physiological responses.

**Mehta et al. [118]** investigated the effects of a prolonged repetitive asymmetric lifting task on behavioral adaptations during repetitive lifting activity and measured of tissue oxygenation and spine kinematics. Subjects repeatedly lifted a box at varied lifting frequency and fifteen percent of maximum lifting strength for a period of one hour. The results showed that overall, perceived workload increased during the repetitive lifting task and behavioral adaptations made by people performing asymmetric repetitive lifting activity may increase risk through increased dynamic loading of the tissues.

### **2.1.3 Effect of Lifting Task on Ground Reaction Forces**

**Kromodihardjo et al. [90]** developed a three dimensional kinetic model for the analysis of dynamic lifting and analyzed ground reaction forces for asymmetrical and symmetrical lifting and concluded that spinal stresses are higher in asymmetrical lifting as compared to symmetrical lifting.

**Burkhardt et al. [21]** evaluated maximal impact and propulsion ground reaction forces during jumping and explosive lifting exercises and concluded that explosive lifts create force levels dangerous to musculoskeletal systems.

**Hagen et al [64]** simulated the aerobic stress during lifting and recorded heart rate, oxygen consumption, sagittal body movements, vertical force plate measurements, and vertical movement during lifting of logs.

**Bentley et al. [16]** determined the effect of different lifting cadences on the ground reaction force during the squat exercise during lifting a barbell mass equal to their body mass. Ground reaction force and velocity sensor data were used to calculate inertial force contributions of both the body and barbell to total inertial force. The results showed that body's inertia forces were larger than the barbell with no effect of cadence.

**McMullian et al. [116]** measured ground reaction force and muscle activation asymmetries for three workers while lifting boxes from table to shoulder height.

**Tsuang et al. [171]** estimated the ground reaction forces when subjects assumed upright and bending postures as well as when they lifted at low and high frequencies of lift.

**Granata et al. [61]** developed a method to measure accurate trunk moments during dynamic lifting exertions.

**Amadio et al. [2]** used the ground reaction force as an indicator of the overload level in the musculoskeletal system during the weight-bearing phase on the ground where the greater mechanical overload occurs in the lower limb.

**Dworak et al. [43]** identified force time characteristics of ground reaction force exerted during take-off and landing phases in the six typical acrobatic elements and permitted an evaluation of the degree of dynamic overloads. Authors suggested that the high levels of dynamic overloads are serious and of traumatogenic character.

**Gwanseob et al. [63]** examined the responses in trunk kinematics and ground reaction forces of different aged subjects during manual lifting task. A lumbar motion monitor and force platform were used to measure the trunk kinematics and the ground reaction forces respectively. It has been observed that age had a significant effect on the trunk kinematics variables (peak velocity and peak acceleration) but did not affect ground reaction forces or other trunk kinematics variables.

**Fong et al. [50]** presented a method to estimate the ground reaction forces in three directions from pressure insoles in walking using developed regression models and compared the results with the real data recorded from force plate. The correlation coefficient and the root mean square error were applied to evaluate the accuracy. The results showed that very good

correlation in all directions and the root mean square error was about 12%, 5% and 28% of the peak recorded value.

#### **2.1.4 Analysis of Lifting Task Neural Networks**

**Mona et al. [123]** developed artificial neural network-based physiological models (ANNs) and multiple regression models (MLR) to predict the energy cost to different prolonged manual lifting tasks for different lifting heights. A combination of task and worker's characteristics was used as inputs. Multilayer Feed forward networks (MLFF) for model construction and Levenberg-Marquardt Back propagation (LMBP) algorithm for training were used. This model has following advantages:

- (1) To accurately predict workers' metabolic energy expenditure during the lifting activity for a wide range of workers' and task characteristics;
- (2) To check the risk assessment of this task with the help of accurately predicted physiological responses of the body to the stress of performing a task;
- (3) Assess physical capabilities of the individual performing the task;
- (4) Help in job recruitment screening in industry and in redesign of the tasks, if worker feels exertion during the task or the predicted oxygen consumption exceeds the permissible physiological fatigue limit (PFL) at any moment during the working period.

The ANNs models outperformed the MLR models developed utilizing the same data sets.

**Kingma et al. [86]** compared the results of three contrasting techniques of measurement of lumbar loading during lifting. Neural network technique showed better results in comparison with the other techniques. Differences in measurement of spinal loading varied as per lifting speed and lifting technique.

**Lee et al. [100]** developed a hybrid neuro-fuzzy system for estimating the magnitude of electromyography responses of trunk muscles based on two lifting task variables (trunk velocity and trunk moment) as model inputs. The mean absolute error (MAE) was calculated between the actual and model estimated value and it was observed that larger errors in left side of trunk occurred due to higher muscular activity.

**Hou et al. [70]** proposed an EMG signal prediction model using artificial neural network (ANN) in manual lifting.

**Karwowskia et al. [81]** studied the electromyographic (EMG) responses model for trunk muscles in manual-lifting tasks aimed at prevention of low back disorders at the workplace using the fuzzy relational rule network (FRRN) and applied it for estimating time domain EMG responses of trunk muscles due to manual lifting under limited task conditions. The trunk-related variables, including sagittal and lateral trunk moments, pelvic tilt and pelvic rotation angles, and sagittal, lateral, and twist trunk angles were used as model inputs in FRRN. The data for testing and training of EMG model was collected using different combinations of weight lifted, asymmetry, and the origin and destination of lift with two repetitions of each condition.

**Hou et al. [71]** proposed a recurrent fuzzy neural network (RFNN) model to establish the kinematics–EMG–force relationship and model the dynamics of muscular activities during manual lifting. The model predicts forces directly from kinematics data, avoiding EMG measurements and the use of biomechanics model.

**Yuchi and Jo [185]** proposed a mathematical prediction model based on the relationship between heart rate and physical activity of real life using the Feed Forward Neural Network (FFNN). The inputs of the predictor are  $HR(n)$  and  $PA(n)$  in the current time step, and the output is the predicted sequence  $HR(n + 1)$  in the next time step. One half of the signal set was used to train the FFNN and the other half to validate the training. The result shows that mean absolute error of the predicted heart rate was restricted inside limits.

**Ruiz et al. [144]** developed and cross validated an artificial neural network (ANN)-equation to estimate maximal oxygen uptake ( $VO_2\text{max}$ ) from 20m shuttle run test performance and the proposed model was been coded in a user friendly spreadsheet.

**Perez and Nussbaum [133]** evaluated the ability of artificial neural network models to predict initial and final lifting postures in 2-D and 3-D scenarios in facilitating the design and evaluation processes for manual materials handling tasks. The models provide a means to predict initial and final postures in commonly occurring manual material handling tasks and provide information about potential lifting strategies.

**Asensio-Cuesta et al. [3]** developed the artificial neural networks for classifying the risk of low back disorders (LBDs) for certain lifting jobs in industry. The training procedure was smartly used to avoid over fitting. With the appropriate size of training data, the approach uses complex architecture networks. Such comparison shows that the prediction of musculoskeletal disorders in a way that is faster and easier than with other procedures. The obtained neural

network is able to correctly classify 81.6 percent of highly repetitive lifting industrial jobs as posing low or high-risk for LBDs.

**Ismailaa et al. [75]** built a prediction model using the neural network to reflect the effects of age, body height, body mass, and resting heart rate on the working heart rate and percent relative heart rate of bricklayers. Heart rate is commonly used to estimate energy expenditure or physical strain in physically demanding jobs. The results showed that the mean percent relative heart rate (RHR) was 57.4 percent. The mean working heart rate and resting heart rate were 120.8 bpm and 68.6 bpm respectively. The neural network could be trained to predict  $H_{\text{Working}}$  and percent RHR. There is a non-linear relationship between the age, body height, body mass, resting heart rate, working heart rate and percent RHR. The neural network results for the  $H_{\text{Working}}$  and percent RHR were dominated by resting heart rate, followed by body mass, age and body height in that order. The predicted values of percent RHR and  $H_{\text{Working}}$  did not differ significantly from the actual values though the relationships were non-linear.

#### **2.1.5 Lifting and Carrying Tasks**

**Louhevaara [110]** simulated the local muscle and circulatory strain in manual handling, continuous parcel lifting, carrying and holding tasks in the laboratory. Heart rate, blood pressure and the overall RPE (rating of perceived exertion) indicated that average circulatory strain in the tasks was low. Strain was significantly higher during lifting than holding, and the difference was accentuated if a subject used the leg lift technique. There were only few differences in local and circulatory strain due to gender.

**Looze [109]** studied the effect of weight and inversely related frequency on spinal load in two bricklaying tasks: building the skin and the floor of a steel ladle. Peak compression increased with higher brick weights. There was no significant difference observed in integrated compression in four combinations of weight and frequency.

**McKean & Potvin [115]** evaluated the effects of a simulated industrial bin on lifting and lowering posture and erector spine activation levels. Subjects handled loads under the following conditions: (1) two directions (loads were lifted from the floor to knuckle height or lowered from knuckle height to the floor), (2) two constraint conditions (the load was placed on the floor allowing a freestyle lift). Surface EMG data were collected from the right lumbar and thoracic erector spine and posture data were collected to represent the knee, pelvis, spine and trunk angles. Peak and average values were recorded for each variable for each trial.

**Lavender et al. [97]** evaluated the peak dynamic bending moments on the spine during sagittal plane lifting and determined the peak bending moment during each lift using “bottom-up” linked segment dynamic model. Load's magnitude, its initial height above the floor, and the lifting speed were the parameters. The subjects lifted the box at varied height, weight and speed. It was observed that the peak moments were significantly greater at low lifting heights, high lifting speeds and heavy loads. Also, a regression model was developed to predict the peak dynamic moment based on the given data of the load magnitude, the starting height, and a qualitative estimate of lifting speed. Comparison was made between this model and the current National Institute for Occupational Safety and Health's (NIOSH) model for control. The peak bending moments acting on the spine as the limits for safe lifting were adjusted according to changes in the initial lifting height.

**Plamondona [137]** examined how the load experienced by ITH drill operators changed when lifting a vertical drilling rod (1.61 meter and 35 kg) using two rod heights and four different foot positions during “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. It was observed 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 and 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).

**Chung et al. [29]** measured heart rate and oxygen uptake while 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.

**Wu [184]** 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 using psychophysical approach. Trained Chinese females performed different load carrying tasks in random order. It was observed that 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.

**Gheldof [58]** conducted the study on the role of work-related physical factors and psychological variables in predicting the development of and recovery from short-term and long-term LBP (low back pain). Odds ratios (ORs) were calculated using simple or multiple logistic regression analysis and categorized result (LBP, high pain severity) according to OR, CI (odd ratio, confidence intervals) and then compared the results and discussed with prospective study.

**Liu [107]** determined preferred backpack load distribution of infantry soldiers and examined the effect of backpack load position, walking speed and surface grade on the physiological responses of infantry soldiers. Questionnaires were prepared for analysis and the result showed that backpack item arrangement was typically determined by convenience and habit. About 33.6% and 30.6% of the soldiers reported placing heavier items in the lower and higher positions, respectively. In the other part of study, soldiers performed treadmill walking bouts at different speed and surface grades carrying 15% of their body weight in upper and lower load arrangement in a backpack. Respiratory frequency, minute ventilation, oxygen consumption and heart rate were measured using the Quark pulmonary system. The multivariate analysis of variance (MANOVA) was completed and results showed that the effect of walking speed was found most significant for all physiological indices. It has been observed that walking on a 6% grade was associated with higher oxygen consumption and heart rate. When the load was in upper position in backpack, mean respiratory frequency was significantly higher and there was a significant interaction between load position and walking grade on oxygen consumption.

**Maiti [114]** evaluated the occupational risk factors related to building construction activities in India in female workers. Workers performed two types of operations in the field; asymmetric lifting during concreting a boundary wall and carrying the concrete mixture. The working heart rate and oxygen uptake were calculated during asymmetric lifting and proposed a method to determine the average steady pause time from fluctuating working heart rate and the lifting frequency. Lower work efficiency and higher relative HR were observed in this type of load handling task. The resting time due to muscular fatigue and environmental load were calculated. It has been observed that workers were not getting sufficient rest and recommended weight limit value in optimum condition was lesser than the actual lifted load. Finally, some guidelines in context with modification of workplace and work methods were suggested to compensate the health hazard conditions.

**Fredericks et al. [52]** studied activities found in small foundries in a simulated metal pouring operation and evaluated the effects of different mold heights and carrying distances on

physiological responses, and maximum acceptable task frequencies (MAF) for metal pouring. The output parameters were oxygen uptake, heart rate, blood pressure and ratings of perceived exertion. The results showed that that carrying distance had a significant effect on both heart rate and oxygen consumption. Recommendations for reducing the risk of injury were also presented.

**Li et al. [102]** studied combined manual materials handling (MMH) tasks, at varied frequencies, lifting and lowering height combinations. Chinese male workers performed specific height lifting, lowering and carrying task with a box .Oxygen uptake, heart rate, and ratings of perceived exertion (RPE) for whole body were measured during the task. Actual energy expenditure of subjects for an hour was calculated. Also, predicted energy expenditure was estimated using regression equation. The results showed that there was no significant difference between actual and predicted energy expenditures statistically. The task frequency, lifting and lowering heights influenced oxygen uptake, heart rate, and the RPE.

**Liyod et al. [108]** compared the subjective perceptual responses to both head-loading and back-loading in a group of women. Subjects were asked to walk for 4 min at varied loads until associated pain or discomfort caused the test to be terminated or a load of 70% body mass was successfully carried on a treadmill on two occasions, head-loading and back-loading. Questionnaires were filled up by subjects to indicate the feelings after the each experiment. The results showed that back-loading was generally associated with more areas of discomfort than head-loading and head-loading was associated with the pain and discomfort in the neck.

**Dieën et al. [42]** investigated the effects of initial horizontal object position on peak L5/S1 total moment (PTM) lifting strategies during manual lifting. Subjects performed two types of lifting tasks, one with transportation of the load and other without any transportation of the load. It was observed that the other one resulted in 6% larger PTMs for the close-positioned box. Familiarization with alternative lifting techniques resulted in a 10% reduction in PTMs for the far-positioned box. This study showed that the effect of horizontal box position on peak L5/S1 moments is dependent on the type of lifting task and familiarity with alternative lifting strategies.

**Hurley et al. [73]** evaluated the prototype courier truck for its ability to reduce courier drivers' Musculoskeletal Disorders (MSDs) risk and double-handling of packages between carts and the truck, decrease the lifting of carts on/off the truck and reduce lifting packages in awkward positions. Courier drivers performed while surface electromyography of the forearms, shoulders and lumbar spine were monitored with a simultaneous video recording. Low back

loading for each lift was calculated based upon video analysis. The results showed that the reduction in total delivery time was 29.5% which was noticeable for stops using a cart.

**Faber et al. [46]** proposed and evaluated the performance of a novel hand force estimation method based on ground reaction forces (GRFs) and body segment accelerations during manual lifting and carrying task in patient handling. The estimated 3D hand forces were calculated by taking the measured GRF vector and subtracting the force vectors due to weight and acceleration of all body segments. The hand force estimation errors were calculated using root-mean-square difference (RMSD) between estimated and measured hand forces.

**Kim et al. [84]** explored the relationship between transfer distance and spine motion during a simulated palletizing task. Subjects performed lifting of 10.9 kg boxes at different location and heights. The results showed that twisting and forward bending decreased with increased transfer distance and the lateral bending increased with increasing transfer distance. Separating the lift origin and destination by 1-1.25 meter yielded the best balance between spine kinematics and productivity.

#### **2.1.6 Application of NIOSH Lifting Equation to Analysis of Lifting Tasks**

The National Institute for Occupational Safety and Health (NIOSH) developed a lifting equation in 1981 to indicate “safe” occupational lifting limits. 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.

**Kim J.Y. [82]** investigated the effects of trunk motion under lifting conditions described by the Work Practices Guide for Manual lifting (NIOSH, 1981). Lift style, load location and subjective lift velocity as input parameters and trunk muscle electromyographic (EMG) activity, actual trunk velocity and load acceleration as output parameters were used under symmetric lifting conditions. It has been observed that there was no effect of lift style and as the trunk velocity increased, EMG activity increased within the latissimus dorsi and rectus abdominis muscles but not within the erector spine muscles.

**Waters [175]** explained the basics for selecting the criteria (biomechanical, physiological, and psychophysical) which were used to define the 1991 revised NIOSH equation, and described the lifting index (LI), an index of relative physical stress, that can be used to identify hazardous lifting tasks. As per the reported literature, the recommended weight limits derived from the revised equation were less than the set limit for task.

**Lee [99]** examined the NIOSH revised weight limit for Korean workers using the psychophysical methodology. The psychophysical and the validation experiment performed by young male Korean subjects at varied lifting frequency and height. The results showed that the obtained load constant was the same as the one recommended in the NIOSH equation, It proves that Korean males are well protected by the NIOSH equation.

**Dempsey & Fathallah [39]** examined the cause of adding the asymmetry multiplier in revised NIOSH equation 1991 and provided an alternative perspective by reviewing additional literature. The application of asymmetric multiplier in revised NIOSH equation manual was discussed with the usability of the asymmetry multiplier in industry for particular tasks. Three different sources were used for data collection to illustrate the problems and variability associated with measuring asymmetry in industry. In conclusion, recommendations for further research and potential modifications to the asymmetry multiplier were presented.

**Granata K. P. [49]** quantified the variability in lifting motions, trunk moments, and spinal loads associated with repeated lifting exertions and identified workplace factors that influence the biomechanical variability. Measurement of trunk dynamics, moments and muscle activities were used as inputs into EMG assisted model of spinal loading. Experienced and inexperienced subjects performed repeated lifts. The results showed that box weight, task asymmetry and job experience influenced the magnitude and variability of spinal load during repeated lifting exertions and experienced subjects demonstrated significantly greater spinal loads in comparison with inexperienced subjects. The mean spinal load was under the NIOSH recommended limit but due to variability about the mean, more than 20% of the lifts exceeded the recommended limit.

**Russell [145]** studied a uniform task of lifting milk cases with varied capacities and compared the results of the NIOSH, ACGIH TLV (the quantified version of the American Conference of Governmental Industrial Hygienists Threshold Limit Value for mono-task hand work), Snook, 3DSSPP (3D static strength prediction program) and WA L&I lifting assessment instruments. The outputs of results were converted to an exposure index similar to the NIOSH Lifting Index. It was observed that all instruments showed higher exposures associated with lifting and the NIOSH, ACGIH TLV and Snook methods results were the same for similar pattern exposure at different height levels. The reasons for instrument differences were explained for better selection of methods and to interpret the results appropriately.

**Okimoto et al. [131]** proposed a detailed description of the procedures for measuring Revised NIOSH Lifting Equation variables to a better understanding of the equation applied to field conditions. The Revised NIOSH Lifting Equation is a tool for assessing two-handed manual lifting tasks. Both movies/films and photographs were used throughout the complete motion to evaluate the lifting/lowering task of steel sheets in an auto parts manufacturing plant. The results showed that Recommended Weight Limit was 5.73 kg and a Lifting Index was 5.8 for given task.

**Lavender et al. [98]** evaluated whether the asymmetry multiplier incorporated in the 1991 National Institute for Occupational Safety and Health lifting equation adequately controls the biomechanical spine loads during asymmetric lifting. From each location, different weighted boxes were lifted at defined lifting speeds. Ground reaction forces were combined with kinematic data of 3-D moments at the base of the spine (L5/S1) and the spine compression forces. The results showed that the twisting and lateral bending moments increased with task asymmetry.

**Potvin et al. [139]** compared the recommended weight limit from the revised NIOSH lifting equation with its three design criteria (biomechanical, psychophysical and physiological). The results showed that RWLs caused compression forces were too low for lifts above knuckle height. The equation's average RWL are acceptable to more than 95% of female workers. The RWL's energy expenditure is much lower at high frequencies. The new developed NIOSH lifting equation presents very conservative and alternative limits.

## **2.2 SUMMARY, LIMITATIONS AND NEED OF STUDY**

The review of literature shows that many researchers have examined the effect of various lifting parameters such as load, lifting frequency, posture, vertical distance and travel distance on oxygen uptake and heart rate. But very little work has been reported on what will be the effect of environmental conditions (for example ambient temperature) on oxygen consumption and heart rate of Indian male workers involved in such lifting/ carrying tasks. The North West region of India experiences very extreme environmental conditions during the year. The temperature in summer routinely goes up to 45° C. Further, high humidity levels cause very harsh work conditions for workers involved in MMH tasks. In winter, the minimum temperature goes below 5<sup>0</sup> C. Furthermore, most manufacturing organizations don't have air conditioning at the workplace because of shortage of power in the region. The workers, especially those on the margins of society, experience some of the toughest conditions to work.

So there is a need to evaluate the effect of lifting parameters on the exertion ( oxygen uptake and heart rate) caused to the workers and to minimize the exertion on the workmen as well as to minimize the risk of subsidence in a lifting task performed in varied ambient temperature conditions.

In literature, many lifting parameters have been studied to measure the effect on responses (for example heart rate and oxygen uptake). All these studies optimize the factors for one response only at a time. No study has been reported that optimizes multiple responses, simultaneously and generates optimal level settings for a manual lifting task under different ambient temperature conditions.

Heart rate and oxygen uptake, commonly known as cardiopulmonary responses of personnel involved in manual material handling tasks has been measured by many researchers. No literature has been reported on the predictive indexes of heart rate and oxygen uptake on Indian male worker for quick evaluation of manual lifting task. Due to different environmental conditions (for example hot and humid weather) in India, such lifting tasks cause excessive exertion to the workers involved in such tasks.

Many researchers studied the effect of vertical ground reaction forces and loading rate on human body during running, walking, jumping but rarely have these been used to evaluate lifting and carrying tasks. Also, none of the studies have been reported for the physiological characteristics and body metabolism of workers in the sub-continent. Such studies can be performed in many ways. Measurement of ground reaction forces in different planes is a good measure of the musculoskeletal stresses being exerted on the workers performing such tasks. So there is a need to evaluate the effect of lifting parameters on the ground reaction forces (GRF), loading rate (LR) of workers in dynamic lifting human activities.

As per the review of the literature, some studies made to predict the cardiopulmonary responses using neural network during manual lifting. However, no study has been reported that used neural network to predict the ground reaction forces (loading rate) in manual lifting tasks. So there is a need to predict exertion caused to workers during a lifting task.

During manual lifting, cardiopulmonary responses have been measured by some researchers. But no study has been reported that optimizes cardiopulmonary responses (heart rate and oxygen uptake and perceived exertion) and ground reaction forces responses (loading rate) simultaneously and generates optimal experimental settings for a manual lifting task. So there is a need to apply various multiple goal decision criteria tools for global optimization of lifting parameters.

## **CHAPTER 3**

### **DESIGN OF STUDY**

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This chapter presents a detailed design of study including the tools and techniques used for analysis and design. The effect of lifting parameters; weight load, lifting frequency, vertical distance from floor, posture (asymmetric angle), coupling (grip), horizontal distance, travel distance and their interaction on responses (oxygen uptake and heart rate) of workers have been evaluated thoroughly in the present research work.

To meet the objective of this study, the research work has been completed in two phases. Figure 3.1 gives the details of overall experimental design and the tools and techniques used. The overall flow chart of the experimental study in detail is shown in Figures 3.2 & 3.3.

#### **3.1 PILOT EXPERIMENTATION**

Subjects routinely engaged in material handling tasks that included lifting of loads were invited to participate with their consent in laboratory simulation study. Each of them had no prior medical history and was in good health. All the subjects were trained for the task before the start of actual experimentation. The subjects were clothed in their working site traditional dress. Each worker was trained to lift a loaded container from its initial position on the floor to the desired position in one continuous motion. They were not permitted to take any stimulant before or throughout the experiment.

During the pilot study of phase I, the factors (load weight, frequency of lift, coupling (grip), posture (asymmetry), vertical distance, horizontal distance from load and travel distance) that may affect the pulmonary oxygen uptake and heart rate in lifting tasks were identified as control factors. As per the literature, many studies reported that load weight, lifting frequency and vertical distance from floor are most influencing factors which lead to low back pain and physical exertion. The maximum level of load weight was set at 23 kg as per the NIOSH (Waters [175]). The lower levels of all factors were selected at which the task caused least exertion to the workers. The highest levels for the factors other than load weight were selected as per those conditions where the task became very stressful. The lower level of load and frequency were selected when it started to affect the output response values significantly. 13 kg load and 110 lifts in 20 minutes lifting frequency were selected as the lower level due to variation in responses (oxygen uptake and heart rate) just started significantly.

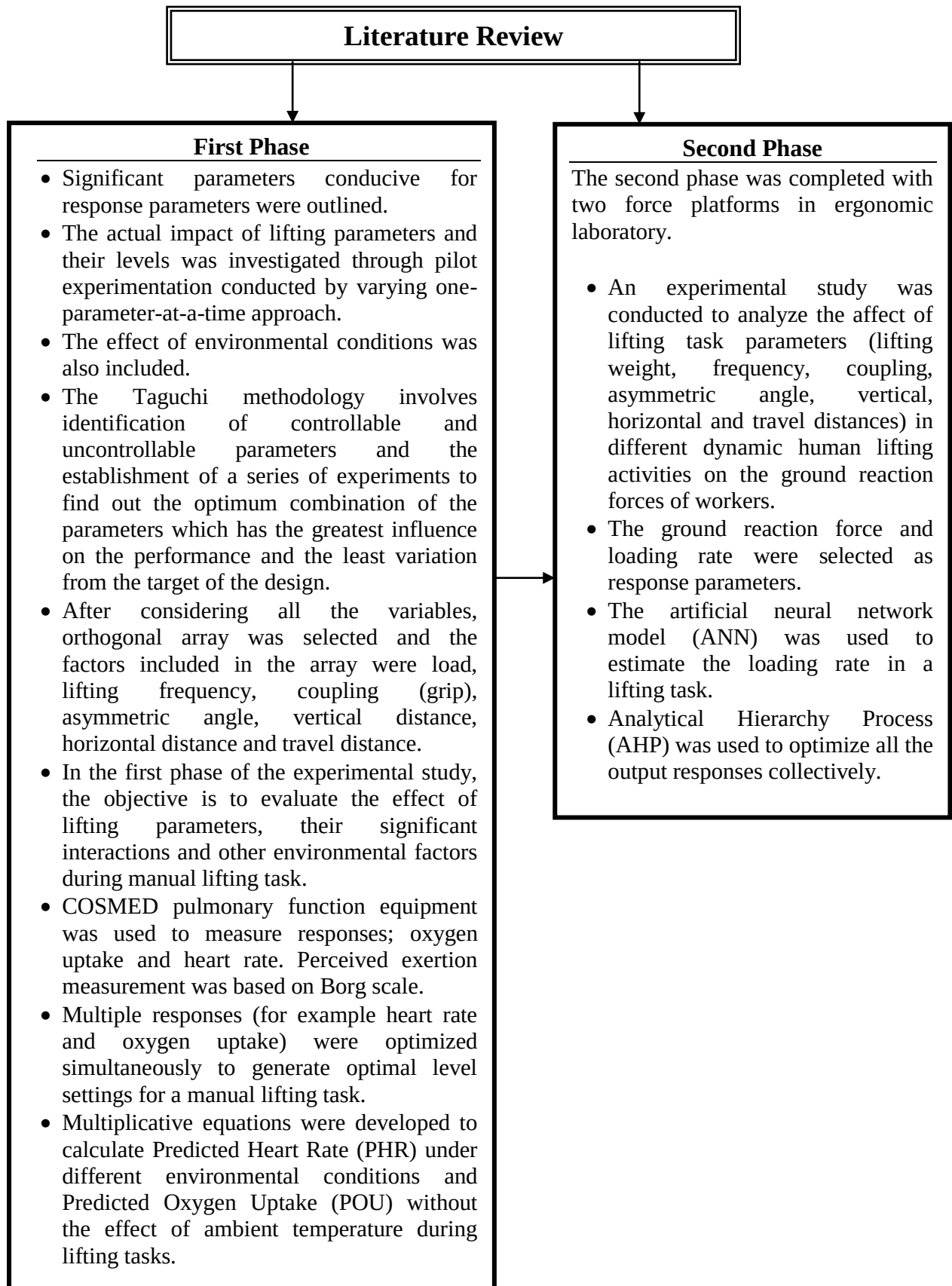


Figure 3.1: Phases of study

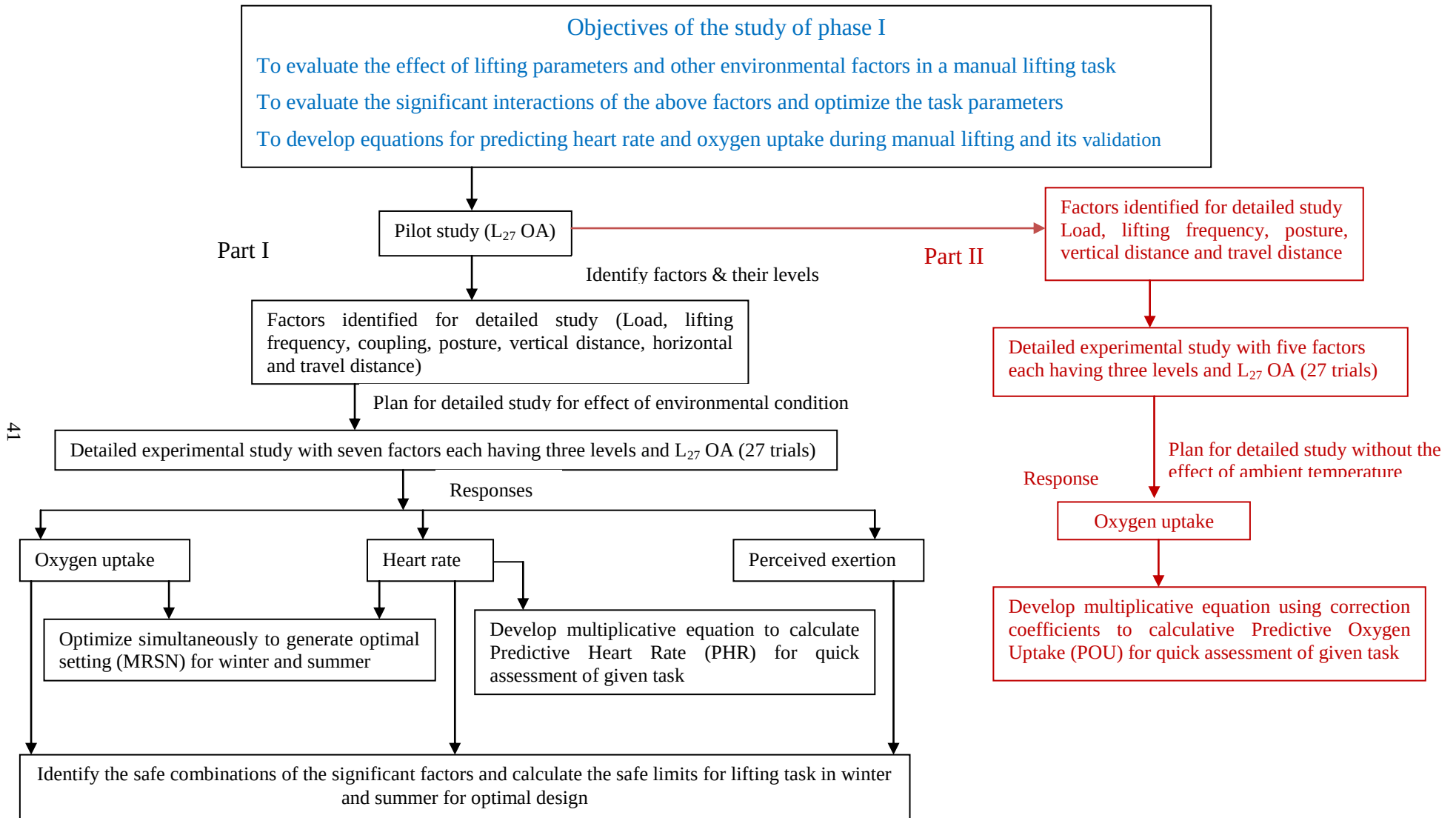


Figure 3.2: Flow chart of the study of phase I

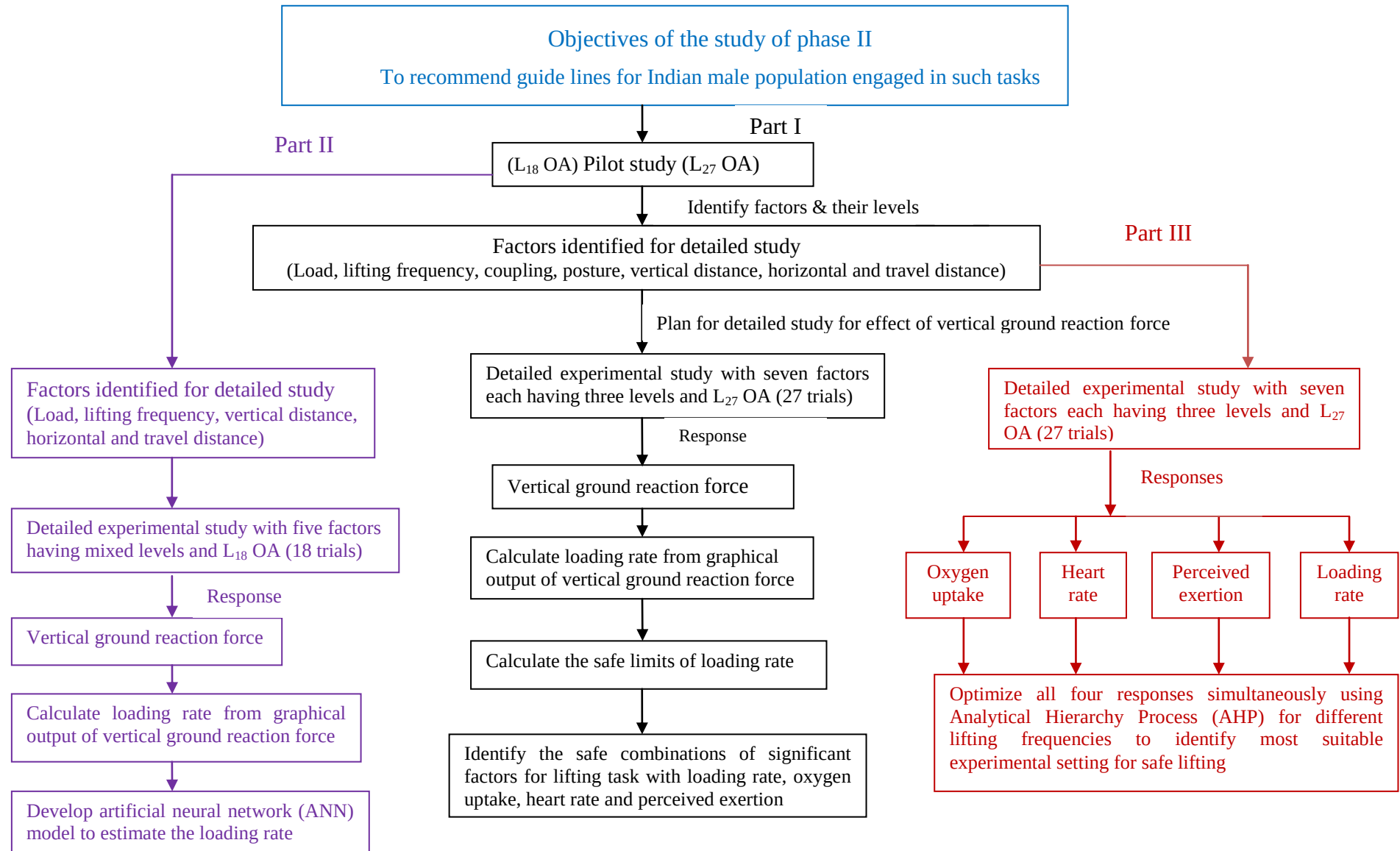


Figure 3.3: Flow chart of the study of phase II

Three levels of load were selected at equal intervals (i.e., 13 kg, 18 kg and 23 kg). As it can be observed from Figure 3.4, the task became very stressful beyond 180 lifts in 20 minutes. So the highest level for frequency of lift was taken as 180 lifts in 20 minutes. Similarly, the lift frequency was varied at three levels, i.e., 110, 140 and 180 lifts in 20 minutes of continuous work. Oxygen uptake was observed to be high while placing the load above shoulder level, as shown in Figure 3.5. Therefore the levels for vertical distance were set at shoulder, waist and knee, which correspond to 150cm, 110 cm and 55 cm respectively. As per demographic details of participants, the average heights of knee, waist and shoulder were fixed 55 cm, 110 cm and 150 cm respectively. These heights were intentionally shown fixed to avoid any kind of confusion for experimental study. The graphs showing the effects of variation of lifting frequency, vertical distance and load weight on oxygen uptake and heart rate are shown in Figures 3.4 to 3.6. Three different types of coupling for ease of handling (with gloves, with cushion and without gloves) were used for measuring the effect of a suitable grip. The horizontal distance was decided as per the worker's arm reach and the most comfortable horizontal position was 25 cm. The horizontal distance was varied at 15 cm, 30 cm and 45 cm.

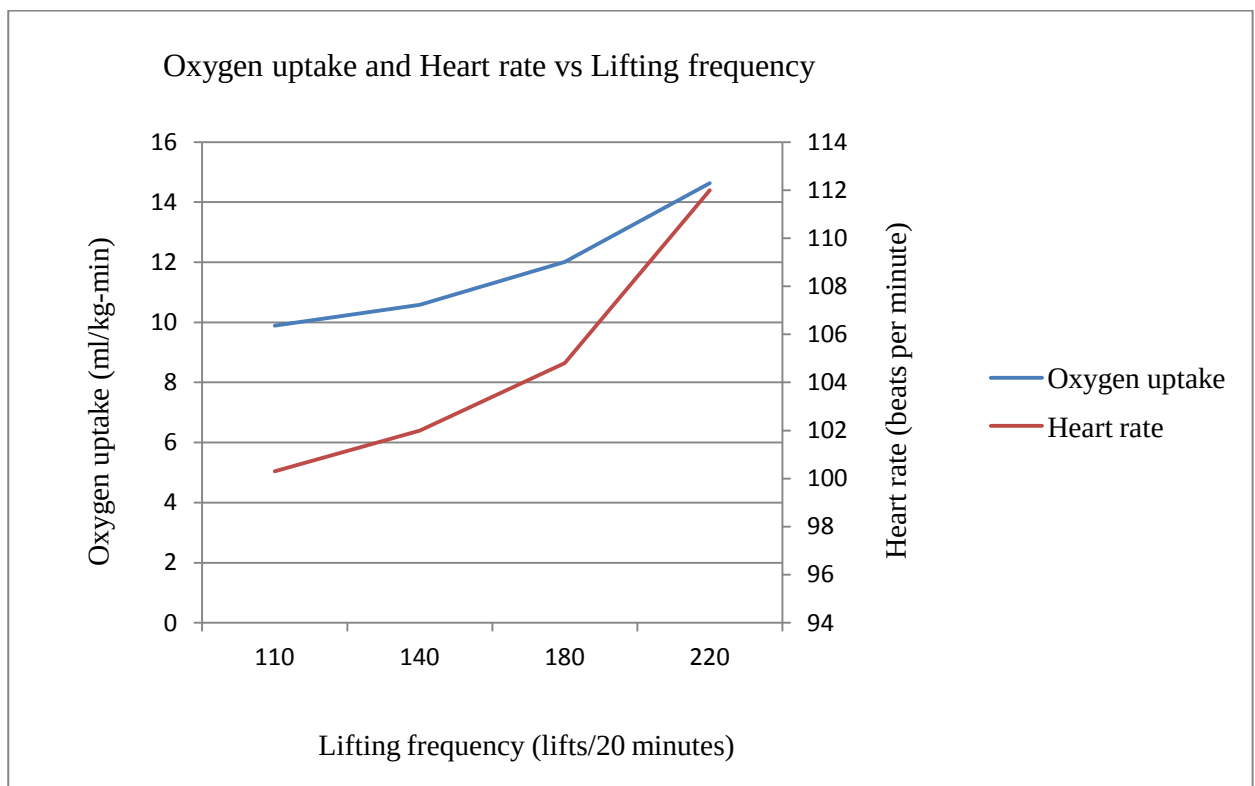


Figure 3.4: The effect of lifting frequency on oxygen uptake and Heart rate

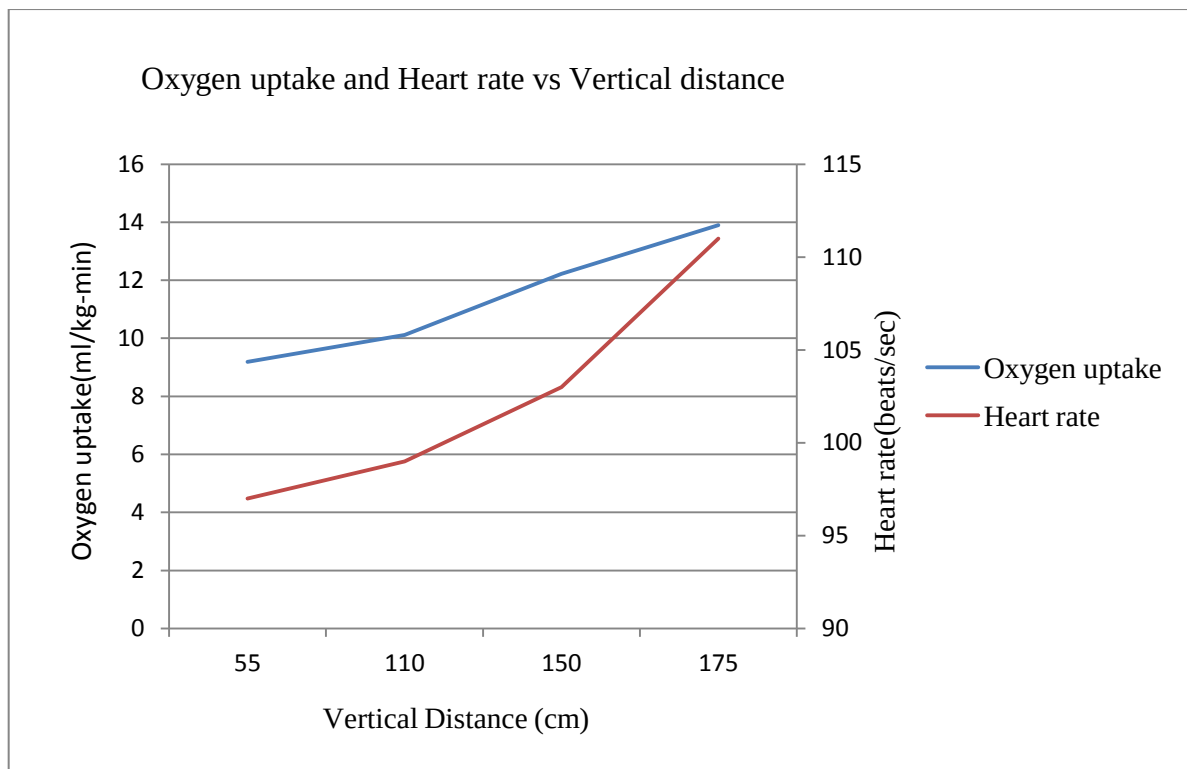


Figure 3.5: The effect of vertical distance on oxygen uptake and heart rate

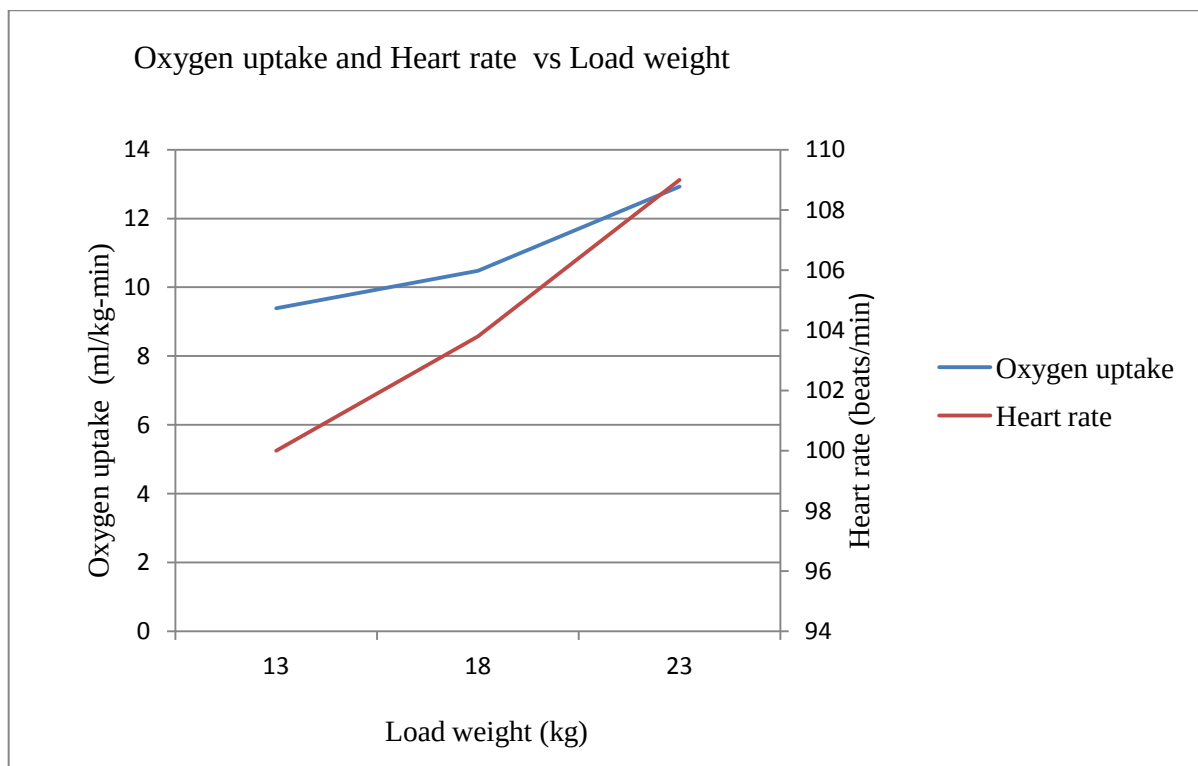


Figure 3.6: The effect of load on oxygen uptake and heart rate

The asymmetric angles for body posture of workmen were varied at three levels of difficulty (neutral 0°, moderate 40° and difficult 60°). In order to simulate a real situation prevalent in Indian manufacturing industry engaged in batch production, the operators were asked to travel a defined distance with load. Therefore, the levels of travel distance were varied at 25, 45 and 60 cm. Table 3.1 shows the factors and their levels identified during pilot study.

Table 3.1: Factors and their levels identified during pilot study

| Factors (unit)                          | Levels      |              |            |
|-----------------------------------------|-------------|--------------|------------|
|                                         | Level – 1   | Level – 2    | Level – 3  |
| Load, A (kg)                            | 13          | 18           | 23         |
| Lifting frequency, B<br>(lifts/ 20 min) | 110         | 140          | 180        |
| Coupling Grip, C                        | With Gloves | With Cushion | W/o Gloves |
| Assy. Angle, D (in °)                   | 0           | 40           | 60         |
| Vertical distance, E (cm)               | Knee        | Waist        | Shoulder   |
| Horizontal distance, F (cm)             | 15          | 30           | 55         |
| Travel Distance, G (cm)                 | 25          | 45           | 60         |

### Phase I (Part I)

As per the results of the pilot study, the effect of different lifting parameters (viz. lifting frequency, load weight, vertical lifting distance from floor, asymmetric angle or posture, grip or coupling, horizontal distance and travel distance etc.) and some interactions between them were studied. Three workers were involved in this part of the study. Oxygen uptake and heart rate and perceived exertion were selected as response variable. The noise factor ambient temperature levels were selected according to the environmental conditions (summer & winter) in India. The effect of temperature on responses has been discussed in chapter 4.

### Phase I (Part II)

For the second part of study of first phase, based on the pilot study results, load, frequency of lift, vertical and travel distance, asymmetric angle and some of their interactions were identified as control factors. Eight workers were participated in this part of study. It has been undertaken to evaluate the main effects of control factors on the oxygen uptake of workers involved in lifting tasks without any consideration of ambient temperature conditions. The details have been given in chapter 5.

## Phase II (Part I)

Before the start of the study of second phase, a pilot experiment was carried out to identify factors and their levels which may affect the vertical component of the ground reaction force ( $F_z$ ) under feet during manual lifting tasks. Based on this analysis, the weight to be lifted, frequency of lift, coupling (grip), posture (asymmetry), vertical and horizontal distance from load, travel distance were identified as control factors. The levels of control parameters were selected as like in the study of first phase. Loading rate plots were drawn with some lifting parameters (load, vertical distance and frequency etc.) and are shown in Figures 3.7, 3.8 and 3.9. The plots clearly show the effect of variation in weight to be lifted, frequency of lifting and vertical distance on loading rate.

In the first part of the experimental study of second phase, effect of different lifting parameters (viz. lifting frequency, load weight, vertical lifting distance from floor, asymmetric angle or posture, grip or coupling, horizontal distance and travel distance etc.) was studied. The experiments were conducted on ten healthy workers (age 21 to 32), with their consent and were routinely engaged in manual lifting tasks. Vertical ground reaction force and loading rate was selected as a principal response. The vertical component of force  $F_z$  is obtained by bending and stretching of the body and measured using the force platform. Loading rate was calculated from vertical ground reaction force for each trial. The effect of lifting parameters on loading rate has been discussed in detail in chapter 6.

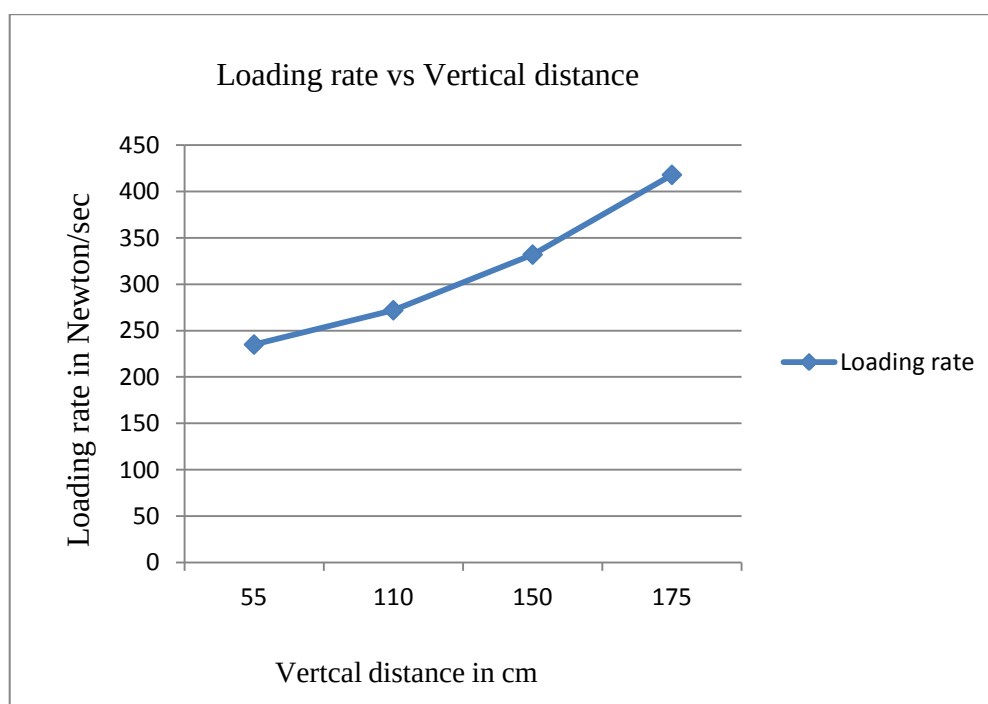


Figure 3.7: Loading rate plot with vertical distance keeping load and frequency constant

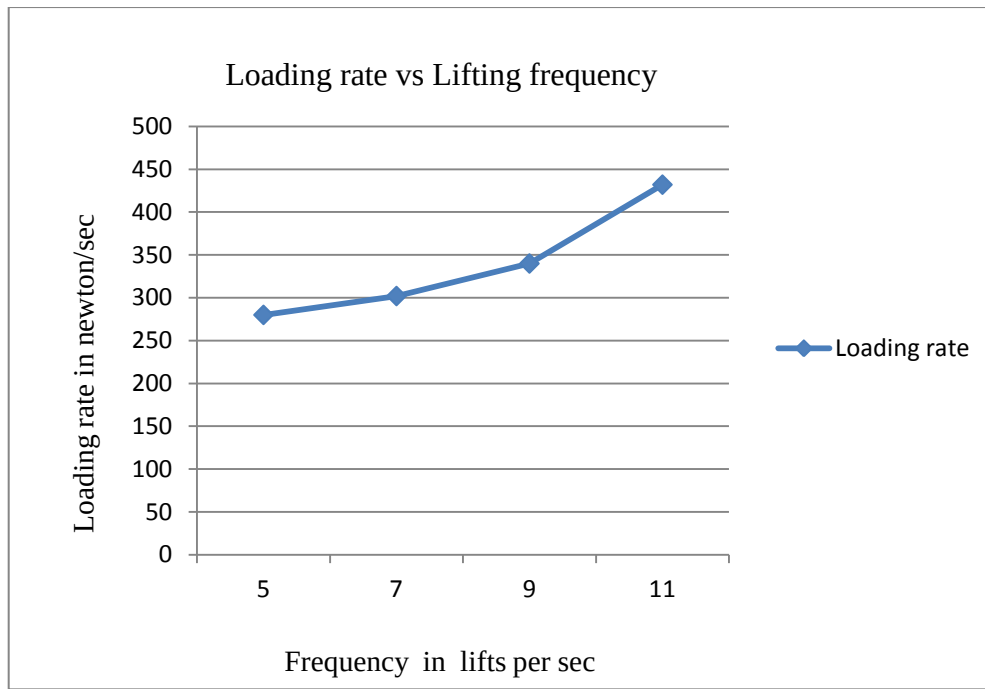


Figure 3.8: Loading rate plot with frequency keeping load and vertical distance constant

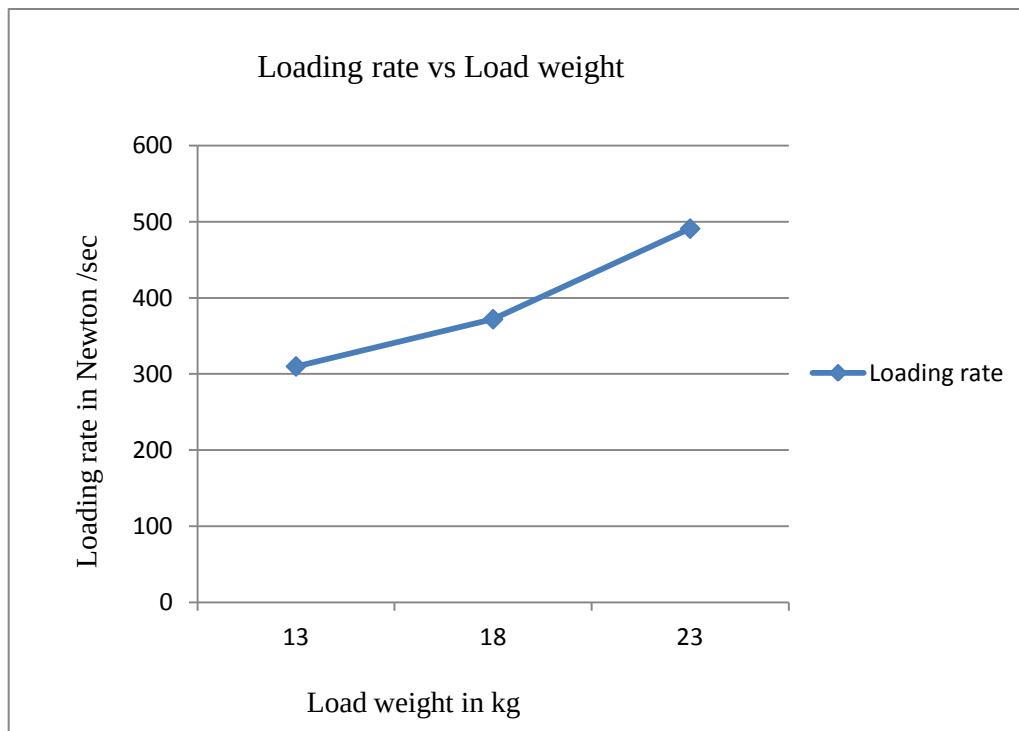


Figure 3.9: Loading rate plot with load weight keeping vertical distance and frequency constant

### Phase II (Part II)

For the second part of study, as per the result of the pilot study of the second phase, lifting parameters affecting the vertical reaction force were identified. These parameters were (i) lifting frequency, (ii) load, (iii) vertical distance and (iv) horizontal and travel distance and

were varied at different levels for detailed study of their effect on ground reaction forces (GRF) during manual lifting. Five out of seven parameters were selected for prediction of loading rate using Artificial Neural Network (ANN). Fourteen workers were participated in this part of the study. The details have been given in chapter 7.

### **Phase II (Part III)**

For the third part of study, on the basis of a previous pilot experimentation results (first phase and second phase), the control factors and their selected levels were chosen by varying one factor at a time and are listed in Table 3.1. The lifting parameters (frequency of lift, load, vertical distance, horizontal distance, grip (coupling), asymmetric angle and travel distance) were identified as control factors. Twelve young male workers who had no previous history of illness or other chronic health problems, with experience in manual material handling, participated in this study. The demographic details (age, height, resting heart rate, resting oxygen uptake, metabolic rate, maximum aerobic capacity) of workers were measured. The oxygen uptake, heart rate, perceived exertion and loading rate were considered as principal responses. The four responses were optimized simultaneously using AHP (see chapter 8).

## **3.2 METHODOLOGY**

The full factorial design is referred as the technique of defining and investigating all possible conditions in an experiment involving multiple factors while the fractional factorial design investigates only a fraction of all the possible combinations. Although these approaches are widely used, they have certain limitations: they are inefficient in time and cost when the number of the variables are large; they require strict mathematical treatment in the design of the experiment and in the analysis of the results; the same experiment may have different designs thus produce different results; further determination of contribution of each factor is normally not permitted in this kind of design. The Taguchi method has been proposed to overcome these limitations by simplifying and standardizing the fractional factorial design (Roy [143]). The methodology involves identification of controllable and uncontrollable parameters and the establishment of a series of experiments to find out the optimum combination of the parameters which has the greatest influence on the performance and the least variation from the target of the design.

## **3.3 PROCEDURES OF TAGUCHI METHOD**

The major initial steps in designing, conducting and analyzing an experiment are as under:

- Establishment of objective function
- Determination of measurement methods
- 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

### **3.3.1 Establishment of Objective Function**

This includes recognition of and specific problem statement. The objective of the present study is to evaluate the effect of lifting parameters, their significant interactions and other environmental factors in a manual lifting task by using factorial analyses of variance.

### **3.3.2 Determine the Measurement Methods**

This includes identification of the performance characteristics and how they are assessed after the experiment is completed.

The response functions of the trial conditions are the following:

- Oxygen uptake
- Heart rate
- Perceived exertion
- Ground reaction forces

### **3.3.3 Determination of Controllable Factors & Their Levels**

In this section, the factors and their levels are identified using the traditional brainstorming method of involving some of the user population involved with Lifting Tasks and experts on Manual Material Handling. Also, a pilot experiment is conducted to define the experimental range and appropriate factors levels. The controllable factors are as under:

- Load weight
- Horizontal distance
- Vertical distance
- Frequency of Lift
- Type of coupling
- Asymmetric angle
- Travel distance

### **3.3.4 Identification of Uncontrollable Factors and Test Conditions**

- Physical Environment like Temperature at place of work.

The factors and their levels are identified using the same method as applied to identify the control factors.

### **3.3.5 Design of Taguchi Crossed Array Layout**

Orthogonal Array (OA) plays a critical part in achieving the high efficiency of the Taguchi method. OA is derived from the full factorial design of the experiment by a series of very sophisticated mathematical algorithms including combinatorics, finite fields, geometry and error-correcting codes (Taguchi et al. [168]). The algorithms ensure that the OA is constructed in a statistically independent manner, each level has an equal number of occurrences within each column; and for each level within one column, each level within any other column will occur an equal number of times as well. Then, the columns are called orthogonal to each other. OAs are available with a variety of factors and levels in the Taguchi method. Since each column is orthogonal to the others, if the results associated with one level of a specific factor are much different at another level, it is because changing that factor from one level to the next has a strong impact on the quality characteristic being measured. Since the levels of the other factors are occurring an equal number of times for each level of the strong factor, any effect by these other factors will be ruled out (Peace [132]). The Taguchi method apparently has the following strengths: (1) consistency in experimental design and analysis; (2) reduction of time and cost of experiments; (3) robustness of performance without removing the noise factors.

The Taguchi crossed array layout consists of an inner array and an outer array. The inner array is made up of the orthogonal array (OA) selected from all the possible combinations of the controllable factors. The outer array contains the combinations of the uncontrollable factors.

Each run from the inner array tests across each run from the outer array. Thus the latter determines the repetition of each trial run of the controllable factors in the inner array. All the possible combinations of the uncontrollable factors work as the outer array (Ross [142]).

### **Selection of appropriate orthogonal array**

A fractional factorial matrix assures a balanced and fair comparison of levels of any factor or interaction of factors. In orthogonal array, all columns can be evaluated independently of one another. It requires comparatively small number of experimental trials to measure the effect of parameters included in the study. There are following methods to select factors, their levels and interactions:

- Similar studies reported in literature review and researchers or experimenters previous experience
- Pilot experimentation and trial and error approach
- Preliminary study.

The selection of orthogonal array depends upon the number of factors and their levels and interactions between the main factors. Degree of freedom is the number of independent measurements available to estimate pieces of information that is estimated from the set of data. It determines the minimum number of treatment conditions.

Some facts of degree of freedom are used for selection of appropriate orthogonal array in the experimentation (Ross [142]).

- The degree of freedom of each factor is the number of levels minus one.
- The degree of freedom for an interaction is the multiplication of the interacting factor's degree of freedom.
- The total degree of freedom available in an orthogonal array is equal to the number of trials minus one.
- The total degree of freedom for an experiment is the sum of all factor's and interactions' degree of freedom.
- The total number of degree of freedom for an orthogonal array must be greater than or equal to minimum required degree of freedom of factors and interactions.
- The following inequality must be satisfied for the selection of the orthogonal array.

The total degree of freedom  $\geq$  degree of freedom required for factors and interactions.

If more than one array is available to satisfy this condition then it is tried to find out best suitable as per economic and minimum possible error results through experimentation. Taguchi has provided two tools to aid in assignment of factors and interaction to OA. These are linear graphs and triangular tables. Finally,  $L_{27}$  array was selected for experimentation.

### 3.3.6 Execution of Experiments According to Trial Conditions

The trial data sheets were constructed to minimize the possibility of errors in setting the proper levels for the trials. The generation of different Factorial Experiment Models was achieved by running a batch file, in which the controllable and uncontrollable factors were parametrically set.

### 3.3.7 Analysis of Results

**Signal-to-noise ratio:** The Taguchi method uses the signal-to noise ratio (S/N) to express the scatter around a target value. A high value of S/N implies that the signal is much higher than the random effects of the noise factors (Roy [143]; Taguchi [167]; Taguchi et al. [168]; Singh [152]). The noise is usually due to the uncontrollable factors, which exist in the environment, often cannot be eliminated and cause variations in the output. Depending upon the objective of the performance characteristic, there are various types of S/N ratios. From the quality point of view, there are three possible categories of the quality characteristics. They are: (1) smaller is better; (2) nominal is better; (3) bigger is better (Montgomery [125]).

In this Lifting Task design situation, the response parameters are “smaller is better”, which is a logarithmic function based on the mean square deviation (MSD), given by equation 3.1.

$$S / N_{LB} = -10 \log \left( \frac{1}{r} \sum_{i=1}^r y_i^2 \right) \dots\dots\dots \text{Equation (3.1)}$$

Where r is the number of tests in a trial (noise of repetitions regardless of noise levels) and  $y_i$  is the observed value of response characteristics.

**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. 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. The analysis of variance (ANOVA) is a common statistical technique to determine the percent contribution of each factor for results of the experiment. It calculates parameters known as sum of squares (SS), pure SS, degree of freedom, variance, F-ratio and percentage of each factor. Since the procedure of ANOVA is very complicated and employs a considerable of statistical formulae, only a brief description is given as following:

The Sum of Squares ( $SS_T$ ) is a measure of the deviation of the experimental data from the mean value of the data as given in equations 3.2 and 3.3.

$$SS_T = \sum_{i=1}^N (y_i - \bar{T})^2 \quad \dots\dots\dots \text{Equation (3.2)}$$

$$SS_A = \sum_{i=1}^N \frac{A_i^2}{n_{Ai}} - \frac{T^2}{N} \quad \dots\dots\dots \text{Equation (3.3)}$$

Before the test data is collected some terms and notations used in order to simplify the mathematics are briefly discussed below:

Let ‘A’ be a factor under investigation,

N = Number of response observations,  $\bar{T}$  is the mean of all observations

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

$A_i$  = Sum of observations under level

$n_{Ai}$  = number of observations under  $A_i$  level

$\bar{A}_i$  = average of observations under  $A_i$  level =  $A_i/n_{Ai}$

N = Total number of observations

T = Sum of all observations

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

$k_A$  = Number of Levels of Factor A

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

$$SS_e = \sum_{j=1}^{k_A} \sum_{i=1}^{n_{Ai}} (y_i - \bar{A}_j)^2 \dots\dots\dots \text{Equation (3.4)}$$

### 3.4 EXPERIMENTAL DESIGN

Taguchi's methodology (Fractional Factorial Experiments (FfEs)) was used to complete experimental design (Ross [142]). Before selecting, a particular orthogonal array for the purpose of designing the experiments a number of parameters and their levels must be identified. As per experimental situations in different parts of the study of first and second phase, number of control factors was different. The details of experiment design and selected orthogonal arrays have been discussed in respective chapters of the study of phase I and phase II.

### 3.5 MULTIPLE REGRESSION MODEL

A multiple regression model was developed to show significance in the statistical procedure and to help calculate the percentage contribution of different parameters based on the individual sum of square values. The purpose of the stepwise linear regression was to identify the important parameters in prediction equation of avg. response calculations. This analysis was used to identify the best set of predictors, one after the other, based on the highest partial correlation for estimating the dependent variables. The data was analyzed using statistical software (Minitab 15, SPSS 18 etc). The percentage contribution indicates the relative power of a factor and /or interaction to reduce variation. The percentage contribution from individual factors was calculated as the percentage of ratio of sum of square obtained from individual factor and total sum of squares.

## CHAPTER 4

### EFFECT OF AMBIENT TEMPERATURE DURING MANUAL LIFTING

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This chapter presents the details of the experiments conducted to ascertain the effect of ambient temperature on the workers during manual lifting. The climate of North West region of India comprises of a wide range of unique environmental conditions during the year. The temperature in summer varies 30 to 45° C. In winter, the minimum temperature goes below 5° C. High ambient temperature coupled with high humidity levels, creates harsh conditions for carrying out MMH task. Volume of oxygen uptake and heart rate changes are two common cardio pulmonary responses which are used to examine the exertion caused to the workers in manual lifting tasks. Perceived exertion using Borg scale (Champaign [25]; Borg, [17]) was measured by combining all sensations and feelings of physical stress, effort, and fatigue reflected by worker at the time of the experimentation. Environmental heat significantly influenced the cardiovascular and thermoregulatory systems in workers performing both light and heavy work tasks (Chad and Brown [24]).

#### 4.1 EXPERIMENTAL DESIGN

Using a causal method and a preliminary pilot study, the factors that may affect the pulmonary oxygen uptake and heart rate in lifting tasks were identified (see chapter 3). Taguchi separates factors into two main groups (i) Control Factors and (ii) Noise Factors (Ross [142]). Control factors are those which are set by the experimenter. Noise Factors are those over which the experimenter has no direct control and vary with the worker's environment such as ambient temperature and humidity. The temperature was induced as an external noise factor to study its effect. This design strategy has been used to dampen the effect of noise (environmental conditions) by choosing a proper level for control functions. Also, the experimental design strategy used in this study separates the control factors from the noise factor by using inner/outer arrays, respectively in the traditional Taguchi design. Temperature, a noise factor has been assigned to the outer array to evaluate its effect on the pulmonary responses and heart rate of workers involved in lifting and carrying tasks. The various levels for the control and noise factors, thus selected for experimentation during the study are listed in Table 4.1.

The demographic details of the three workers and their resting metabolic rate (RMR) and maximum aerobic capacity are given in Table 4.2. Also, since each of these workers had

similar resting heart rate, the same was not normalized after they completed the task as per the requirements of the experiment.

Table 4.1: Factors and their levels involved in the study

| Factors (unit)                                           | Levels      |              |            |
|----------------------------------------------------------|-------------|--------------|------------|
|                                                          | Level – 1   | Level – 2    | Level – 3  |
| Load, A (kg)                                             | 13          | 18           | 23         |
| Lifting frequency, B<br>(lifts/ 20 min)                  | 110         | 140          | 180        |
| Coupling Grip, C                                         | With Gloves | With Cushion | W/o Gloves |
| Assy. Angle, D (in $^{\circ}$ )                          | 0           | 40           | 60         |
| Vertical distance, E (cm)                                | Knee        | Waist        | Shoulder   |
| Horizontal distance, F (cm)                              | 15          | 30           | 55         |
| Travel Distance, G (cm)                                  | 25          | 45           | 60         |
| Noise factor, T (Ambient<br>Temperature in $^{\circ}$ C) | 10          | 35           | -          |

Table 4.2: Demographic details of the subjects

| Subject | Age<br>(years) | Height<br>(cm) | RMR<br>(kcal/day) | Resting heart<br>rate<br>(beats/min) | Resting<br>oxygen<br>uptake<br>(ml/kg-min) | Max aerobic<br>capacity<br>(ml/kg-min) |
|---------|----------------|----------------|-------------------|--------------------------------------|--------------------------------------------|----------------------------------------|
| 1       | 30             | 172            | 1822              | 71                                   | 3.5                                        | 39.6                                   |
| 2       | 32             | 167            | 1780              | 70                                   | 3.4                                        | 38.2                                   |
| 3       | 30             | 170            | 1772              | 68                                   | 3.6                                        | 38.6                                   |
| Mean    | 30.6           | 169.6          | 1791.3            | 69.6                                 | 3.5                                        | 38.8                                   |

The experimental design was completed using the Taguchi's Fractional Factorial Experiments (FEEs) (Ross [142]). In the present experimental situation, there are seven factors varied during the experiment. With each factor varied at three levels, two degrees of freedom is associated with each factor thus requiring 14 degrees of freedom. Also, some interactions between the main factors were believed to be significant as per the results of pilot study and were analyzed. Three interactions namely (i) weight and frequency ( $A \times B$ ) (ii) weight and vertical distance ( $A \times E$ ) (iii) frequency and vertical distance ( $B \times E$ ) were studied to measure their influence on responses. The degrees of freedom required for each two-level interaction are 4 and with three interactions of interest the total degrees of freedom required for the

interactions would be 12. The total degrees of freedom required for designing an orthogonal experiment were thus calculated to be 26. Taguchi  $L_{27}$  orthogonal array (OA) provides for 26 degrees of freedom, and was adopted for this experimental study. The assignment of factors was completed using the Taguchi Linear Graphs and Triangular Tables (Ross [142]) in combination with MINITAB 15, a statistical software to aid this analysis. The final form of the  $L_{27}$  Orthogonal Array that was adopted for conducting the trials is shown in Table 4.3.

Each worker was asked to perform asymmetrical free style lifting of load as per the experimental trial conditions for 20 minutes. Sufficient break was given after each lifting to recover from the fatigue. An open rectangular shaped galvanized iron (GI) sheet container (45 cm  $\times$  30 cm) with handles on each side was used for lifting the load. The heart rate (beats/min), the pulmonary oxygen uptake (ml/kg-min) and the perceived exertion were considered as the principal response parameters.

The responses (heart rate & the oxygen uptake) were measured simultaneously using the COSMED pulmonary function equipment (Model: *Fitmate PRO*-C09066-02-99, Make: COSMED, Rome, Italy). The setup arrangement is shown in Figure 4.1. A stop watch and measuring tape was used for measuring the work and rest periods and distances varied in the study respectively.

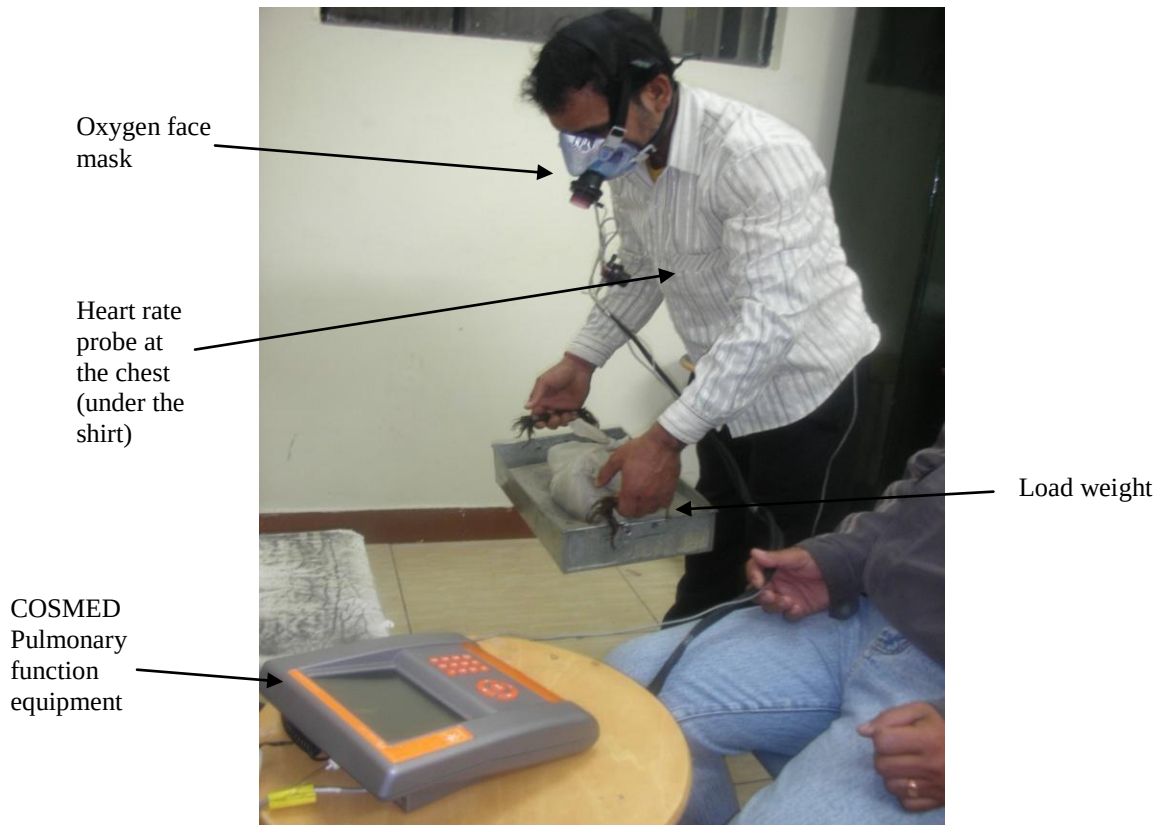


Figure 4.1: COSMED (*Fitmate-PRO*) pulmonary function equipment being used for lifting task

Table 4.3: L<sub>27</sub> Experimental design for first part of the study of first phase

| Trial No. | Load (kg)<br>A | Frequency (lifts/20min)<br>B | Grip<br>C    | Assy. Angle (°)<br>D | Vertical Distance (cm)<br>E | Horizontal Distance (cm)<br>F | Travel Distance (cm)<br>G |
|-----------|----------------|------------------------------|--------------|----------------------|-----------------------------|-------------------------------|---------------------------|
| 1         | 13             | 110                          | With Gloves  | 0                    | Knee                        | 15                            | 25                        |
| 2         | 13             | 110                          | With Cushion | 40                   | Waist                       | 30                            | 45                        |
| 3         | 13             | 110                          | W/o Gloves   | 60                   | Shoulder                    | 55                            | 60                        |
| 4         | 13             | 140                          | With Gloves  | 0                    | Knee                        | 55                            | 60                        |
| 5         | 13             | 140                          | With Cushion | 40                   | Waist                       | 15                            | 25                        |
| 6         | 13             | 140                          | W/o Gloves   | 60                   | Shoulder                    | 30                            | 45                        |
| 7         | 13             | 180                          | With Gloves  | 0                    | Knee                        | 30                            | 45                        |
| 8         | 13             | 180                          | With Cushion | 40                   | Waist                       | 55                            | 60                        |
| 9         | 13             | 180                          | W/o Gloves   | 60                   | Shoulder                    | 15                            | 25                        |
| 10        | 18             | 110                          | With cushion | 60                   | Knee                        | 30                            | 60                        |
| 11        | 18             | 110                          | W/o Gloves   | 0                    | Waist                       | 55                            | 25                        |
| 12        | 18             | 110                          | With Gloves  | 40                   | Shoulder                    | 15                            | 45                        |
| 13        | 18             | 140                          | With cushion | 60                   | Knee                        | 15                            | 45                        |
| 14        | 18             | 140                          | W/o Gloves   | 0                    | Waist                       | 30                            | 60                        |
| 15        | 18             | 140                          | With Gloves  | 40                   | Shoulder                    | 55                            | 25                        |
| 16        | 18             | 180                          | With cushion | 60                   | Knee                        | 55                            | 25                        |
| 17        | 18             | 180                          | W/o Gloves   | 0                    | Waist                       | 15                            | 45                        |
| 18        | 18             | 180                          | With Gloves  | 40                   | Shoulder                    | 30                            | 60                        |
| 19        | 23             | 110                          | W/o Gloves   | 40                   | Knee                        | 55                            | 45                        |
| 20        | 23             | 110                          | With Gloves  | 60                   | Waist                       | 15                            | 60                        |
| 21        | 23             | 110                          | With cushion | 0                    | Shoulder                    | 30                            | 25                        |
| 22        | 23             | 140                          | W/o Gloves   | 40                   | Knee                        | 30                            | 25                        |
| 23        | 23             | 140                          | With Gloves  | 60                   | Waist                       | 55                            | 45                        |
| 24        | 23             | 140                          | With cushion | 0                    | Shoulder                    | 15                            | 60                        |
| 25        | 23             | 180                          | W/o Gloves   | 40                   | Knee                        | 15                            | 60                        |
| 26        | 23             | 180                          | With Gloves  | 60                   | Waist                       | 30                            | 25                        |
| 27        | 23             | 180                          | With cushion | 0                    | Shoulder                    | 55                            | 45                        |

## 4.2 ANALYSIS OF OXYGEN UPTAKE AND HEART RATE

Three repetitions for each of the 27 trial conditions laid down by Taguchi's  $L_{27}$  matrix were completed to measure oxygen uptake and heart rate in summer and winter separately and are given in Tables 4.4 and 4.5 respectively. The results were analyzed using Analysis of Variance (ANOVA) for identifying the significant factors and interactions affecting the performance measures. The ANOVA results for the mean oxygen uptake and heart rate are given in Tables 4.6 and 4.7 respectively. The last and the second last column of ANOVA table show the percentage contribution and the F value respectively for each factor. From the F value and percent contribution calculated in Tables 4.6 and 4.7, load, lift frequency, vertical distance of lift and the ambient temperature were observed to be significant factors affecting the oxygen uptake. A two factor interaction between load and the lift frequency was observed to be significant. All the remaining factors were insignificant. From the plots shown in Figure 4.2, it can be seen that the ambient temperature contributes to significant changes in the oxygen uptake when plotted for each factor separately. Also, it can be observed from these plots that oxygen uptake significantly increases during winter under the same experimental conditions. This signifies an increased exertion to the workers engaged in lifting tasks during winter as compared to summer.

Table 4.4: Results for oxygen uptake & heart rate (summer)

| Trial No. | Oxygen uptake (ml/kg-min) summer |       |       | Mean oxygen uptake (ml/kg-min) summer | Heart rate (beats/min) summer |        |        | Mean heart rate (beats/min) summer |
|-----------|----------------------------------|-------|-------|---------------------------------------|-------------------------------|--------|--------|------------------------------------|
|           | I                                | II    | III   |                                       | I                             | II     | III    |                                    |
| 1         | 9.19                             | 10.08 | 8.43  | 9.23                                  | 93.80                         | 100.18 | 96.23  | 96.73                              |
| 2         | 10.22                            | 9.74  | 10.36 | 10.11                                 | 97.28                         | 102.76 | 95.95  | 98.66                              |
| 3         | 10.37                            | 11.32 | 12.37 | 11.36                                 | 98.20                         | 104.75 | 97.63  | 100.19                             |
| 4         | 10.59                            | 9.24  | 10.93 | 10.25                                 | 92.10                         | 91.43  | 86.86  | 90.13                              |
| 5         | 10.74                            | 9.74  | 10.05 | 10.18                                 | 94.55                         | 99.97  | 102.92 | 99.15                              |
| 6         | 10.50                            | 11.12 | 14.22 | 11.95                                 | 97.91                         | 103.73 | 108.88 | 103.51                             |
| 7         | 9.56                             | 9.40  | 13.64 | 10.87                                 | 95.73                         | 97.37  | 97.40  | 96.83                              |
| 8         | 12.94                            | 11.46 | 12.83 | 12.41                                 | 108.84                        | 94.43  | 103.74 | 102.34                             |
| 9         | 12.16                            | 11.38 | 14.52 | 12.69                                 | 106.87                        | 98.18  | 106.37 | 103.81                             |
| 10        | 10.57                            | 11.21 | 14.45 | 12.08                                 | 90.41                         | 106.13 | 104.71 | 100.42                             |
| 11        | 8.63                             | 10.92 | 11.15 | 10.23                                 | 101.10                        | 101.44 | 106.54 | 103.03                             |
| 12        | 8.53                             | 14.66 | 15.20 | 12.79                                 | 103.80                        | 109.60 | 97.25  | 103.55                             |

|      |       |       |       |       |        |        |        |        |
|------|-------|-------|-------|-------|--------|--------|--------|--------|
| 13   | 10.41 | 10.93 | 14.51 | 11.95 | 98.16  | 97.73  | 101.39 | 99.09  |
| 14   | 11.17 | 11.23 | 14.19 | 12.20 | 105.47 | 109.38 | 105.77 | 106.87 |
| 15   | 11.13 | 12.96 | 13.09 | 12.39 | 99.46  | 107.92 | 108.74 | 105.37 |
| 16   | 12.10 | 10.93 | 11.42 | 11.48 | 99.64  | 98.21  | 96.66  | 98.17  |
| 17   | 13.16 | 12.09 | 11.07 | 12.11 | 99.50  | 95.01  | 99.05  | 97.85  |
| 18   | 13.97 | 14.32 | 16.45 | 14.91 | 102.14 | 107.96 | 106.31 | 105.47 |
| 19   | 11.41 | 13.79 | 12.79 | 12.66 | 96.84  | 97.27  | 101.71 | 98.61  |
| 20   | 10.98 | 13.72 | 14.38 | 13.03 | 104.19 | 107.69 | 106.84 | 106.24 |
| 21   | 12.10 | 14.40 | 14.34 | 13.61 | 108.63 | 108.34 | 109.06 | 108.67 |
| 22   | 14.22 | 13.25 | 14.14 | 13.87 | 101.26 | 113.40 | 107.36 | 107.34 |
| 23   | 14.39 | 14.01 | 13.89 | 14.10 | 108.58 | 118.13 | 106.18 | 110.96 |
| 24   | 13.71 | 15.16 | 12.05 | 13.64 | 111.16 | 120.34 | 109.38 | 113.63 |
| 25   | 10.42 | 15.15 | 11.82 | 12.46 | 109.53 | 110.76 | 105.01 | 108.44 |
| 26   | 11.68 | 15.14 | 12.02 | 12.95 | 110.27 | 117.86 | 103.22 | 110.45 |
| 27   | 13.72 | 15.78 | 14.30 | 14.60 | 110.16 | 123.98 | 107.80 | 113.98 |
| Mean |       |       |       | 12.22 |        |        |        | 103.31 |

Table 4.5: Results for oxygen uptake & heart rate (winter)

| Trial No. | Mean oxygen uptake (ml/kg-min) winter |       |       | Mean oxygen uptake (ml/kg-min) winter | Mean heart rate (beats/min) winter |        |        | Mean heart rate (beats/min) winter |
|-----------|---------------------------------------|-------|-------|---------------------------------------|------------------------------------|--------|--------|------------------------------------|
|           | I                                     | II    | III   |                                       | I                                  | II     | III    |                                    |
| 1         | 10.11                                 | 11.64 | 9.52  | 10.42                                 | 105.21                             | 104.71 | 104.95 | 104.96                             |
| 2         | 10.93                                 | 11.77 | 12.94 | 11.88                                 | 108.80                             | 109.42 | 105.24 | 107.82                             |
| 3         | 12.01                                 | 12.68 | 13.92 | 12.87                                 | 112.83                             | 113.54 | 118.06 | 114.81                             |
| 4         | 9.95                                  | 12.50 | 13.07 | 11.84                                 | 101.53                             | 109.45 | 109.52 | 106.83                             |
| 5         | 11.53                                 | 12.15 | 12.01 | 11.90                                 | 107.53                             | 105.04 | 106.51 | 106.36                             |
| 6         | 15.30                                 | 13.33 | 16.84 | 15.16                                 | 118.18                             | 122.89 | 127.08 | 122.72                             |
| 7         | 11.06                                 | 14.73 | 14.22 | 13.34                                 | 111.45                             | 115.04 | 104.96 | 110.48                             |
| 8         | 13.96                                 | 13.68 | 14.43 | 14.02                                 | 127.75                             | 106.63 | 111.82 | 115.40                             |
| 9         | 15.55                                 | 12.64 | 16.71 | 14.97                                 | 121.82                             | 102.55 | 113.86 | 112.74                             |
| 10        | 11.45                                 | 13.10 | 14.69 | 13.08                                 | 110.10                             | 112.38 | 112.97 | 111.82                             |
| 11        | 12.23                                 | 11.63 | 15.11 | 12.99                                 | 110.97                             | 103.48 | 123.32 | 112.59                             |
| 12        | 16.72                                 | 12.62 | 18.84 | 16.06                                 | 122.20                             | 116.95 | 127.32 | 122.16                             |
| 13        | 12.52                                 | 10.68 | 14.84 | 12.68                                 | 100.54                             | 99.47  | 116.39 | 105.47                             |

|      |       |       |       |       |        |        |        |        |
|------|-------|-------|-------|-------|--------|--------|--------|--------|
| 14   | 12.98 | 14.90 | 16.07 | 14.65 | 123.05 | 121.66 | 119.81 | 121.51 |
| 15   | 14.54 | 11.62 | 16.17 | 14.11 | 122.10 | 114.66 | 112.39 | 116.38 |
| 16   | 17.62 | 12.86 | 14.04 | 14.84 | 121.50 | 105.10 | 117.81 | 114.80 |
| 17   | 12.64 | 13.61 | 18.13 | 14.79 | 116.70 | 122.64 | 120.40 | 119.91 |
| 18   | 15.42 | 14.37 | 18.24 | 16.01 | 121.34 | 116.49 | 127.18 | 121.67 |
| 19   | 14.94 | 11.89 | 15.12 | 13.98 | 107.16 | 104.40 | 105.60 | 105.72 |
| 20   | 16.76 | 14.67 | 14.05 | 15.16 | 129.87 | 112.18 | 112.77 | 118.27 |
| 21   | 14.86 | 12.90 | 17.63 | 15.13 | 122.76 | 110.93 | 121.00 | 118.23 |
| 22   | 13.74 | 14.52 | 14.31 | 14.19 | 117.10 | 119.42 | 115.14 | 117.22 |
| 23   | 16.41 | 14.50 | 14.06 | 14.99 | 129.74 | 125.12 | 113.71 | 122.85 |
| 24   | 15.91 | 15.65 | 15.73 | 15.76 | 135.04 | 127.94 | 117.96 | 126.98 |
| 25   | 15.69 | 13.00 | 13.32 | 14.00 | 130.32 | 124.45 | 116.86 | 123.88 |
| 26   | 15.97 | 14.89 | 12.58 | 14.48 | 133.47 | 125.65 | 129.06 | 129.39 |
| 27   | 17.35 | 16.10 | 17.84 | 17.09 | 125.63 | 129.34 | 129.35 | 128.10 |
| Mean |       |       |       | 14.09 |        |        |        | 116.24 |

Table 4.6: Pooled ANOVA for oxygen uptake

| Source                  | SS     | DOF | V     | F     | PC    |
|-------------------------|--------|-----|-------|-------|-------|
| A                       | 136.68 | 2   | 68.34 | 30.38 | 31.66 |
| B                       | 38.14  | 2   | 19.07 | 8.48  | 10.58 |
| E                       | 89.88  | 2   | 44.94 | 19.98 | 26.85 |
| A $\times$ B            | 17.34  | 4   | 4.335 | 1.93  | 2.62  |
| e <sub>1</sub>          | 35.982 | 16  | 2.25  |       |       |
| SS <sub>T1</sub>        | 318.02 | 26  |       |       |       |
| T (temp)                | 140.3  | 1   | 140.3 | 152.5 | 28.86 |
| A $\times$ T            | 2.6    | 2   | 1.3   | 1.42  | 0.157 |
| B $\times$ T            | 1.83   | 2   | 0.915 | 0.997 |       |
| E $\times$ T            | 3.11   | 2   | 1.56  | 1.26  | 0.264 |
| A $\times$ B $\times$ T | 2.4    | 4   | 0.6   | 0.652 |       |
| e <sub>2</sub>          | 14.68  | 16  | 0.92  |       |       |
| SS <sub>T2</sub>        | 482.94 | 53  |       |       |       |
| e <sub>3</sub>          | 302.69 | 108 | 2.81  |       |       |
| SS <sub>T3</sub>        | 785.63 | 161 |       |       |       |

(Note : A=Load, B= Frequency, E= Vertical distance, A  $\times$  B= Interaction, e =Pooled error, SS = Sum of square, DOF= Degrees of freedom, V = Variance, PC = Percent contribution)

Table 4.7: Pooled ANOVA for heart rate

| Source                  | SS        | DOF | V        | F       | PC     |
|-------------------------|-----------|-----|----------|---------|--------|
| A                       | 2543.221  | 2   | 1271.611 | 34.085  | 40.971 |
| B                       | 564.221   | 2   | 282.111  | 7.562   | 8.126  |
| E                       | 1807.221  | 2   | 903.611  | 24.221  | 28.756 |
| A $\times$ B            | 480.381   | 4   | 120.095  | 3.219   | 5.496  |
| e <sub>1</sub>          | 630.156   | 16  | 39.384   |         |        |
| SS <sub>T1</sub>        | 6025.2    | 26  |          |         |        |
| T                       | 6773.9629 | 1   | 6773.963 | 330.343 | 50.104 |
| A $\times$ T            | 24.8371   | 2   | 12.419   | 0.606   |        |
| B $\times$ T            | 137.2371  | 2   | 68.619   | 3.346   | 0.714  |
| C $\times$ T            | 10.4371   | 2   | 5.219    | 0.254   |        |
| E $\times$ T            | 36.4371   | 2   | 18.219   | 0.888   |        |
| A $\times$ B $\times$ T | 139.65    | 4   | 34.913   | 1.703   | 0.428  |
| B $\times$ E $\times$ T | 125.97    | 4   | 31.493   | 1.536   | 0.326  |
| e <sub>2</sub>          | 205.0587  | 10  | 20.506   |         |        |
| SS <sub>T2</sub>        | 13478.79  | 53  |          |         |        |
| e <sub>3</sub>          | 3243.683  | 108 | 30.034   |         |        |
| SS <sub>T3</sub>        | 16722.473 | 161 |          |         |        |

The ANOVA results for heart rate showed a trend similar to oxygen uptake. The ambient temperature induced into the experimental study was the most contributing factor affecting the heart rate of the workers involved in the experimental study. The middle three columns of Table 4.8 show the increase in heart rate for the task completed in winter as compared to its completion in summer. Also, like the results for oxygen uptake, load, lifting frequency, vertical distance, interaction of load and frequency were the other significant factors affecting the heart rate. The plots for heart rate when the work is completed in summer and winter are shown in Figure 4.3. This plot shows variation of heart rate for each factor in summer and winter. The heart rate (beats/min) increases with the lowering of ambient temperature (summer to winter) for all lifting parameters. Figure 4.4 shows the plots of all the 27 trials plotted together during summer and winter showing a steep increase in the oxygen uptake and heart rate in winter. The percentage change in the mean oxygen uptake during summer and winter is given in Table 4.8. The maximum and the minimum change in oxygen uptake between summer and winter were observed in trial 16 and trial 22 respectively.

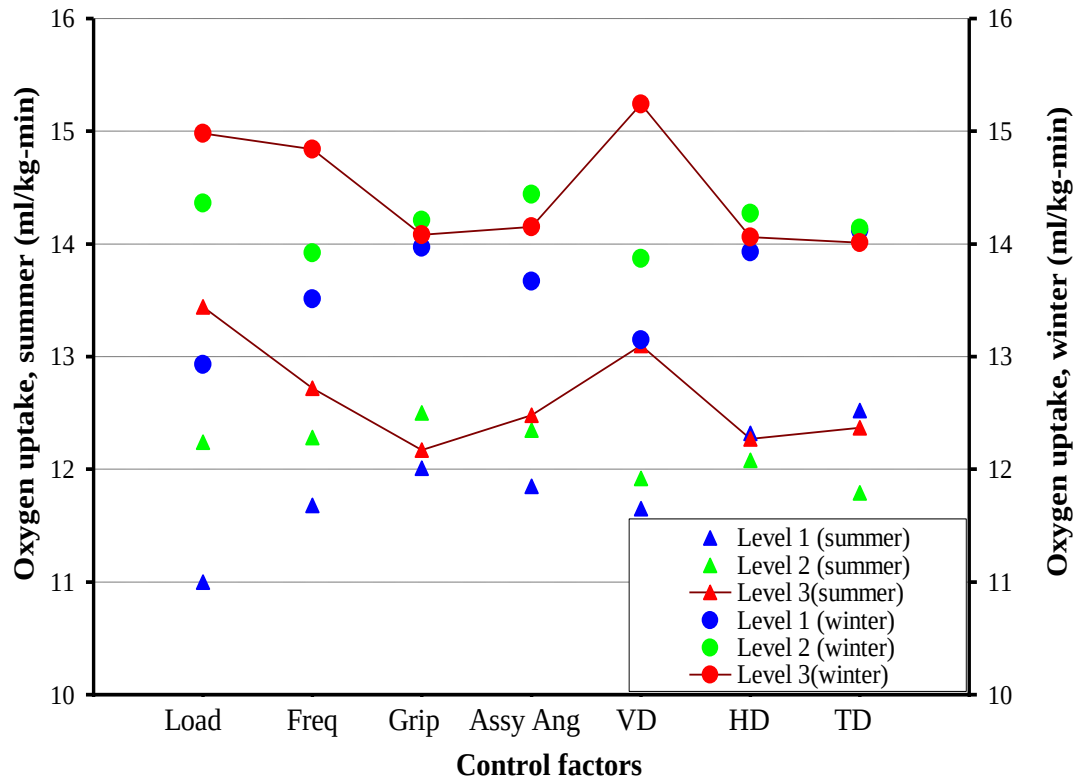


Figure 4.2: Level effect for each factor on oxygen uptake during summer and winter

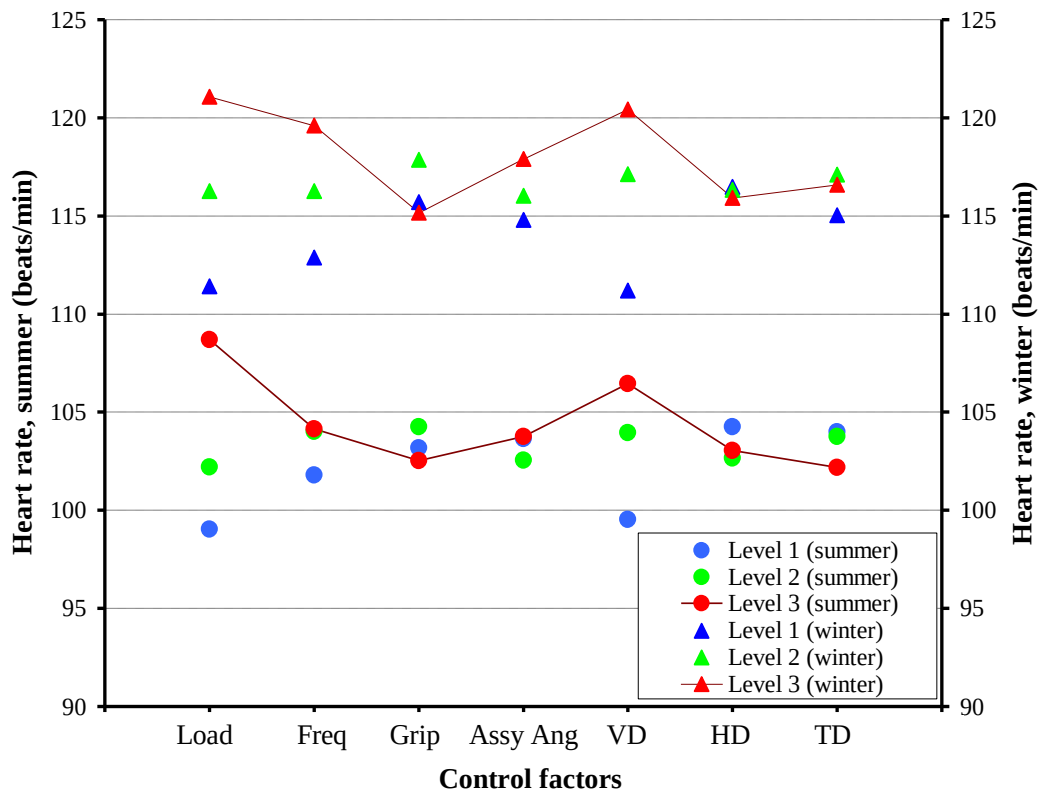


Figure 4.3: Level effect for each factor on heart rate during summer and winter

From Figure 4.2 and Figure 4.3, it can be observed that the oxygen uptake and heart rate significantly increases with the increase in load, lifting frequency and vertical distance. No significant changes were observed with the change of grip, horizontal distance, asymmetric angle and travel distance except due to ambient temperature conditions. While the effect of all the parameters were known from previous studies reported in the literature, the effect of ambient temperature has been experimentally documented in this study.

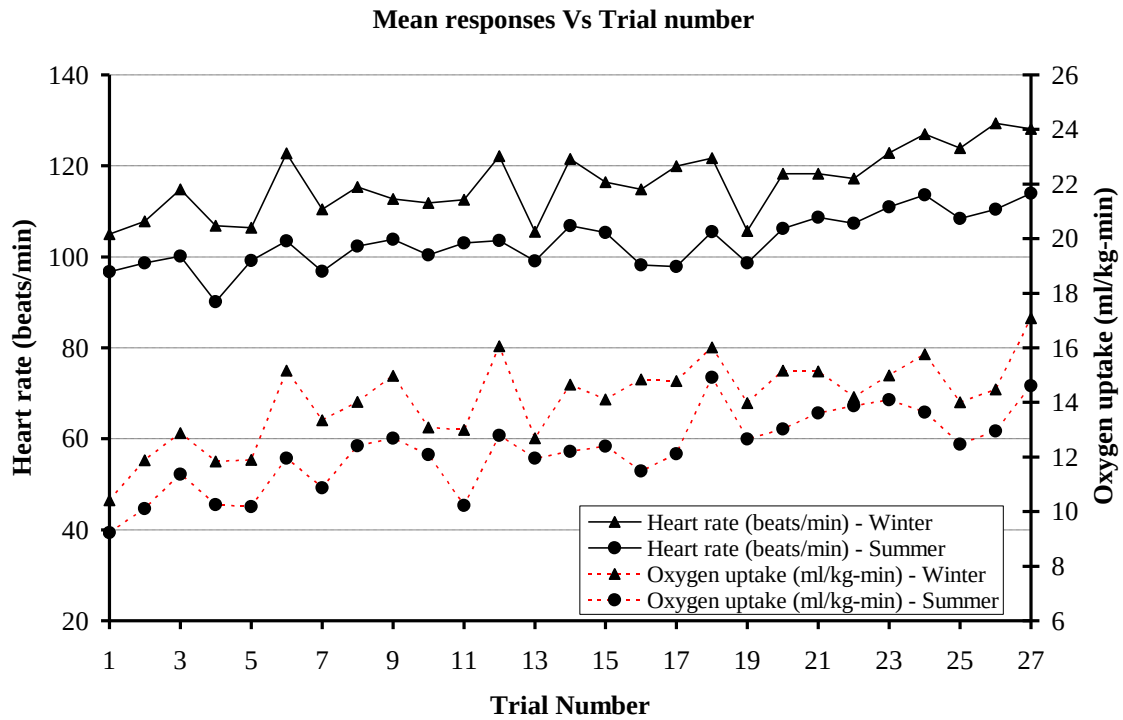


Figure 4.4: Mean responses during each trial at summer and winter

Table 4.8: Seasonal percentage change in oxygen uptake, heart rate and perceived exertion

| Trial No. | Mean oxygen uptake (ml/kg-min) |        | Percentage change | Mean heart rate (beats/min) |        | Percentage change | Perceived Exertion (Borg RPE Scale) |        | Percentage change |
|-----------|--------------------------------|--------|-------------------|-----------------------------|--------|-------------------|-------------------------------------|--------|-------------------|
|           | Summer                         | Winter |                   | Summer                      | Winter |                   | Summer                              | Winter |                   |
| 1         | 9.23                           | 10.42  | 12.89             | 96.73                       | 104.96 | 8.50              | 10                                  | 11     | 8.33              |
| 2         | 10.11                          | 11.88  | 17.51             | 98.66                       | 107.82 | 9.28              | 11                                  | 13     | 15.38             |
| 3         | 11.36                          | 12.87  | 13.29             | 100.19                      | 114.81 | 14.59             | 13                                  | 16     | 18.75             |
| 4         | 10.25                          | 11.84  | 15.51             | 90.13                       | 106.83 | 18.53             | 11                                  | 13     | 15.38             |
| 5         | 10.18                          | 11.90  | 16.90             | 99.15                       | 106.36 | 7.27              | 11                                  | 13     | 15.38             |
| 6         | 11.95                          | 15.16  | 26.86             | 103.51                      | 122.72 | 18.56             | 13                                  | 18     | 27.78             |
| 7         | 10.87                          | 13.34  | 22.72             | 96.83                       | 110.48 | 14.10             | 11                                  | 17     | 35.29             |
| 8         | 12.41                          | 14.02  | 12.97             | 102.34                      | 115.40 | 12.76             | 14                                  | 17     | 17.65             |
| 9         | 12.69                          | 14.97  | 17.97             | 103.81                      | 112.74 | 8.60              | 14                                  | 18     | 22.22             |

|    |       |       |       |        |        |       |    |    |       |
|----|-------|-------|-------|--------|--------|-------|----|----|-------|
| 10 | 12.08 | 13.08 | 8.28  | 100.42 | 111.82 | 11.35 | 14 | 16 | 12.50 |
| 11 | 10.23 | 12.99 | 26.98 | 103.03 | 112.59 | 9.28  | 12 | 16 | 25.00 |
| 12 | 12.79 | 16.06 | 25.57 | 103.55 | 122.16 | 17.97 | 14 | 19 | 26.32 |
| 13 | 11.95 | 12.68 | 6.11  | 99.09  | 105.47 | 6.44  | 13 | 13 | 0.00  |
| 14 | 12.20 | 14.65 | 20.08 | 106.87 | 121.51 | 13.70 | 15 | 18 | 16.67 |
| 15 | 12.39 | 14.11 | 13.88 | 105.37 | 116.38 | 10.45 | 15 | 17 | 11.76 |
| 16 | 11.48 | 14.84 | 29.27 | 98.17  | 114.80 | 16.94 | 12 | 16 | 25.00 |
| 17 | 12.11 | 14.79 | 22.13 | 97.85  | 119.91 | 22.54 | 14 | 17 | 17.65 |
| 18 | 14.91 | 16.01 | 7.38  | 105.47 | 121.67 | 15.36 | 18 | 19 | 5.26  |
| 19 | 12.66 | 13.98 | 10.43 | 98.61  | 105.72 | 7.21  | 13 | 14 | 7.14  |
| 20 | 13.03 | 15.16 | 16.35 | 106.24 | 118.27 | 11.32 | 17 | 18 | 5.56  |
| 21 | 13.61 | 15.13 | 11.17 | 108.67 | 118.23 | 8.80  | 17 | 18 | 5.56  |
| 22 | 13.87 | 14.19 | 2.31  | 107.34 | 117.22 | 9.20  | 17 | 17 | 0.00  |
| 23 | 14.10 | 14.99 | 6.31  | 110.96 | 122.85 | 10.72 | 18 | 18 | 0.00  |
| 24 | 13.64 | 15.76 | 15.54 | 113.63 | 126.98 | 11.75 | 17 | 19 | 10.53 |
| 25 | 12.46 | 14.00 | 12.36 | 108.44 | 123.88 | 14.24 | 15 | 18 | 16.67 |
| 26 | 12.95 | 14.48 | 11.81 | 110.45 | 129.39 | 17.15 | 17 | 19 | 10.53 |
| 27 | 14.60 | 17.09 | 17.05 | 113.98 | 128.10 | 12.39 | 19 | 20 | 5.00  |

---

The mean values (at each level) for all the seven factors for oxygen uptake and heart rate with their significance rank are shown in Tables 4.9 and 4.10. Last row of these tables show the rank of each which implies the level of significance of the factor on response. These values have been used to calculate the optimal values of oxygen uptake and heart rate so as to cause least exertion to workers involved in lifting and carrying tasks.

### 4.3 ANALYSIS OF PERCEIVED EXERTION

A secondary analysis based on perceived exertion caused to each of the three workers participating in the study was carried out. The 27 trial conditions as given in Table 4.3 provide enough information about the exertion that would be caused to the workers involved in such tasks. Each of the workers involved in the study was asked to provide a rating for perceived exertion on a scale of 6 to 20 using the Borg Rating of Perceived Exertion (RPE) scale (Champaign [25]; Borg [17]. The greater the exertion felt, greater would be the number reported by individual being tested. The Borg scale increases linearly with physiological measures like oxygen uptake and heart rate as the work intensity increases. The perceived exertion rating has been classified into three groups (i) trials that caused low exertion (6-12

ml/kg-min); (ii) trials that caused moderate exertion (13-14 ml/kg-min); and (iii) trials that caused high exertion (15-20 ml/kg-min). The results of this analysis are given in the last three columns of Table 4.8.

Based on the above classification for RPE, the results for oxygen uptake were analyzed. High exertion was reported during trials 14, 15, 18, 20 to 27 in summer and 3, 6 to 12, 15 to 18 and 21 to 27 in winter. The trials where the perceived exertion was rated as low or moderate had lower load to be lifted or lower lift frequency and vertical distance. Also, the perceived exertion for 11 different trials was reported as high in summer, whereas the exertion was perceived to be high in as many as 21 trials during winter thus indicating that ambient temperature significantly effects the exertion experienced by the workers. Cold ambient conditions caused greater exertion as compared to summer under similar trial conditions. Thus, lifting tasks performed in winters must have different relaxation or fatigue allowances built into the cycle time of the task to compensate for higher exertion experienced during winter. Moderate to low exertion was reported during trials 1 to 13, 16, 17 and 19 in summer and trial 1, 2, 4, 5, 13 and 19 in winter. All these trial conditions indicate lower load to be lifted coupled with low lifting frequency and up to waist high vertical distance. The higher ambient temperature conditions as discussed above help in lowering the perceived exertion.

The output plots for oxygen uptake and heart rate from COSMED *Fitmate PRO* were generated for all trials. Four such plots (two each for summer and winter) which are representative plots of the perceived conditions causing high (Figure 4.5 (a) and (b)) and low exertion (Figure 4.6 (a) and (b)) are shown. Others sample COSMED outputs of trials are also shown in Figures 4.7, 4.8 and 4.9.

#### **4.4 OPTIMAL DESIGN**

Three control factors namely, (i) load weight; (ii) lifting frequency and (iii) vertical distance were identified as significant after ANOVA for oxygen uptake and heart rate and their plots were used to establish their most appropriate levels which will result in lower exertion and improved work conditions. The ambient temperature which was induced as a noise factor in the experimentation, however, showed the maximum affect on the two response parameters. The optimal design for the two responses would be meaningless in the traditional way defined by Taguchi wherein those levels are chosen which would lower the oxygen uptake and heart rate, thus causing least exertion to the workers.

Table 4.9: Response table for mean oxygen uptake

| Level | Wt. load |        | Frequency |        | Grip   |        | Assy. Angle |        | Vertical Dist. |        | Horizontal Dist. |        | Travel Dist. |        |
|-------|----------|--------|-----------|--------|--------|--------|-------------|--------|----------------|--------|------------------|--------|--------------|--------|
|       | Summer   | Winter | Summer    | Winter | Summer | Winter | Summer      | Winter | Summer         | Winter | Summer           | Winter | Summer       | Winter |
| 1     | 11.00    | 12.93  | 11.68     | 13.51  | 12.01  | 13.97  | 11.85       | 13.67  | 11.65          | 13.15  | 12.32            | 13.93  | 12.52        | 14.12  |
| 2     | 12.24    | 14.36  | 12.28     | 13.92  | 12.50  | 14.21  | 12.35       | 14.44  | 11.92          | 13.87  | 12.08            | 14.27  | 11.79        | 14.14  |
| 3     | 13.44    | 14.98  | 12.72     | 14.84  | 12.17  | 14.08  | 12.48       | 14.15  | 13.10          | 15.24  | 12.27            | 14.06  | 12.37        | 14.01  |
| Delta | 2.44     | 2.05   | 1.04      | 1.33   | 0.49   | 0.24   | 0.63        | 0.77   | 1.45           | 2.09   | 0.24             | 0.34   | 0.73         | 0.13   |
| Rank  | 1        | 2      | 3         | 3      | 6      | 6      | 5           | 4      | 2              | 1      | 7                | 5      | 4            | 7      |

29

Table 4.10: Response table for mean heart rate

| Level | Wt. load |        | Frequency |        | Grip   |        | Assy. Angle |        | Vertical Dist. |        | Horizontal Dist. |        | Travel Dist. |        |
|-------|----------|--------|-----------|--------|--------|--------|-------------|--------|----------------|--------|------------------|--------|--------------|--------|
|       | Summer   | Winter | Summer    | Winter | Summer | Winter | Summer      | Winter | Summer         | Winter | Summer           | Winter | Summer       | Winter |
| 1     | 99.04    | 111.41 | 101.79    | 112.89 | 103.17 | 115.70 | 103.64      | 114.81 | 99.53          | 111.20 | 104.25           | 116.48 | 104.00       | 115.04 |
| 2     | 102.20   | 116.26 | 104.01    | 116.26 | 104.25 | 117.87 | 102.56      | 116.03 | 103.95         | 117.12 | 102.65           | 116.33 | 103.76       | 117.10 |
| 3     | 108.70   | 121.07 | 104.15    | 119.60 | 102.53 | 115.17 | 103.75      | 117.91 | 106.46         | 120.42 | 103.04           | 115.93 | 102.18       | 116.60 |
| Delta | 9.66     | 9.66   | 2.36      | 6.71   | 1.72   | 2.7    | 1.19        | 3.1    | 6.93           | 9.22   | 1.6              | 0.55   | 1.82         | 2.06   |
| Rank  | 1        | 1      | 3         | 3      | 5      | 5      | 7           | 4      | 2              | 2      | 6                | 7      | 4            | 6      |

By using this method, if the oxygen uptake and heart rate have to be minimized then the weight, lifting frequency and vertical distance are to be kept low. However, such a solution will not be optimal as the labour productivity will be very low with such level settings. The best way to search for an optimal solution would be to fix the oxygen uptake and heart rate values at a level which would cause low to moderate exertion and then appropriately select the settings for the three significant factors. The optimal setting for oxygen uptake has been calculated by measuring the maximum aerobic capacity of the workers. The optimal oxygen uptake value should not exceed a value of 33% of an individual's  $VO_{2max}$  which is the maximum aerobic capacity over an 8-hour shift (Bridger [18]). The maximum aerobic capacity of the workers was measured by performing a standard test on the treadmill. The resting metabolic values and  $VO_2$  were recorded using the same measuring equipment used during the experimentation. The three workers who participated in the study were asked to run on the treadmill at their maximum capacity until a clear plateau of the oxygen uptake versus time was obtained. The point after which the oxygen uptake remained unchanged is defined as  $VO_{2max}$ . The maximum aerobic capacity measured in terms of maximum oxygen uptake for each worker is given in the last column of Table 4.2.

The mean aerobic capacity of the three workers was calculated to be 38.8 ml/kg-min (Table 4.2). As defined by NIOSH (Bridger [18]), the energy expenditure should not exceed 33% of individual's maximum aerobic capacity for a work performed over a period of 8 hours to prevent risks related to cardiovascular or musculoskeletal system..

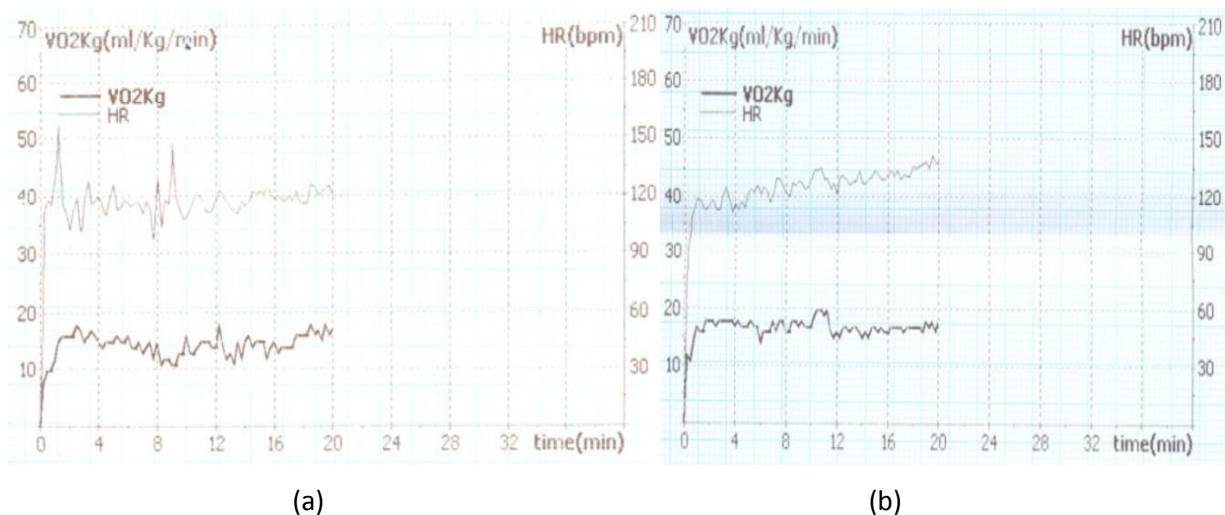


Figure 4.5: Sample COSMED output of oxygen uptake and heart rate for trials where high exertion was reported (a) 27<sup>th</sup> trial (summer), (b) 26<sup>th</sup> trial (winter)

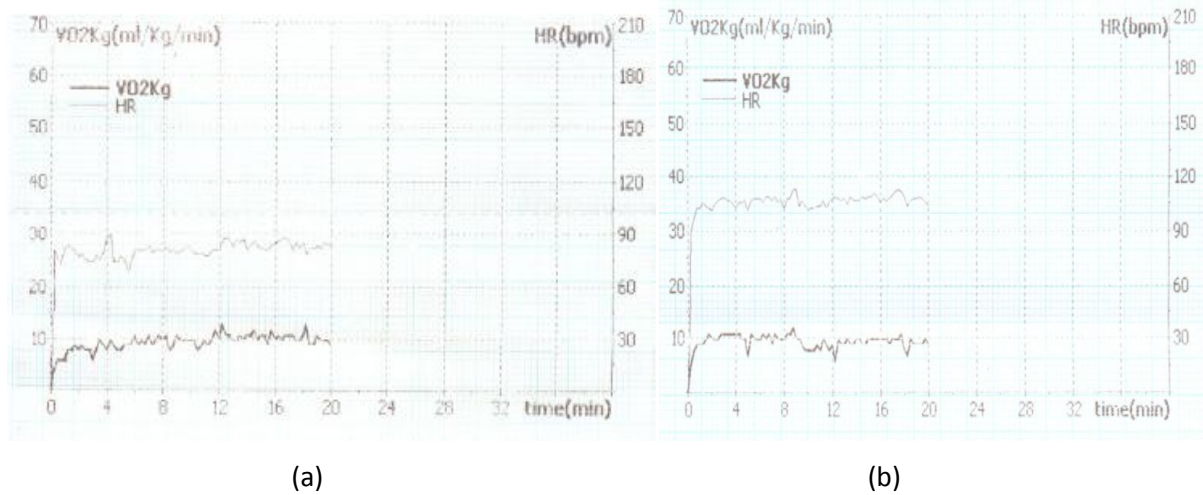


Figure 4.6: Sample COSMED output of oxygen uptake and heart rate for trials where low exertion was reported (a) 2<sup>nd</sup> trial (summer) (b) 1<sup>st</sup> trial (winter)

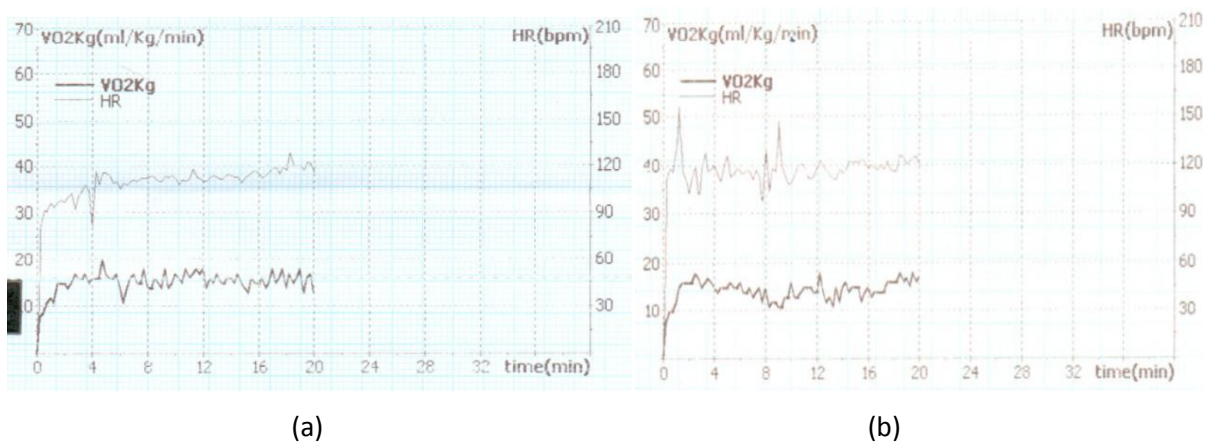


Figure 4.7: Sample COSMED output of oxygen uptake and heart rate for trials (a) 23<sup>rd</sup> trial, (b) 27<sup>th</sup> trial (summer)

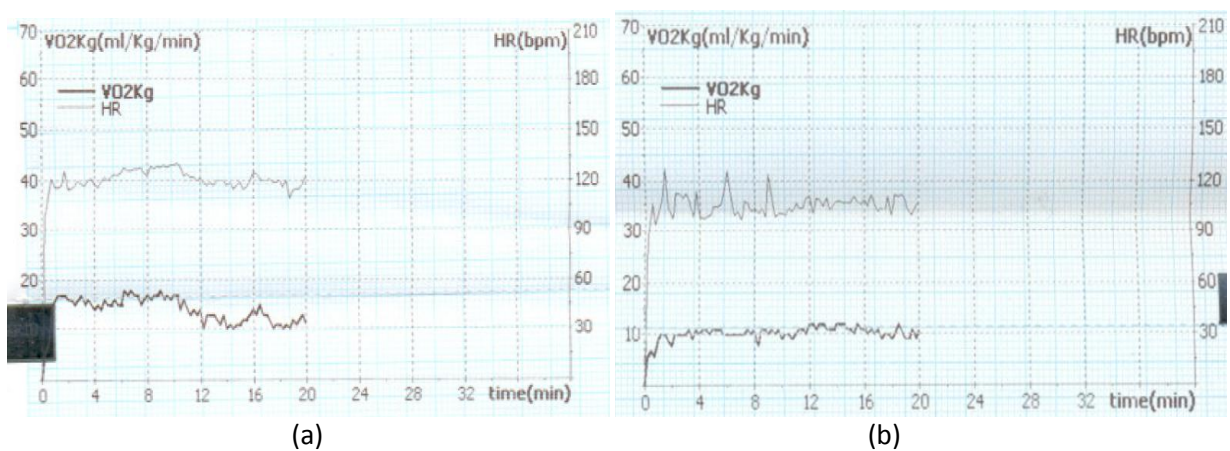


Figure 4.8: Sample COSMED output of oxygen uptake and heart rate for trials (a) 15<sup>th</sup> trial (summer), (b) 17<sup>th</sup> trial (winter)

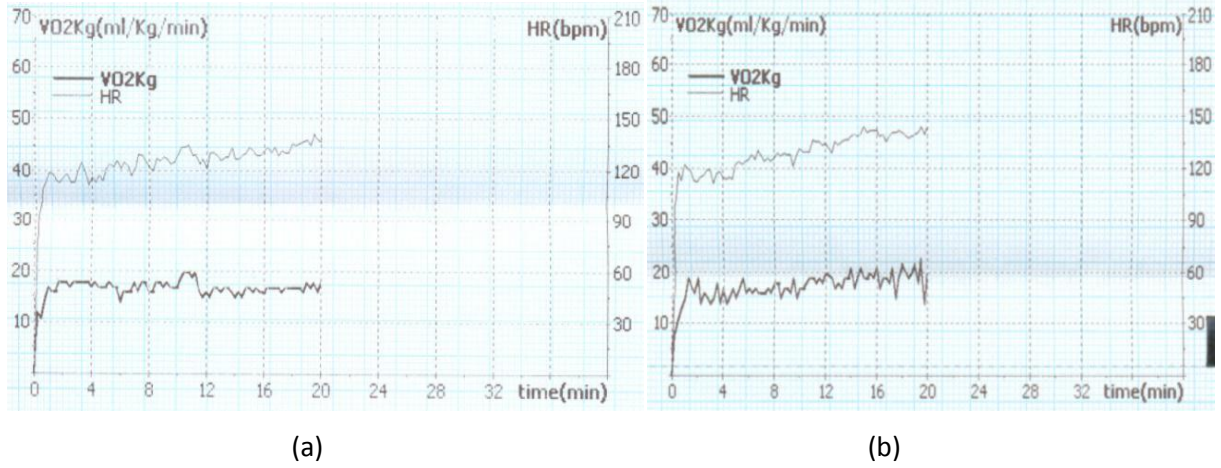


Figure 4.9: Sample COSMED output of oxygen uptake and heart rate for trials  
(a) 26<sup>th</sup> trial (b) 27<sup>th</sup> trial (winter)

Using this as a benchmark, the oxygen uptake which would cause least exertion to the workers is 12.93 ml/kg/min (33% of 38.8). Also, the heart rate for moderate work should lie between 90-110 beats/min (Astrand and Rhodahl [4]). The mean heart rate for moderately exerting work has been taken as 110 beats/min.

#### 4.4.1 Optimal design for Oxygen uptake and Heart rate

Three factors, load weight, lift frequency and vertical distance along with ambient temperature significantly affected the oxygen uptake and heart rate as per ANOVA. The estimated mean oxygen uptake and mean heart rate were calculated using the Taguchi's additive model for all the 27 different combinations of these three 3-level significant factors and are given in Table 4.11.

One sample calculation for estimated oxygen uptake and heart rate when the factors are set at level 1 (Load 13 kg; Lift frequency 3 lifts/min and Vertical Distance 50 mm) during summer is given below.

$$\text{Oxy}_{A_1B_2E_3} = \bar{A}_1 + \bar{B}_2 + \bar{E}_3 - 2\bar{T} = 11 + 12.28 + 13.1 - 2 \times 12.2267 = 11.93 \text{ ml/kg-min}$$

$$\text{HR}_{A_3B_2E_1} = \bar{A}_3 + \bar{B}_2 + \bar{E}_1 - 2\bar{T} = 108.7 + 104.01 + 99.53 - 2 \times 103.313 = 105.6 \text{ beats/min}$$

Where  $\text{Oxy}_{A_1B_2E_3}$  and  $\text{HR}_{A_3B_2E_1}$  are the estimated mean oxygen uptake and heart rate respectively when factor A (load) is taken at level 1, factor B (lifting frequency) at level 2, factor E (vertical distance) at level 3, during summer and  $\bar{T}$  is the mean of all responses.

## 4.5 EFFECT OF AMBIENT TEMPERATURE

### 4.5.1 Analysis for Summer (Ambient temperature 35° C)

As per the results obtained in Table 4.11, several combinations of load, lift frequency and vertical distance would be allowed in manual lifting tasks. All the combinations where the oxygen uptake and heart rate are less than 12.93 ml/kg/min and 110 beats/min respectively can be considered as safe tasks which would cause exertion within the acceptable limits. The conditions in which the task becomes unacceptable are when the load to be lifted is 23 kg coupled with a frequency of more than 7 lifts/min and vertical distance is more than waist high. Consequently, 8 different combinations of the three factors would cause high amount of exertion. All the remaining combinations would cause low to moderate exertion.

Table 4.11: Decision matrix for identifying safe lifting task (options for optimal designs)

| Trial No. | Load           | Lift frequency | Vertical distance | Optimum oxygen uptake ml/kg-min |        | Decision with Safe limit $\leq 12.93$ ml/kg-min (Summer/Winter) | Optimum heart rate beats/min |        | Decision with Safe limit $\leq 110$ beats/min (Summer/Winter) |
|-----------|----------------|----------------|-------------------|---------------------------------|--------|-----------------------------------------------------------------|------------------------------|--------|---------------------------------------------------------------|
|           |                |                |                   | Summer                          | Winter |                                                                 | Summer                       | Winter |                                                               |
| 1         | A <sub>1</sub> | B <sub>1</sub> | E <sub>1</sub>    | 9.89                            | 11.41  | Y / Y                                                           | 93.74                        | 103.02 | Y / Y                                                         |
| 2         |                |                | E <sub>2</sub>    | 10.16                           | 12.13  | Y / Y                                                           | 98.16                        | 108.94 | Y / Y                                                         |
| 3         |                |                | E <sub>3</sub>    | 11.34                           | 13.5   | Y / N                                                           | 100.67                       | 112.24 | Y / N                                                         |
| 4         |                | B <sub>2</sub> | E <sub>1</sub>    | 10.44                           | 11.82  | Y / Y                                                           | 95.96                        | 106.30 | Y / Y                                                         |
| 5         |                |                | E <sub>2</sub>    | 10.76                           | 12.54  | Y / Y                                                           | 100.38                       | 112.31 | Y / N                                                         |
| 6         |                |                | E <sub>3</sub>    | 11.94                           | 13.91  | Y / N                                                           | 102.89                       | 115.61 | Y / N                                                         |
| 7         |                | B <sub>3</sub> | E <sub>1</sub>    | 10.93                           | 12.74  | Y / Y                                                           | 96.1                         | 109.73 | Y / Y                                                         |
| 8         |                |                | E <sub>2</sub>    | 11.2                            | 13.46  | Y / N                                                           | 100.52                       | 115.65 | Y / N                                                         |
| 9         |                |                | E <sub>3</sub>    | 11.94                           | 14.83  | Y / N                                                           | 103.03                       | 118.95 | Y / N                                                         |
| 10        | A <sub>2</sub> | B <sub>1</sub> | E <sub>1</sub>    | 11.16                           | 10.84  | Y / Y                                                           | 96.9                         | 107.87 | Y / Y                                                         |
| 11        |                |                | E <sub>2</sub>    | 11.4                            | 13.56  | Y / N                                                           | 101.32                       | 113.79 | Y / N                                                         |
| 12        |                |                | E <sub>3</sub>    | 12.58                           | 14.93  | Y / N                                                           | 103.83                       | 117.09 | Y / N                                                         |
| 13        |                | B <sub>2</sub> | E <sub>1</sub>    | 11.73                           | 13.25  | Y / N                                                           | 99.12                        | 111.24 | Y / N                                                         |
| 14        |                |                | E <sub>2</sub>    | 12                              | 13.97  | Y / N                                                           | 103.54                       | 117.16 | Y / N                                                         |
| 15        |                |                | E <sub>3</sub>    | 13.18                           | 15.34  | N / N                                                           | 106.05                       | 120.46 | Y / N                                                         |
| 16        |                | B <sub>3</sub> | E <sub>1</sub>    | 12.17                           | 14.17  | Y / N                                                           | 99.26                        | 114.58 | Y / N                                                         |

|    |                |                |                |       |       |        |        |        |       |
|----|----------------|----------------|----------------|-------|-------|--------|--------|--------|-------|
| 17 |                | E <sub>2</sub> | 12.44          | 14.89 | Y / N | 103.68 | 120.5  | Y / N  |       |
| 18 |                | E <sub>3</sub> | 13.62          | 16.26 | N / N | 106.19 | 123.8  | Y / N  |       |
| 19 |                | E <sub>1</sub> | 12.33          | 13.82 | Y / N | 103.4  | 112.68 | Y / N  |       |
| 20 | B <sub>1</sub> | E <sub>2</sub> | 12.6           | 13.88 | Y / N | 107.82 | 118.6  | Y / N  |       |
| 21 |                | E <sub>3</sub> | 13.78          | 15.55 | N / N | 110.33 | 121.9  | N / N  |       |
| 22 |                | E <sub>1</sub> | 12.93          | 13.87 | Y / N | 105.62 | 116.05 | Y / N  |       |
| 23 | A <sub>3</sub> | B <sub>2</sub> | E <sub>2</sub> | 13.2  | 14.59 | N / N  | 110.04 | 121.97 | N / N |
| 24 |                | E <sub>3</sub> | 14.38          | 15.96 | N / N | 112.55 | 125.27 | N / N  |       |
| 25 |                | E <sub>1</sub> | 13.37          | 14.79 | N / N | 105.76 | 119.39 | Y / N  |       |
| 26 | B <sub>3</sub> | E <sub>2</sub> | 13.64          | 15.51 | N / N | 110.18 | 125.31 | N / N  |       |
| 27 |                | E <sub>3</sub> | 14.82          | 16.88 | N / N | 112.69 | 128.61 | N / N  |       |

(Note: A<sub>i</sub> = Factor A set at i<sup>th</sup> level, Y=Safe lifting task, N=Unsafe lifting task)

#### 4.5.2 Analysis for Winter (Ambient temperature 5° - 10° C)

Unlike the results obtained in summer, the oxygen uptake and heart rate in winter was observed to be high. Using the same safe limits for oxygen uptake and heart rate, fewer combinations exhibited safe work conditions and thus the load, lifting frequency and vertical distance would have to be significantly lowered in relative comparison to the results for summer. The results also depict a strong impact of ambient temperature on the exertion caused to the workers. In controlled temperature conditions of up to 30° C, the load weight and lifting frequency can be increased significantly as compared to cold conditions.

Figures 4.10 and 4.11 show the graphical representation of the above discussion. The optimum mean oxygen uptake and heart rate for 27 different combinations of the three significant factors namely (i) Factor A, load; (ii) Factor B, lift frequency; and (iii) Factor E, vertical distance described in Table 4.11 have been plotted as a bar charts separately. Each trial on horizontal axis depicts one combination. For example, A1 B2 E3 to be read as: factor A (load) set at level 1 (13 kg), factor B (lift frequency) set at level 2 (7lift/min) and factor E (vertical distance) set at level 3 (shoulder height) and so on. All the trials beyond the safe limit of oxygen uptake @ 12.93 ml/kg-min and heart rate @ 110 beats/min would cause high exertion to the workers and should be treated as unsafe in the long run. All trials that are beyond the horizontal bold line in Figure 4.10 and Figure 4.11 depict the unsafe combinations of load, frequency and vertical distance. The plots also depict the oxygen uptake and heart rate in summer and winter. The effect of cold conditions on the two responses can also be visualized in these plots.

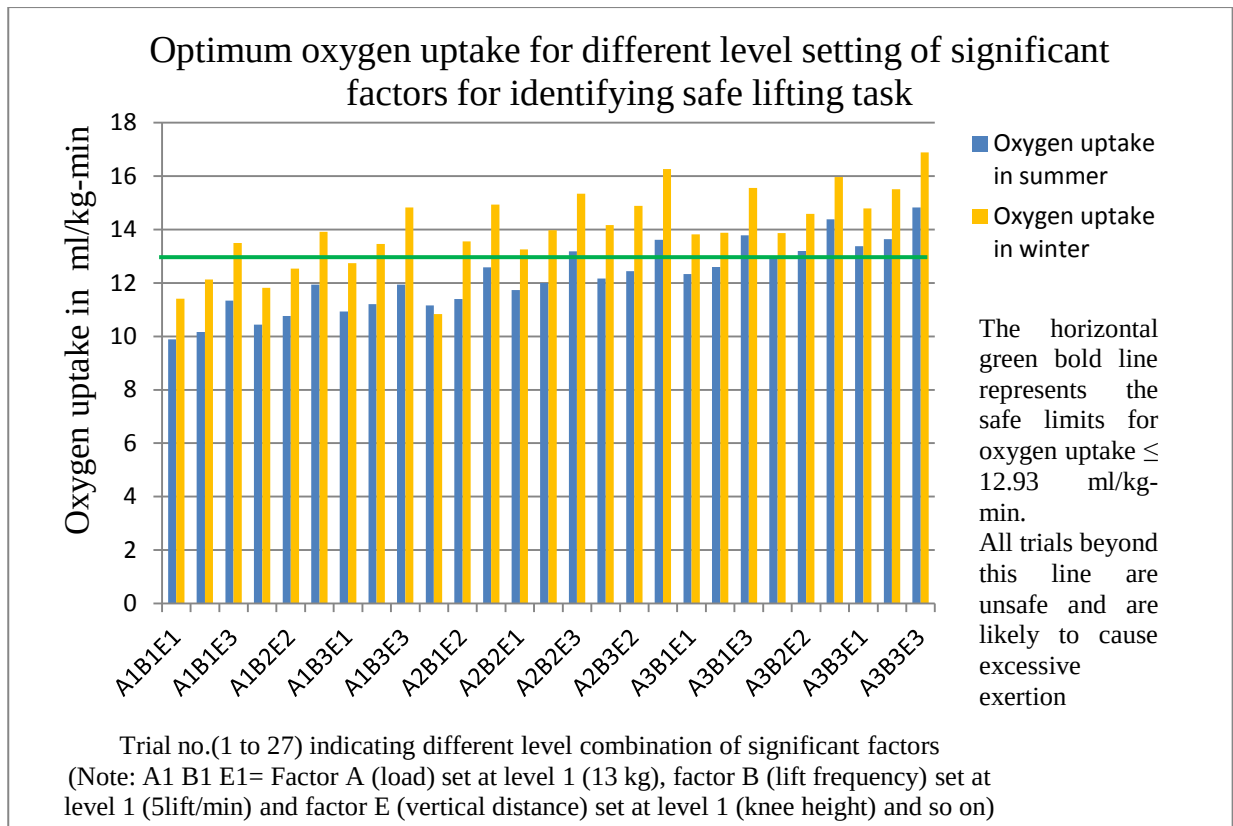


Figure 4.10: Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task in summer and winter

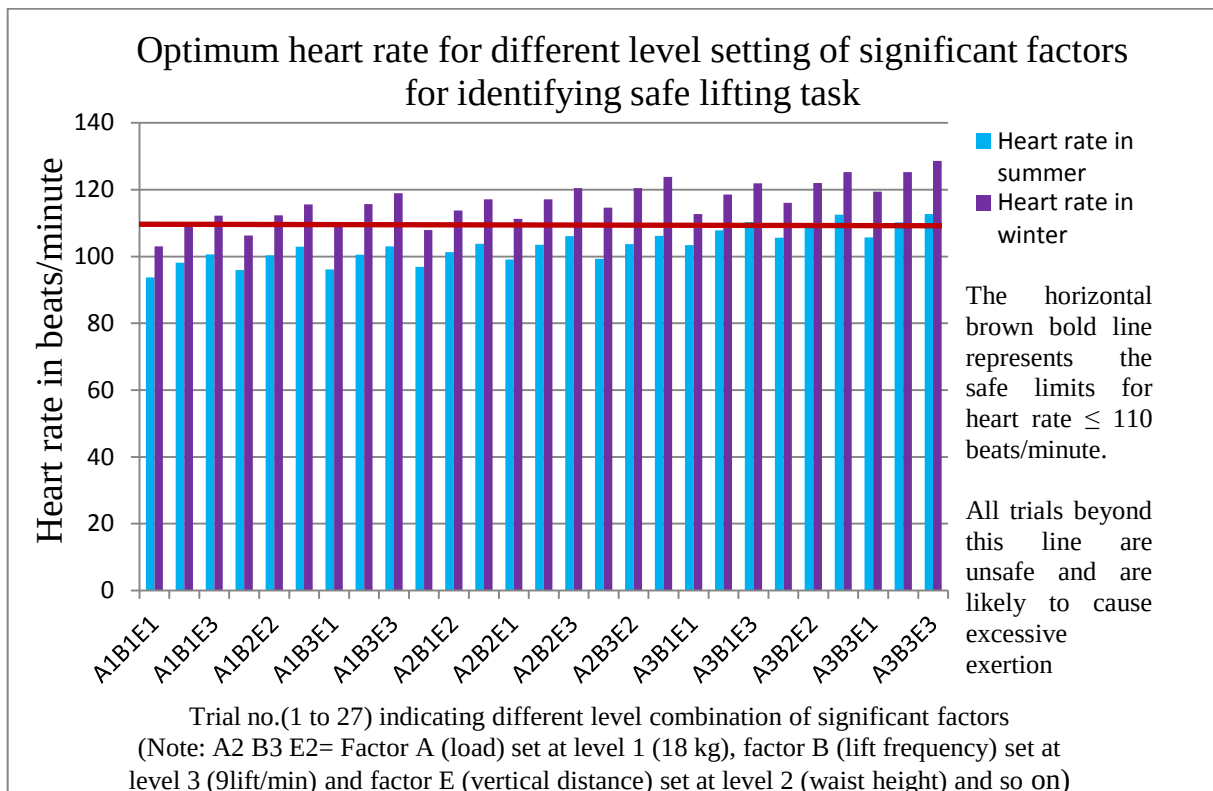


Figure 4.11: Optimum heart rate for different level setting of significant factors for identifying safe lifting task in summer and winter

#### 4.6 MULTI-RESPONSE OPTIMIZATION

Multi-Response Signal to Noise ratio (MRSN) methodology was used to optimize various input parameters (Chen [28]). All observations of each trial for both the responses in different climates were transformed into Taguchi's S/N ratio (see Table 4.12 and Table 4.13). The S/N ratio consolidates several repetitions into one value. Here, both oxygen consumption and heart rate are “lower is better” type of responses.

In order to optimize both the responses simultaneously, a method explained by Chen [28] was used to convert the multiple S/N ratios to a single value. Since S/N ratio is always targeted to be the highest for best performance, therefore, the S/N ratio of each response needs to be normalized using the equation 4.1.

$$\bar{s}_i = \frac{s_i - \min_i s_i}{\max_i s_i - \min_i s_i} \dots\dots\dots \text{Equation (4.1)}$$

Where  $s_i$  is the S/N ratio for  $i^{\text{th}}$  trial for a particular response,  $\bar{s}_i =$  one and zero for the best and worst performance respectively for both types of response characteristics. Table 4.14 shows the normalized results for heart rate and oxygen consumption for S/N ratio. It is necessary to convert the S/N ratio for the two responses into an equivalent responses scale. Finally, a multi-response S/N ratio (MRSN) for each trial was calculated to convert these multiple S/N responses into a single response using weight matrix. Chen [28] described the procedure of assigning weight to the individual responses as under:

An appropriate Taguchi orthogonal array ( $L_9$  or an  $L_{18}$ ) was selected as per the number of responses. For two responses, a  $L_9$  OA was identified with four columns and nine rows representing nine trial conditions. Column 1 and 2 of the  $L_9$  matrix were assigned to responses treating as control factor and the remaining columns were left unassigned. The levels 1, 2 or 3 on the weight matrix representing the low, medium and high level of a column were used to define the weight of the responses. MRSN is maximized by using Taguchi Method to obtain the optimal weight-ratio of each trial. The MRSN was calculated by multiplying the individual normalized S/N ratio with the corresponding weight in the  $L_9$  matrix and summing it for all the responses. The following equation was used for calculation of MRSN:

$$MRSN = \sum_{i=1}^4 w_i \bar{s}_i \dots\dots\dots \text{Equation (4.2)}$$

Where MRSN is the multi-response S/N,  $\bar{s}_i$  and  $w_i$  are the individual normalized signal-to-noise ratio (S/N) and the respective assigned weight taken from the  $L_9$  matrix. A decision

matrix of multi-responses S/N was generated by obtaining the optimal weight ratio of each trial through matrix multiplication of the row and the weight matrix. In the next section, the MRSN calculation method of trial 3 has been explained. Same methodology was used to calculate the MRSN for all 27 trials.

Table 4.12: Results for oxygen uptake & heart rate (winter)

| Exp.<br>no. | Oxygen uptake in winter |                    |                    | Signal to noise<br>ratio for<br>oxygen uptake | Heart rate in winter |                    |                    | Signal to<br>noise ratio<br>for heart rate |
|-------------|-------------------------|--------------------|--------------------|-----------------------------------------------|----------------------|--------------------|--------------------|--------------------------------------------|
|             | Response<br>1 (W1)      | Response<br>2 (W2) | Response<br>3 (W3) |                                               | Response<br>1 (W1)   | Response<br>2 (W2) | Response<br>3 (W3) |                                            |
| 1           | 10.11                   | 11.64              | 9.52               | -20.39                                        | 105.61               | 106.11             | 104.95             | -40.47                                     |
| 2           | 10.93                   | 11.77              | 12.94              | -21.52                                        | 108.80               | 109.42             | 105.24             | -40.66                                     |
| 3           | 12.01                   | 12.68              | 13.92              | -22.21                                        | 112.83               | 113.54             | 118.06             | -41.20                                     |
| 4           | 9.95                    | 12.50              | 13.07              | -21.52                                        | 101.53               | 109.45             | 109.52             | -40.58                                     |
| 5           | 11.53                   | 12.15              | 12.01              | -21.51                                        | 107.53               | 105.04             | 106.51             | -40.54                                     |
| 6           | 15.30                   | 13.33              | 16.84              | -23.65                                        | 118.18               | 122.89             | 127.08             | -41.78                                     |
| 7           | 11.06                   | 14.73              | 14.22              | -22.57                                        | 111.45               | 115.04             | 104.96             | -40.87                                     |
| 8           | 13.96                   | 13.68              | 14.43              | -22.94                                        | 127.75               | 106.63             | 111.82             | -41.27                                     |
| 9           | 15.55                   | 12.64              | 16.71              | -23.56                                        | 121.82               | 102.55             | 113.86             | -41.06                                     |
| 10          | 11.45                   | 13.10              | 14.69              | -22.38                                        | 110.10               | 112.38             | 112.97             | -40.97                                     |
| 11          | 12.23                   | 11.63              | 15.11              | -22.33                                        | 110.97               | 103.48             | 123.32             | -41.05                                     |
| 12          | 16.72                   | 12.62              | 18.84              | -24.23                                        | 122.20               | 116.95             | 127.32             | -41.74                                     |
| 13          | 12.52                   | 10.68              | 14.84              | -22.14                                        | 100.54               | 99.47              | 116.39             | -40.49                                     |
| 14          | 12.98                   | 14.90              | 16.07              | -23.35                                        | 123.05               | 121.66             | 119.81             | -41.69                                     |
| 15          | 14.54                   | 11.62              | 16.17              | -23.07                                        | 122.10               | 114.66             | 112.39             | -41.32                                     |
| 16          | 17.62                   | 12.86              | 14.04              | -23.51                                        | 121.50               | 105.10             | 117.81             | -41.22                                     |
| 17          | 12.64                   | 13.61              | 18.13              | -23.51                                        | 116.70               | 122.64             | 120.40             | -41.58                                     |
| 18          | 15.42                   | 14.37              | 18.24              | -24.13                                        | 121.34               | 116.49             | 127.18             | -41.71                                     |
| 19          | 14.94                   | 11.89              | 15.12              | -22.96                                        | 106.16               | 103.40             | 104.60             | -40.40                                     |
| 20          | 16.76                   | 14.67              | 14.05              | -23.64                                        | 129.87               | 112.18             | 112.77             | -41.48                                     |
| 21          | 14.86                   | 12.90              | 17.63              | -23.67                                        | 122.76               | 110.93             | 121.00             | -41.46                                     |
| 22          | 13.74                   | 14.52              | 14.31              | -23.04                                        | 117.10               | 119.42             | 115.14             | -41.38                                     |
| 23          | 16.41                   | 14.50              | 14.06              | -23.53                                        | 129.74               | 125.12             | 113.71             | -41.80                                     |
| 24          | 15.91                   | 15.65              | 15.73              | -23.95                                        | 135.04               | 127.94             | 117.96             | -42.09                                     |
| 25          | 15.69                   | 13.00              | 13.32              | -22.96                                        | 130.32               | 124.45             | 116.86             | -41.87                                     |
| 26          | 15.97                   | 14.89              | 12.58              | -23.26                                        | 133.47               | 125.65             | 129.06             | -42.24                                     |
| 27          | 17.35                   | 16.10              | 17.84              | -24.67                                        | 125.63               | 129.34             | 129.35             | -42.15                                     |

Table 4.13: Results for oxygen uptake &amp; heart Rate (summer)

| Exp.<br>no. | Oxygen uptake in summer |                    |                    | Signal to noise<br>ratio for<br>oxygen uptake | Heart rate in summer |                    |                    | Signal to<br>noise ratio<br>for heart rate |
|-------------|-------------------------|--------------------|--------------------|-----------------------------------------------|----------------------|--------------------|--------------------|--------------------------------------------|
|             | Response<br>4 (S1)      | Response<br>5 (S2) | Response<br>6 (S3) |                                               | Response<br>4 (S1)   | Response<br>5 (S2) | Response<br>6 (S3) |                                            |
| 1           | 9.19                    | 10.08              | 8.43               | -19.33                                        | 93.80                | 100.18             | 96.23              | -39.71                                     |
| 2           | 10.22                   | 9.74               | 10.36              | -20.10                                        | 97.28                | 102.76             | 95.95              | -39.89                                     |
| 3           | 10.37                   | 11.32              | 12.37              | -21.13                                        | 98.20                | 104.75             | 97.63              | -40.02                                     |
| 4           | 10.59                   | 9.24               | 10.93              | -20.24                                        | 92.10                | 91.43              | 86.86              | -39.10                                     |
| 5           | 10.74                   | 9.74               | 10.05              | -20.16                                        | 94.55                | 99.97              | 102.92             | -39.93                                     |
| 6           | 10.50                   | 11.12              | 14.22              | -21.62                                        | 97.91                | 103.73             | 108.88             | -40.31                                     |
| 7           | 9.56                    | 9.40               | 13.64              | -20.86                                        | 95.73                | 97.37              | 97.40              | -39.72                                     |
| 8           | 12.94                   | 11.46              | 12.83              | -21.89                                        | 108.84               | 94.43              | 103.74             | -40.22                                     |
| 9           | 12.16                   | 11.38              | 14.52              | -22.11                                        | 106.87               | 98.18              | 106.37             | -40.33                                     |
| 10          | 10.57                   | 11.21              | 14.45              | -21.72                                        | 90.41                | 106.13             | 104.71             | -40.06                                     |
| 11          | 8.63                    | 10.92              | 11.15              | -20.25                                        | 101.10               | 101.44             | 106.54             | -40.26                                     |
| 12          | 8.53                    | 14.66              | 15.20              | -22.38                                        | 103.80               | 109.60             | 97.25              | -40.31                                     |
| 13          | 10.41                   | 10.93              | 14.51              | -21.65                                        | 98.16                | 97.73              | 101.39             | -39.92                                     |
| 14          | 11.17                   | 11.23              | 14.19              | -21.78                                        | 105.47               | 109.38             | 105.77             | -40.58                                     |
| 15          | 11.13                   | 12.96              | 13.09              | -21.88                                        | 99.46                | 107.92             | 108.74             | -40.46                                     |
| 16          | 12.10                   | 10.93              | 11.42              | -21.21                                        | 99.64                | 98.21              | 96.66              | -39.84                                     |
| 17          | 13.16                   | 12.09              | 11.07              | -21.68                                        | 99.50                | 95.01              | 99.05              | -39.81                                     |
| 18          | 13.97                   | 14.32              | 16.45              | -23.49                                        | 102.14               | 107.96             | 106.31             | -40.46                                     |
| 19          | 11.41                   | 13.79              | 12.79              | -22.08                                        | 96.84                | 97.27              | 101.71             | -39.88                                     |
| 20          | 10.98                   | 13.72              | 14.38              | -22.35                                        | 104.19               | 107.69             | 106.84             | -40.53                                     |
| 21          | 12.10                   | 14.40              | 14.34              | -22.71                                        | 108.63               | 108.34             | 109.06             | -40.72                                     |
| 22          | 14.22                   | 13.25              | 14.14              | -22.85                                        | 101.26               | 113.40             | 107.36             | -40.62                                     |
| 23          | 14.39                   | 14.01              | 13.89              | -22.98                                        | 108.58               | 118.13             | 106.18             | -40.91                                     |
| 24          | 13.71                   | 15.16              | 12.05              | -22.73                                        | 111.16               | 120.34             | 109.38             | -41.12                                     |
| 25          | 10.42                   | 15.15              | 11.82              | -22.02                                        | 109.53               | 110.76             | 105.01             | -40.71                                     |
| 26          | 11.68                   | 15.14              | 12.02              | -22.30                                        | 110.27               | 117.86             | 103.22             | -40.88                                     |
| 27          | 13.72                   | 15.78              | 14.30              | -23.30                                        | 110.16               | 123.98             | 107.80             | -41.15                                     |

Table 4.14: Normalization of Signal to Noise ratio of the responses

| Exp.<br>No. | Winter     |                  |               |                  | Summer     |                  |               |                  |
|-------------|------------|------------------|---------------|------------------|------------|------------------|---------------|------------------|
|             | Heart rate |                  | Oxygen uptake |                  | Heart rate |                  | Oxygen uptake |                  |
|             | S/N ratio  | Normalized value | S/N ratio     | Normalized value | S/N ratio  | Normalized value | S/N ratio     | Normalized value |
| 1           | -40.47     | 0.961957         | -20.39        | 1                | -39.71     | 0.7024           | -19.33        | 1.0000           |
| 2           | -40.66     | 0.858696         | -21.52        | 0.735981         | -39.89     | 0.6146           | -20.10        | 0.8149           |
| 3           | -41.20     | 0.565217         | -22.21        | 0.574766         | -40.02     | 0.5512           | -21.13        | 0.5673           |
| 4           | -40.58     | 0.902174         | -21.52        | 0.735981         | -39.10     | 1.0000           | -20.24        | 0.7813           |
| 5           | -40.54     | 0.923913         | -21.51        | 0.738318         | -39.93     | 0.5951           | -20.16        | 0.8005           |
| 6           | -41.78     | 0.25             | -23.65        | 0.238318         | -40.31     | 0.4098           | -21.62        | 0.4495           |
| 7           | -40.87     | 0.744565         | -22.57        | 0.490654         | -39.72     | 0.6976           | -20.86        | 0.6322           |
| 8           | -41.27     | 0.527174         | -22.94        | 0.404206         | -40.22     | 0.4537           | -21.89        | 0.3846           |
| 9           | -41.06     | 0.641304         | -23.56        | 0.259346         | -40.33     | 0.4000           | -22.11        | 0.3317           |
| 10          | -40.97     | 0.690217         | -22.38        | 0.535047         | -40.06     | 0.5317           | -21.72        | 0.4255           |
| 11          | -41.05     | 0.646739         | -22.33        | 0.546729         | -40.26     | 0.4341           | -20.25        | 0.7788           |
| 12          | -41.74     | 0.271739         | -24.23        | 0.102804         | -40.31     | 0.4098           | -22.38        | 0.2668           |
| 13          | -40.49     | 0.951087         | -22.14        | 0.591121         | -39.92     | 0.6000           | -21.65        | 0.4423           |
| 14          | -41.69     | 0.298913         | -23.35        | 0.308411         | -40.58     | 0.2780           | -21.78        | 0.4111           |
| 15          | -41.32     | 0.5              | -23.07        | 0.373832         | -40.46     | 0.3366           | -21.88        | 0.3870           |
| 16          | -41.22     | 0.554348         | -23.51        | 0.271028         | -39.84     | 0.6390           | -21.21        | 0.5481           |
| 17          | -41.58     | 0.358696         | -23.51        | 0.271028         | -39.81     | 0.6537           | -21.68        | 0.4351           |
| 18          | -41.71     | 0.288043         | -24.13        | 0.126168         | -40.46     | 0.3366           | -23.49        | 0.0000           |
| 19          | -40.40     | 1                | -22.96        | 0.399533         | -39.88     | 0.6195           | -22.08        | 0.3389           |
| 20          | -41.48     | 0.413043         | -23.64        | 0.240654         | -40.53     | 0.3024           | -22.35        | 0.2740           |
| 21          | -41.46     | 0.423913         | -23.67        | 0.233645         | -40.72     | 0.2098           | -22.71        | 0.1875           |
| 22          | -41.38     | 0.467391         | -23.04        | 0.380841         | -40.62     | 0.2585           | -22.85        | 0.1538           |
| 23          | -41.80     | 0.23913          | -23.53        | 0.266355         | -40.91     | 0.1171           | -22.98        | 0.1226           |
| 24          | -42.09     | 0.081522         | -23.95        | 0.168224         | -41.12     | 0.0146           | -22.73        | 0.1827           |
| 25          | -41.87     | 0.201087         | -22.96        | 0.399533         | -40.71     | 0.2146           | -22.02        | 0.3534           |
| 26          | -42.24     | 0                | -23.26        | 0.329439         | -40.88     | 0.1317           | -22.30        | 0.2861           |
| 27          | -42.15     | 0.048913         | -24.67        | 0                | -41.15     | 0.0000           | -23.30        | 0.0457           |

Table 4.15: Normalized S/N ratio of responses converted to MRSN using  $L_9$  OA as weight matrix (sample calculations for 3<sup>rd</sup> trial, winter)

| Exp. No. | Normalized S/N ratio for Heart rate | Normalized S/N ratio for Oxygen uptake | e | e |         | Heart rate | Oxygen uptake | e | e |
|----------|-------------------------------------|----------------------------------------|---|---|---------|------------|---------------|---|---|
| 1        | 0.9620                              | 1.0000                                 | 0 | 0 |         | 1          | 1             | 1 | 1 |
| 2        | 0.8587                              | 0.7360                                 | 0 | 0 |         | 1          | 2             | 2 | 2 |
| 3        | 0.5652                              | 0.5748                                 | 0 | 0 | →       | 1          | 3             | 3 | 3 |
| 4        | 0.9022                              | 0.7360                                 | 0 | 0 |         | 2          | 1             | 2 | 3 |
| 5        | 0.9239                              | 0.7383                                 | 0 | 0 | W =     | 2          | 2             | 3 | 1 |
| 6        | 0.2500                              | 0.2383                                 | 0 | 0 | (Weight | 2          | 3             | 1 | 2 |
| 7        | 0.7446                              | 0.4907                                 | 0 | 0 | Matrix) | 3          | 1             | 3 | 2 |
| 8        | 0.5272                              | 0.4042                                 | 0 | 0 |         | 3          | 2             | 1 | 3 |
| 9        | 0.6413                              | 0.2593                                 | 0 | 0 |         | 3          | 3             | 2 | 1 |
| 10       | 0.6902                              | 0.5350                                 | 0 | 0 |         |            |               |   |   |
| 11       | 0.6467                              | 0.5467                                 | 0 | 0 |         | Heart rate | Oxygen uptake | e | e |
| 12       | 0.2717                              | 0.1028                                 | 0 | 0 |         | 0.5652     | 0.5748        | 0 | 0 |
| 13       | 0.9511                              | 0.5911                                 | 0 | 0 |         | 0.5652     | 1.1496        | 0 | 0 |
| 14       | 0.2989                              | 0.3084                                 | 0 | 0 |         | 0.5652     | 1.7244        | 0 | 0 |
| 15       | 0.5000                              | 0.3738                                 | 0 | 0 |         | 1.1304     | 0.5748        | 0 | 0 |
| 16       | 0.5543                              | 0.2710                                 | 0 | 0 |         | 1.1304     | 1.1496        | 0 | 0 |
| 17       | 0.3587                              | 0.2710                                 | 0 | 0 |         | 1.1304     | 1.7244        | 0 | 0 |
| 18       | 0.2880                              | 0.1262                                 | 0 | 0 |         | 1.6956     | 0.5748        | 0 | 0 |
| 19       | 1.0000                              | 0.3995                                 | 0 | 0 |         | 1.6956     | 1.1496        | 0 | 0 |
| 20       | 0.4130                              | 0.2407                                 | 0 | 0 |         | 1.6956     | 1.7244        | 0 | 0 |
| 21       | 0.4239                              | 0.2336                                 | 0 | 0 |         |            |               |   |   |
| 22       | 0.4674                              | 0.3808                                 | 0 | 0 |         |            |               |   |   |
| 23       | 0.2391                              | 0.2664                                 | 0 | 0 |         |            |               |   |   |
| 24       | 0.0815                              | 0.1682                                 | 0 | 0 |         |            |               |   |   |
| 25       | 0.2011                              | 0.3995                                 | 0 | 0 |         |            |               |   |   |
| 26       | 0.0000                              | 0.3294                                 | 0 | 0 |         |            |               |   |   |
| 27       | 0.0489                              | 0.0000                                 | 0 | 0 |         |            |               |   |   |

Table 4.16: Normalized S/N ratio of responses converted to MRSN using  $L_9$  OA as weight matrix (sample for 3<sup>rd</sup> trial, summer)

| Exp. No. | Normalized S/N ratio for Heart rate | Normalized S/N ratio for Oxygen uptake | e | e |         | Heart rate | Oxygen uptake | e | e      |
|----------|-------------------------------------|----------------------------------------|---|---|---------|------------|---------------|---|--------|
| 1        | 0.7024                              | 1.0000                                 | 0 | 0 |         | 1          | 1             | 1 | 1      |
| 2        | 0.6146                              | 0.8149                                 | 0 | 0 |         | 1          | 2             | 2 | 2      |
| 3        | 0.5512                              | 0.5673                                 | 0 | 0 | →       | 1          | 3             | 3 | 3      |
| 4        | 1.0000                              | 0.7813                                 | 0 | 0 |         | 2          | 1             | 2 | 3      |
| 5        | 0.5951                              | 0.8005                                 | 0 | 0 | W =     | 2          | 2             | 3 | 1      |
| 6        | 0.4098                              | 0.4495                                 | 0 | 0 | (Weight | 2          | 3             | 1 | 2      |
| 7        | 0.6976                              | 0.6322                                 | 0 | 0 | Matrix) | 3          | 1             | 3 | 2      |
| 8        | 0.4537                              | 0.3846                                 | 0 | 0 |         | 3          | 2             | 1 | 3      |
| 9        | 0.4000                              | 0.3317                                 | 0 | 0 |         | 3          | 3             | 2 | 1      |
| 10       | 0.5317                              | 0.4255                                 | 0 | 0 |         |            |               |   |        |
| 11       | 0.4341                              | 0.7788                                 | 0 | 0 |         |            |               |   |        |
| 12       | 0.4098                              | 0.2668                                 | 0 | 0 |         |            |               |   |        |
| 13       | 0.6000                              | 0.4423                                 | 0 | 0 |         | Heart rate | Oxygen uptake | e | e      |
| 14       | 0.2780                              | 0.4111                                 | 0 | 0 |         | 0.5512     | 0.5673        | 0 | 0      |
| 15       | 0.3366                              | 0.3870                                 | 0 | 0 |         | 0.5512     | 1.1346        | 0 | 0      |
| 16       | 0.6390                              | 0.5481                                 | 0 | 0 |         | 0.5512     | 1.7019        | 0 | 0      |
| 17       | 0.6537                              | 0.4351                                 | 0 | 0 |         | 1.1024     | 0.5673        | 0 | 0      |
| 18       | 0.3366                              | 0.0000                                 | 0 | 0 |         | 1.1024     | 1.1346        | 0 | 0      |
| 19       | 0.6195                              | 0.3389                                 | 0 | 0 |         | 1.1024     | 1.7019        | 0 | 0      |
| 20       | 0.3024                              | 0.2740                                 | 0 | 0 |         | 1.6536     | 0.5673        | 0 | 0      |
| 21       | 0.2098                              | 0.1875                                 | 0 | 0 |         | 1.6536     | 1.1346        | 0 | 0      |
| 22       | 0.2585                              | 0.1538                                 | 0 | 0 |         | 1.6536     | 1.7019        | 0 | 0      |
| 23       | 0.1171                              | 0.1226                                 | 0 | 0 |         |            |               |   |        |
| 24       | 0.0146                              | 0.1827                                 | 0 | 0 |         |            |               |   |        |
| 25       | 0.2146                              | 0.3534                                 | 0 | 0 |         |            |               |   |        |
| 26       | 0.1317                              | 0.2861                                 | 0 | 0 |         |            |               |   |        |
| 27       | 0.0000                              | 0.0457                                 | 0 | 0 |         |            |               |   |        |
|          |                                     |                                        |   |   |         |            |               |   | MRSN   |
|          |                                     |                                        |   |   |         |            |               |   | 1.1185 |
|          |                                     |                                        |   |   |         |            |               |   | 1.6858 |
|          |                                     |                                        |   |   |         |            |               |   | 2.2531 |
|          |                                     |                                        |   |   |         |            |               |   | 1.6697 |
|          |                                     |                                        |   |   |         |            |               |   | 2.2370 |
|          |                                     |                                        |   |   |         |            |               |   | 2.8043 |
|          |                                     |                                        |   |   |         |            |               |   | 2.2209 |
|          |                                     |                                        |   |   |         |            |               |   | 2.7882 |
|          |                                     |                                        |   |   |         |            |               |   | 3.3555 |

Table 4.17: Weight effect of responses at each level (sample representation of 3<sup>rd</sup> trial)

| Weight level                             | Winter     |               |        |        | Summer     |               |        |        |
|------------------------------------------|------------|---------------|--------|--------|------------|---------------|--------|--------|
|                                          | Heart rate | Oxygen uptake | e      | e      | Heart rate | Oxygen uptake | e      | e      |
| 1                                        | 1.7148     | 1.7052        | 2.28   | 2.28   | 1.6858     | 1.6697        | 2.2370 | 2.2370 |
| 2                                        | 2.28       | 2.28          | 2.28   | 2.28   | 2.2370     | 2.2370        | 2.2370 | 2.2370 |
| 3                                        | 2.8452     | 2.8548        | 2.28   | 2.28   | 2.7882     | 2.8043        | 2.2370 | 2.2370 |
| Max – Min                                | 1.1304     | 1.1496        | 0.0000 | 0.0000 | 1.1024     | 1.1346        | 0.0000 | 0.0000 |
| Max. MRSN using Taguchi's additive model | 3.4200     |               |        |        | 3.3555     |               |        |        |

#### 4.6.1 Sample MRSN Calculation

The responses; oxygen uptake and heart rate were assigned to two columns with levels weight 1, 2, 3 and rest two columns were left empty in  $L_9$  weight matrix which is applied for trial 3. From Tables 4.15 and 4.16, the result of the multiplication of normalized individual S/N ratio to the levels representing weight was used to obtain the MRSN for trial 3 which is shown in the last column of the decision matrix. The weight effect of responses at each level is then given in Table 4.17. The additive model of Taguchi was used to calculate the maximum MRSN (winter) for trial 3 which is given by:

$$MRSN_{\text{trial 3}} = \overline{MRSN}_{\text{Heart rate}} + \overline{MRSN}_{\text{Oxy. uptake}} - \bar{T} = 3.4200 \text{ (winter)}$$

Where  $\overline{MRSN}_{\text{Heart rate}}$  and  $\overline{MRSN}_{\text{oxy uptake}}$  represent the maximum mean multi-response S/N ratio for heart rate and oxygen uptake of 2.4862 and 2.8548 respectively (from Table 4.17).

Same methodology was adopted to calculate the maximum MRSN (summer) for trial 3 which is given by the following equation:

$$MRSN_{\text{trial 3}} = \overline{MRSN}_{\text{Heart rate}} + \overline{MRSN}_{\text{Oxy. uptake}} - \bar{T} = 3.5550 \text{ (summer)}$$

Where  $\overline{MRSN}_{\text{Heart rate}}$  and  $\overline{MRSN}_{\text{oxy uptake}}$  represents the maximum mean multi-response S/N ratio for heart rate and oxygen uptake, 2.7882 and 2.8043 respectively (from Table 4.17 ).

Table 4.18: Final MRSN corresponding to each trial (winter & summer)

| Exp. No. | Final MRSN |        |
|----------|------------|--------|
|          | Winter     | Summer |
| 1        | 5.8860     | 5.1072 |
| 2        | 4.7841     | 4.2885 |
| 3        | 3.4200     | 3.3555 |
| 4        | 4.9146     | 5.3439 |
| 5        | 4.9866     | 4.1868 |
| 6        | 1.4649     | 2.5779 |
| 7        | 3.7059     | 3.9894 |
| 8        | 2.7942     | 2.5149 |
| 9        | 2.7018     | 2.1951 |
| 10       | 3.6756     | 2.8716 |
| 11       | 3.5802     | 3.6387 |
| 12       | 1.1235     | 2.0298 |
| 13       | 4.6266     | 3.1269 |
| 14       | 1.8219     | 2.0673 |
| 15       | 2.6214     | 2.1708 |
| 16       | 2.4759     | 3.5613 |
| 17       | 1.8891     | 3.2664 |
| 18       | 1.2426     | 1.0098 |
| 19       | 4.1985     | 2.8752 |
| 20       | 1.9611     | 1.7292 |
| 21       | 1.9725     | 1.1919 |
| 22       | 2.5446     | 1.2369 |
| 23       | 1.5165     | 0.7191 |
| 24       | 0.7491     | 0.5919 |
| 25       | 1.8018     | 1.7040 |
| 26       | 0.9882     | 1.2534 |
| 27       | 0.1467     | 0.1371 |

Table 4.19: Response table/ level effect of control factors (winter)

| Level                                    | Wt. load      | Frequency     | Grip          | Assy. Angle                     | Vertical Dist. | Horizontal Dist. | Travel Dist.  |
|------------------------------------------|---------------|---------------|---------------|---------------------------------|----------------|------------------|---------------|
| 1                                        | <b>3.8511</b> | <b>3.4002</b> | <b>2.8584</b> | <b>3.0841</b>                   | <b>3.7588</b>  | 2.7650           | <b>2.9085</b> |
| 2                                        | 2.5622        | 2.8051        | 2.4667        | 2.6062                          | 2.7024         | 2.6397           | 2.5716        |
| 3                                        | 1.7644        | 1.9718        | 2.8520        | 2.4868                          | 1.7158         | <b>2.7723</b>    | 2.6970        |
| Max – Min                                | 2.0867        | 1.4284        | 0.3917        | 0.5974                          | 2.0430         | 0.1326           | 0.3369        |
| Rank                                     | 1             | 3             | 5             | 4                               | 2              | 7                | 6             |
| Max. MRSN using Taguchi's additive model |               |               |               | Mean=2.7257<br>Max MRSN=11.7306 |                |                  |               |

Table 4.20: Response table/ level effect of control factors (summer)

| Level                                    | Wt. load      | Frequency     | Grip          | Assy. Angle                     | Vertical Dist. | Horizontal Dist. | Travel Dist.  |
|------------------------------------------|---------------|---------------|---------------|---------------------------------|----------------|------------------|---------------|
| 1                                        | <b>3.7288</b> | <b>3.0097</b> | 2.6597        | <b>2.7269</b>                   | <b>3.3129</b>  | 2.3989           | 2.3521        |
| 2                                        | 2.6381        | 2.4468        | 2.2763        | 2.5567                          | 2.6294         | <b>2.6896</b>    | <b>2.6946</b> |
| 3                                        | 1.2710        | 2.1813        | <b>2.7018</b> | 2.3542                          | 1.6955         | 2.5493           | 2.5911        |
| Max – Min                                | 2.4578        | 0.8285        | 0.4255        | 0.3727                          | 1.6174         | 0.2907           | 0.3425        |
| Rank                                     | 1             | 3             | 4             | 5                               | 2              | 7                | 6             |
| Max. MRSN using Taguchi's additive model |               |               |               | Mean=2.5460<br>Max MRSN=10.6807 |                |                  |               |

Table 4.21: ANOVA table for MRSN (winter)

| Source                       | DOF         | Sum of Square  | Variance      | F-value      | p-value      | PC (Percentage Contribution) |
|------------------------------|-------------|----------------|---------------|--------------|--------------|------------------------------|
| <b>Weight</b>                | <b>2</b>    | <b>19.988</b>  | <b>9.994</b>  | <b>21.14</b> | <b>0.001</b> | <b>32.74</b>                 |
| <b>Frequency</b>             | <b>2</b>    | <b>9.2662</b>  | <b>4.6331</b> | <b>9.80</b>  | <b>0.007</b> | <b>14.25</b>                 |
| Coupling (grip) (pooled)     | 2           | 0.905806       | -             |              |              |                              |
| Asymmetric angle             | 2           | 1.79866        | 0.8993        | 1.90         | 0.995        |                              |
| <b>Vertical distance</b>     | <b>2</b>    | <b>18.7896</b> | <b>9.3948</b> | <b>19.87</b> | <b>0.002</b> | <b>30.67</b>                 |
| Horizontal distance (pooled) | 2           | 0.10000        | -             |              |              |                              |
| Travel distance(pooled)      | 2           | 0.5217         | -             |              |              |                              |
| Weight × Frequency           | 4           | 1.5536         | 0.3881        | 0.82         | 0.999        |                              |
| Weight × V.D. (pooled)       | 4           | 1.0486         | -             | -            |              |                              |
| Frequency × V.D.(pooled)     | 4           | 0.08645        | -             | -            |              |                              |
| Residual pooled error        | (2+2+2+4+4) | 6.61843        | 0.4727        |              |              |                              |
| Total                        | 26          | 58.01450       |               |              |              |                              |

Table 4.22: ANOVA table for MRSN (summer)

| Source                          | DOF         | Sum of Square  | Variance       | F-value       | p-value      | PC<br>(Percentage contribution) |
|---------------------------------|-------------|----------------|----------------|---------------|--------------|---------------------------------|
| <b>Weight</b>                   | <b>2</b>    | <b>27.2988</b> | <b>13.6494</b> | <b>51.383</b> | <b>0.000</b> | <b>54.82</b>                    |
| <b>Frequency</b>                | <b>2</b>    | <b>3.2212</b>  | <b>1.6106</b>  | <b>6.063</b>  | <b>0.009</b> | <b>11.33</b>                    |
| Coupling (grip) (pooled)        | 2           | 0.9895         | -              | -             |              |                                 |
| Asymmetric angle (pooled)       | 2           | 0.6265         | -              | -             |              |                                 |
| <b>Vertical distance</b>        | <b>2</b>    | <b>11.8651</b> | <b>5.9325</b>  | <b>22.332</b> | <b>0.003</b> | <b>44.66</b>                    |
| Horizontal distance (pooled)    | 2           | 0.3803         | -              | -             |              |                                 |
| Travel distance (pooled)        | 2           | 0.5553         | -              | -             |              |                                 |
| Weight $\times$ Frequency       | 4           | 2.1900         | 0.5475         | 2.061         | 0.951        | 4.18                            |
| Weight $\times$ V.D.(pooled)    | 4           | 1.0420         | -              | -             |              |                                 |
| Frequency $\times$ V.D.(pooled) | 4           | 0.5733         | -              | -             |              |                                 |
| Residual error                  | 2+2+2+2+4+4 | 4.2503         | 0.26564        |               |              |                                 |
| Total                           | 26          | 48.8254        |                |               |              |                                 |

#### 4.6.2 Maximum MRSN for All Trials

The maximum MRSN for each trial was calculated using the above methodology and is shown in Table 4.18. The mean values (at each level) for all the seven factors for MRSN with their significance rank were presented in Table 4.19 (winter) & Table 4.20 (summer). The rank presented in last row of tables implies the significance of factors. The most and least significant factors represent rank 1 and 7 respectively. Analysis of Variance (ANOVA) was used for identifying the significant factors and interactions affecting the MRSN. The last columns of ANOVA table (Table 4.21 (winter) & Table 4.22 (summer)) show the F value, p-value and percentage contribution, PC for each factor and the interactions. Factors having a p value less than 0.05 (for confidential level 95%) considered significant. The principle of PC is that, the larger the PC value, larger would be the contribution to response value, while the principle of the F test is that the larger the F value for a particular parameter, the greater would be its effect on response values. As per ANOVA table (Table 4.23 (winter) & Table 4.24 (summer)) the load weight, vertical distance and lifting frequency in that order, were found to be most significant factors affecting the MRSN ratio. The coupling (grip), asymmetric angle, travel distance and horizontal distance had no significant effect on MRSN. MRSN (winter) is more than the MRSN (summer) in trials 18-27. This indicates that exertion leads to higher

MRSN. Graphical representations of MRSN (winter & summer) have been shown in Figures 4.12 and 4.13.

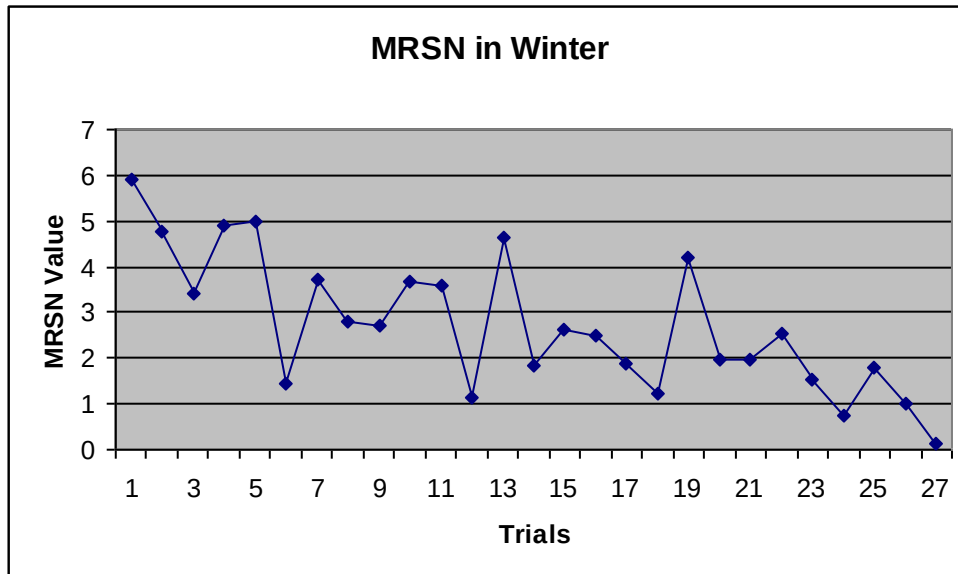


Figure 4.12: Graphical representation of MRSN (winter)

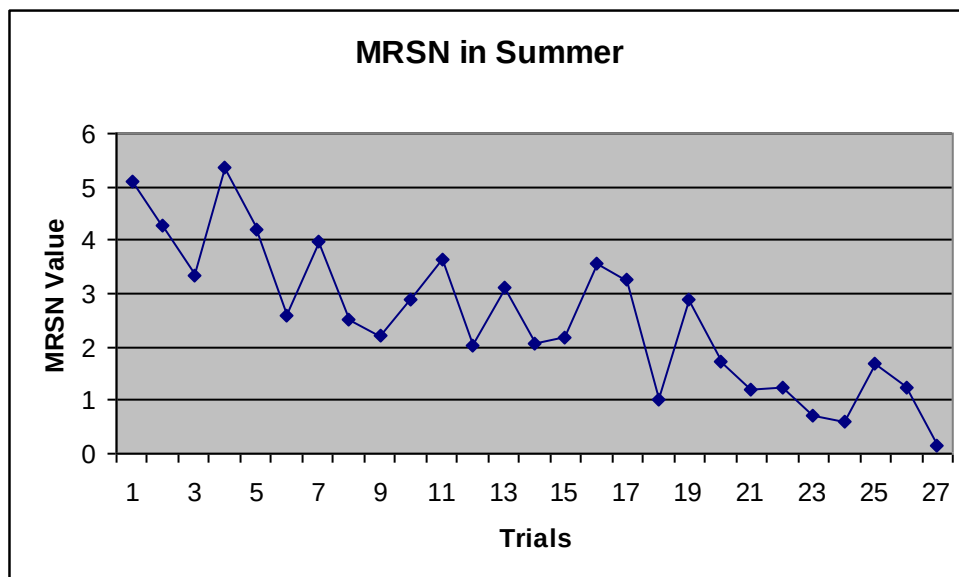


Figure 4.13: Graphical representation of MRSN (summer)

#### 4.6.3 Main Effect and Interaction Plots

The main effect and interaction plots have been drawn to analyze the variation of MRSN ratio for each factor which is shown in Figures 4.14, 4.15, 4.16 and 4.17. The x- axis represents the levels of factor and y axis shows the resultant change in MRSN ratio. The mean response is represented by a horizontal line. It can be observed from Figure 4.16 that the MRSN ratio

increases almost linearly with increase in load weight, vertical distance and lifting frequency. This increase is most prominent with increased load weight. There was no significant effect on the MRSN ratio of coupling (grip), asymmetric angle, horizontal distance and travel distance. The review of the interaction plots (Figure 4.15 & Figure 4.17) and ANOVA (Table 4.21 & Table 4.22) also indicates that none of the interactions (weight vs. frequency, weight vs. vertical distance and frequency vs. vertical distance) were found to be significant. The Taguchi's additive model was used to calculate the maximized MRSN ratio (winter) for all the trials and is given below:

$$\begin{aligned} \overline{MRSN} = & \overline{MRSN}_{Loadweight_1} + \overline{MRSN}_{frequency_1} + \overline{MRSN}_{grip_1} + \overline{MRSN}_{angle_1} \\ & + \overline{MRSN}_{v.distance_1} + \overline{MRSN}_{H.distance_3} + \overline{MRSN}_{T.distance_1} - 4\bar{T} = 11.7306 (winter) \end{aligned}$$

Where  $\overline{MRSN}_{loadweight_1}$  represents the maximum mean multi-response S/N ratio at level 1 for load weight= 3.8511 (from Table 4.19) and so on.  $\bar{T}$  is the mean of all MRSN = 2.7257 (from Table 4.18)

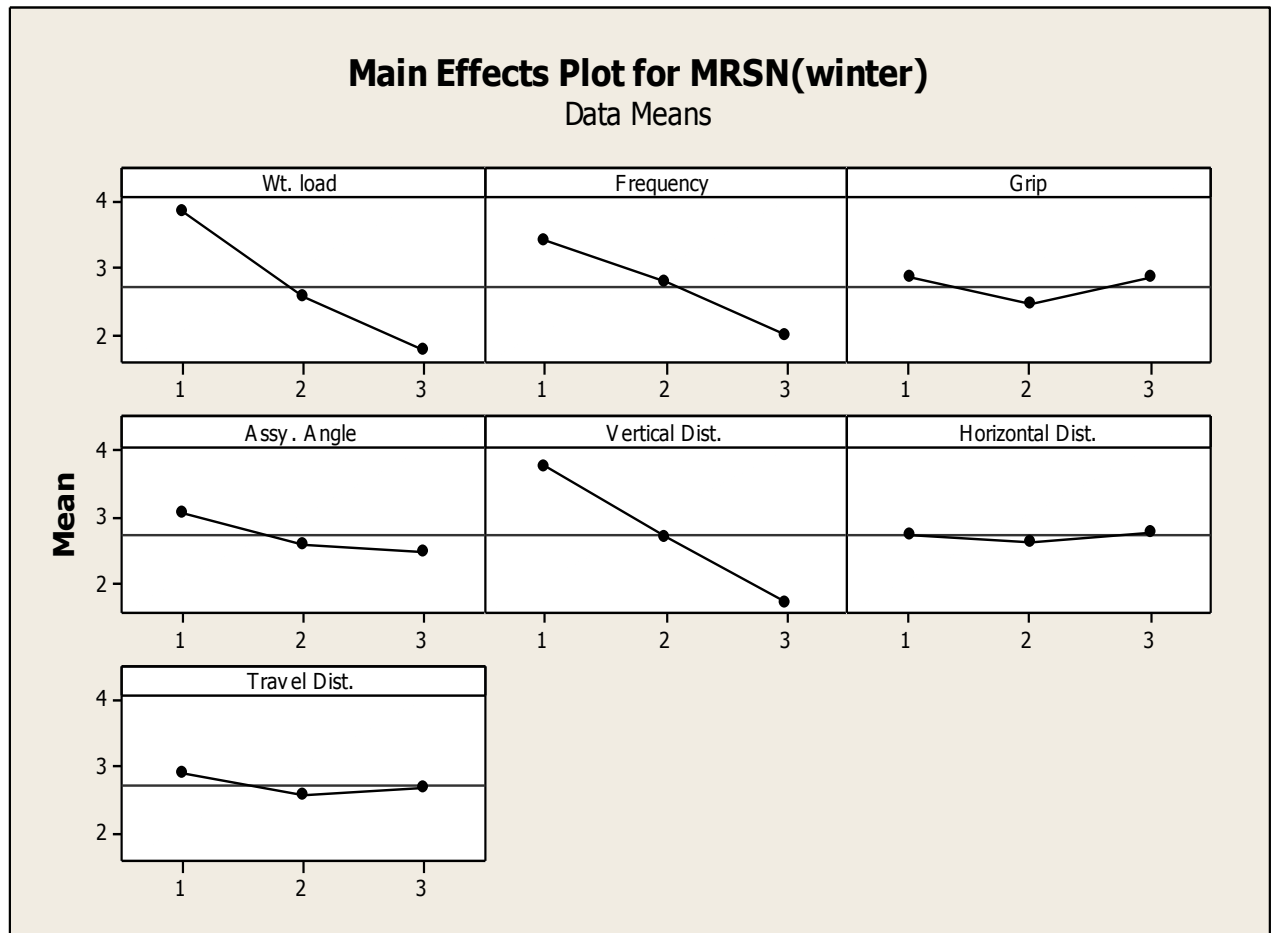


Figure 4.14: Main Effects Plot for MRSN (winter)

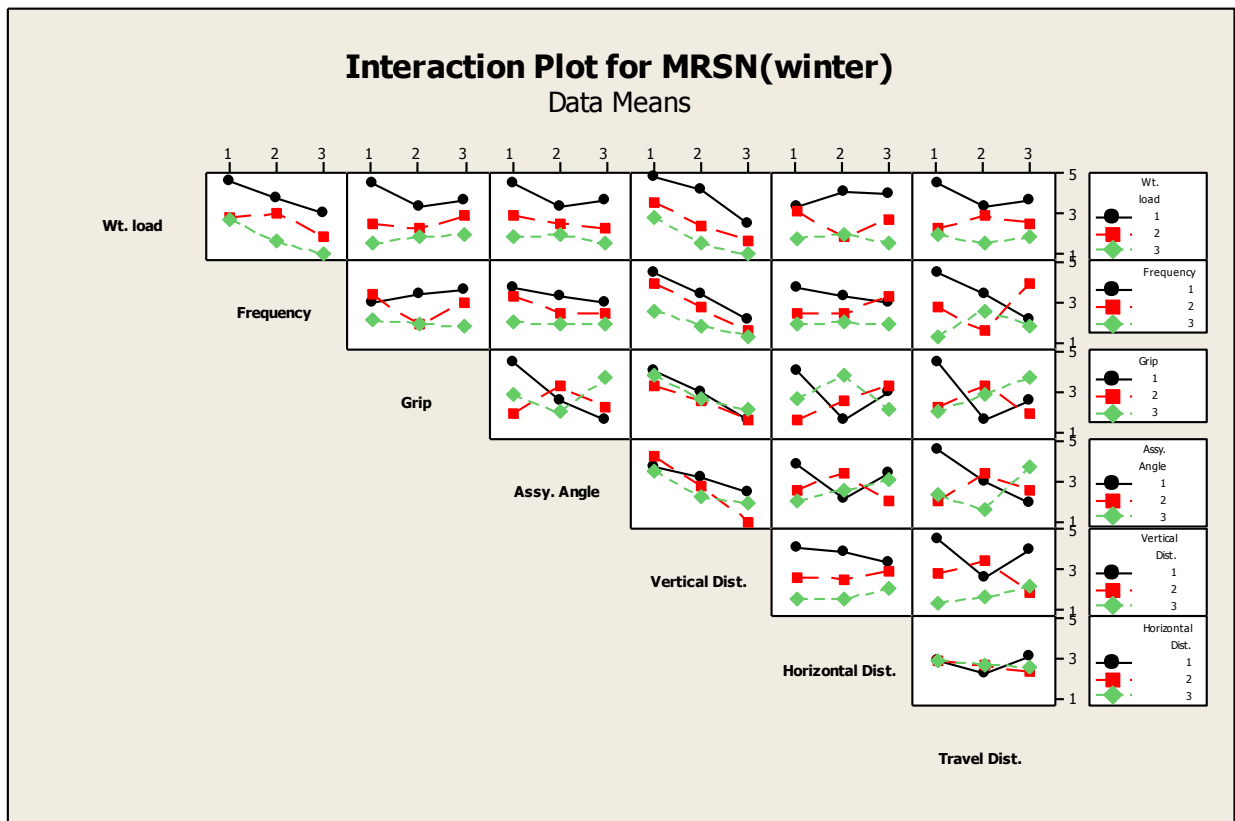


Figure 4.15: Interaction plot for MRSN (winter)

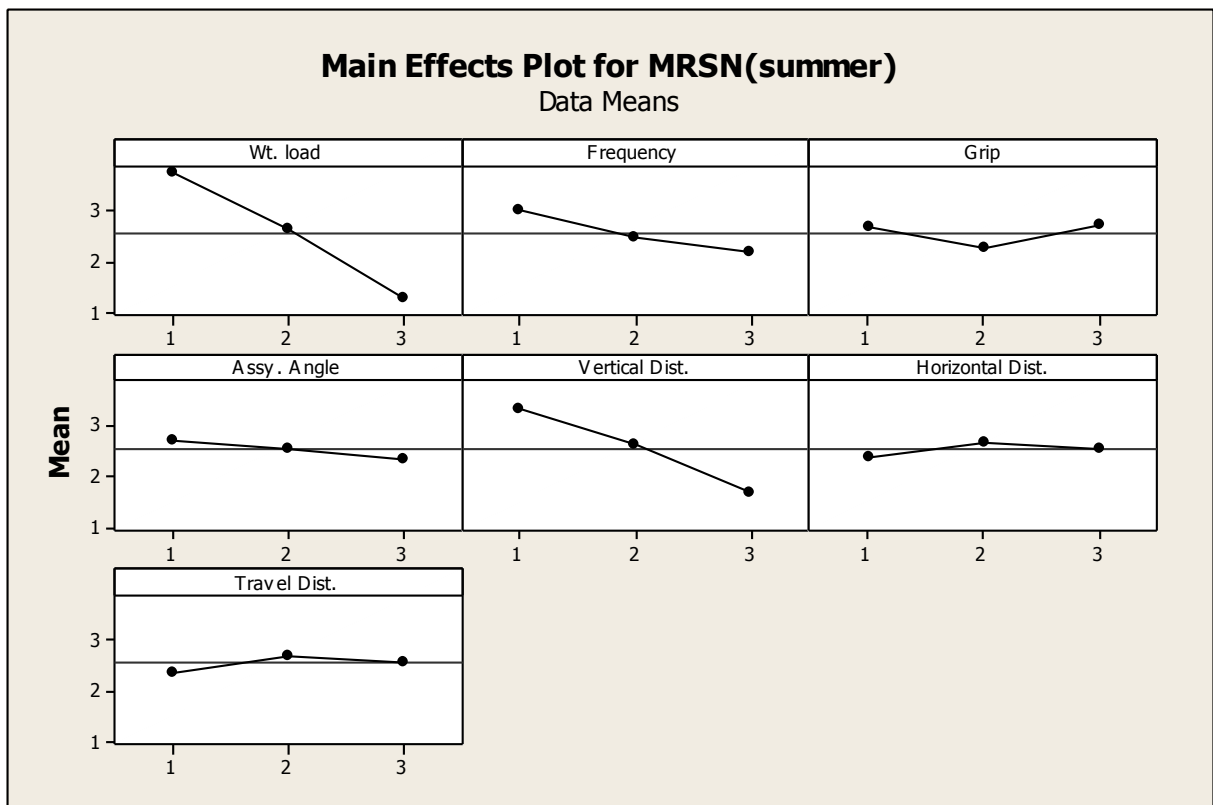


Figure 4.16: Main Effects Plot for MRSN (summer)

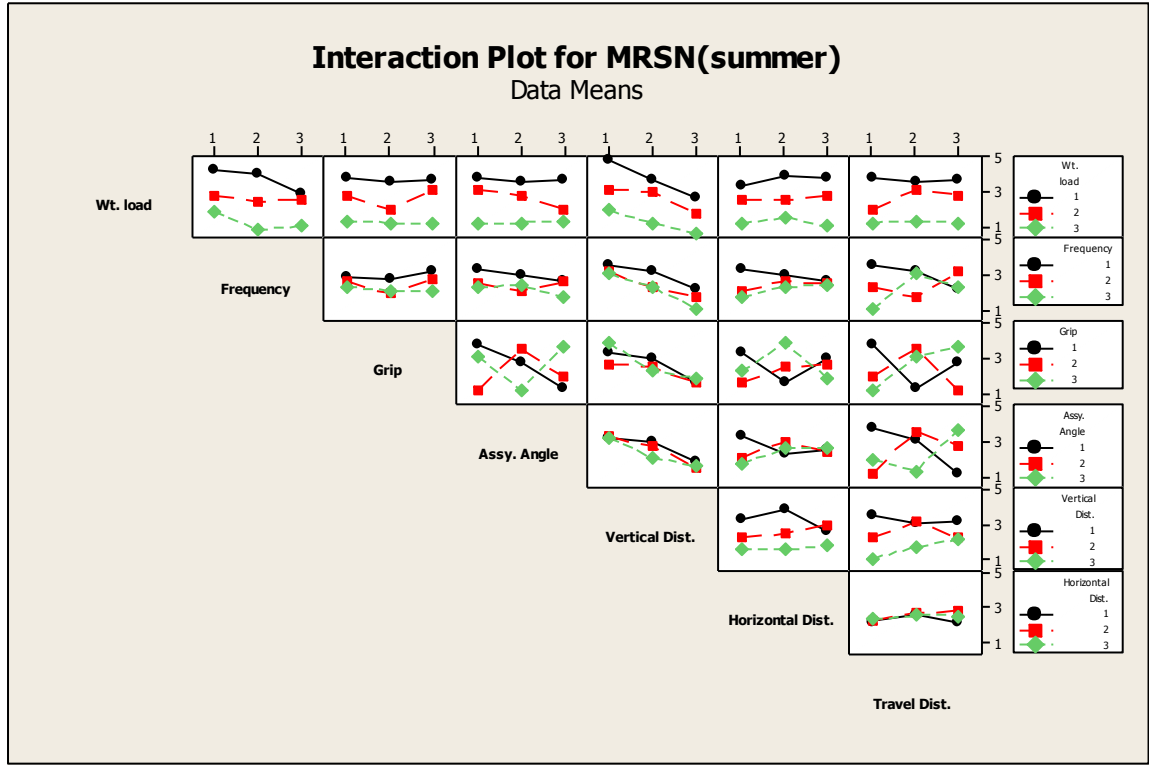


Figure 4.17: Interaction plot for MRSN (summer)

The above methodology is used to calculate the maximized MRSN ratio (summer) for all the trial conditions and is given below:

$$\overline{MRSN} = \overline{MRSN}_{Loadweight_t} + \overline{MRSN}_{frequency_{\chi}} + \overline{MRSN}_{grip_3} + \overline{MRSN}_{aangle} + \overline{MRSN}_{v.distance_1} + \overline{MRSN}_{H.distance_2} + \overline{MRSN}_{T.distance_2} - 4\bar{T} = 10.6807 \text{ (summer)}$$

Where  $\overline{MRSN}_{Loadweight_t}$  represents the maximum mean multi-response S/N ratio at level 1 for load weight = 3.7288 (from Table 4.20) and so on.  $\bar{T}$  is the mean of all MRSN = 2.5460 (from Table 4.18)

The maximized MRSN ratio has been calculated with three significant contributing levels to obtain the most optimal settings which would lead to minimize the exertion during lifting task.

$$\begin{aligned} MRSN &= \overline{MRSN}_{Loadweight_t} + \overline{MRSN}_{frequency_{\chi}} + \overline{MRSN}_{v.distance_1} - 2\bar{T} \\ &= 3.8511 + 3.4002 + 3.7588 - 2 \times 2.7257 = 5.5587 \text{ (winter)} \end{aligned}$$

$$\begin{aligned} MRSN &= \overline{MRSN}_{Loadweight_t} + \overline{MRSN}_{frequency_{\chi}} + \overline{MRSN}_{v.distance_1} - 2\bar{T} \\ &= 3.7288 + 3.0097 + 3.3129 - 2 \times 2.5460 = 4.9594 \text{ (summer)} \end{aligned}$$

Confidence Interval was calculated for around the estimated maximum MRSN value at  $\alpha$  level of 0.05(95%) which is given below

$$CI = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} = 0.7508 \text{ (winter)}$$

Where  $F_{\alpha, v_1, v_2} = 4.6001$ ,  $v_1 = \text{dof for mean which is always 1}$ ,  $v_2 = \text{dof for pooled error} = 14$ ,  
 $V_e = \text{variance of pooled error} = 0.4727$  (Table 4.21),

$$CI = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}} = 0.5563 \text{ (summer)}$$

Where  $F_{\alpha, v_1, v_2} = 4.4940$ ,  $v_1 = \text{dof for mean which is always 1}$ ,  $v_2 = \text{dof for pooled error} = 16$ ,  
 $V_e = \text{variance of pooled error} = 0.26564$  (Table 4.22),

$N = \text{Total number of trials} = 27$  and  $n_{eff} = \text{Number of tests under that condition using the participating factors, which is calculated as under:}$

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

Thus, the maximum MRSN (winter) is expected to lie between  $11.7346 \pm 0.7508$  at 95% confidence level and the maximum MRSN (summer) is expected to lie between  $10.6807 \pm 0.5563$  at 95% confidence level.

#### 4.6.4 Regression Analysis for MRSN

The regression analysis was completed using load weight, vertical distance and frequency as the predictors. The insignificant factors (coupling (grip), asymmetric angle, horizontal distance and travel distance) were counted as not useful predictors for regression equation and removed for developing an empirical model. The analysis of variance was used for regression equation which is given in Table 4.23. The last column of F and P values in the table explain the significance of the model. Predictor coefficients of the significant factors are shown in Table 4.24. The value of R-Sq interprets that approximately how much percent of the total variation in MRSN is explained by the model. S value means the standard deviation of the random error. The regression equation of MRSN was evaluated and is given by:

*For winter*

$$MRSN = 9.09 - 1.04 W - 0.714 F - 1.02 V.D$$

*For summer*

$$MRSN = 7.39 - 1.23 W - 0.414 F - 0.809 V.D$$

where the W is load weight in kg, F frequency in lifts per minute and V.D vertical distance in cm. The above equations are in generalized form for winter and summer and can be used to predict the MRSN in different environmental conditions.

Table 4.23: Analysis of Variance for regression analysis for significance of model

| Source         | DOF | Winter  |        |       |         | Summer  |        |       |         |
|----------------|-----|---------|--------|-------|---------|---------|--------|-------|---------|
|                |     | Seq SS  | Adj MS | F     | p-value | Seq SS  | Adj MS | F     | p-value |
| Regression     | 7   | 49.3627 | 7.0518 | 15.49 | 0.000   | 43.0364 | 6.1481 | 20.18 | 0.0000  |
| Residual Error | 19  | 8.6518  | 0.4554 |       |         | 5.7890  | 0.3047 |       |         |
| Total          | 26  | 58.0145 |        |       |         | 48.8254 |        |       |         |

(DOF=Degree of Freedom, Seq SS=Sum of square, Adj MS=Variance)

Table 4.24: Regression analysis for MRSN

| Predictor         | Winter  |         |           |         | Summer   |         |         |           |
|-------------------|---------|---------|-----------|---------|----------|---------|---------|-----------|
|                   | Coef    | SE Coef | T         | P-value | Coef     | SE Coef | T       | P-value   |
| Constant          | 9.0915  | 0.8516  | 10.68     | 0.000   | 7.3909   | 0.6966  | 10.61   | 0.000     |
| Weight            | -1.0433 | 0.1591  | -6.56     | 0.000   | -1.2289  | 0.1301  | -9.45   | 0.000     |
| Vertical distance | -1.0215 | 0.1591  | -6.42     | 0.000   | -0.8087  | 0.1301  | -6.22   | 0.000     |
| Frequency         | -0.7142 | 0.1591  | -4.49     | 0.000   | -0.4142  | 0.1301  | -3.18   | 0.005     |
| S =               |         | R-Sq    | R-Sq(adj) |         | S =      |         | R-Sq    | R-Sq(adj) |
| 0.674801          |         | = 85.1% | = 79.6%   |         | 0.551984 |         | = 88.1% | = 83.8%   |

(Coef=coefficient, SE Coef= SE coefficient and others are regression analysis term)

#### 4.7 DEVELOPMENT OF A MULTIPLICATIVE EQUATION TO CALCULATE PREDICTED HEART RATE (PHR)

A generalized multiplicative equation has been developed on the lines of NIOSH lifting equation [128] which could be used for quick calculation of Predicted Heart Rate (PHR). This value can then be used for identifying a task as safe or unsafe depending on the maximum HR of the working population of the region where applied. The multiplicative equation uses the resting HR of the workers which is corrected by using correction coefficients for the four significant factors (i) load, (ii) lifting frequency (iii) vertical distance and (iv) ambient

temperature. In the best case, when each correction coefficient is 1, the PHR will be equal to the resting HR. The PHR can thus be given by equation 4.3.

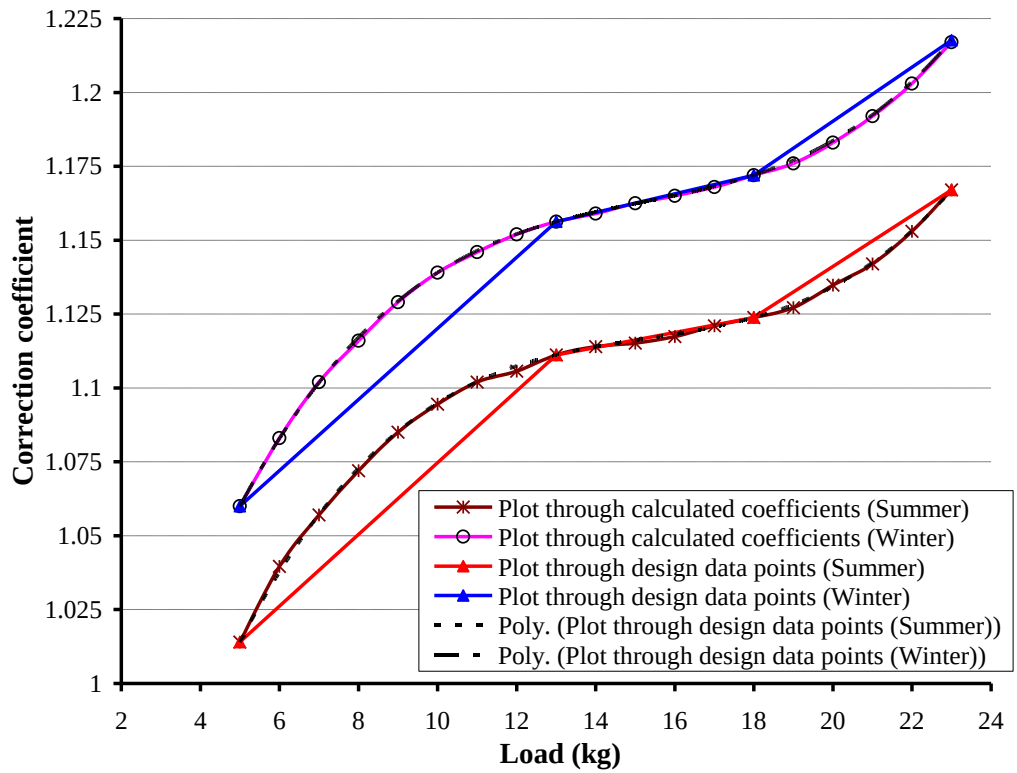
$$\text{PHR} = \text{RestingHR} \times \alpha(\text{Load}) \times \beta(\text{Lift frequency}) \times \gamma(\text{Vertical Distance}) \times \delta(\text{Ambient})$$

.....Equation (4.3)

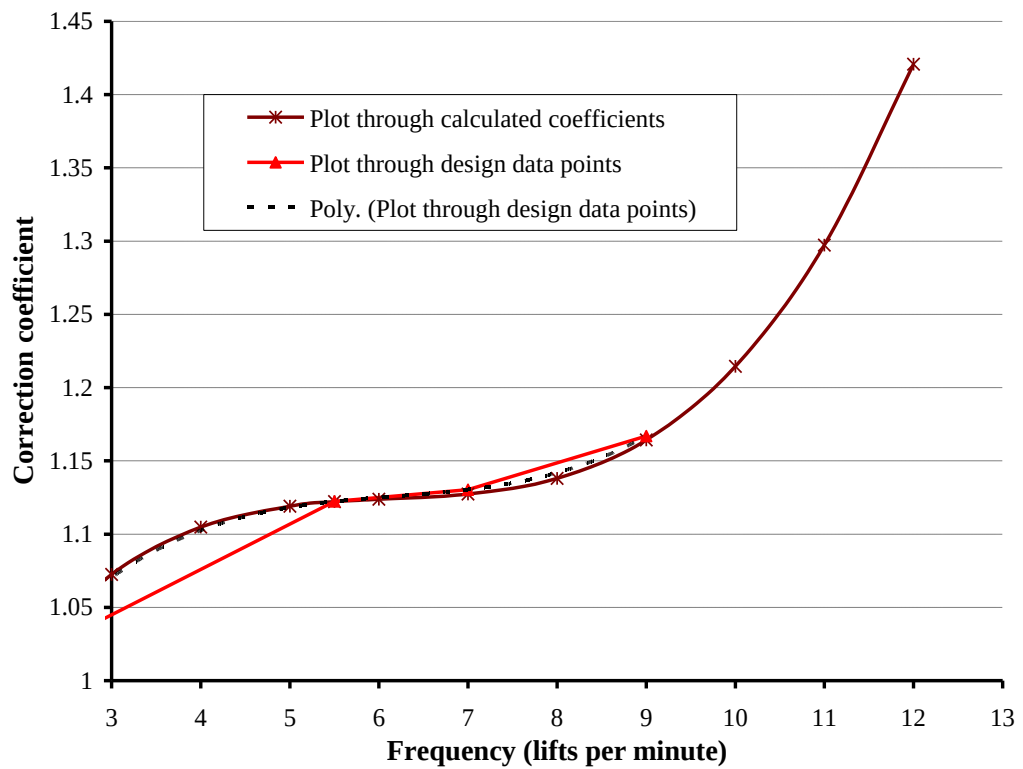
Where  $\alpha$ ,  $\beta$  and  $\gamma$  are the correction coefficients (CC) for the three significant factors and  $\delta$  is a constant value depicting the ambient temperature conditions affecting HR.

#### 4.7.1 Determining the Correction Coefficients

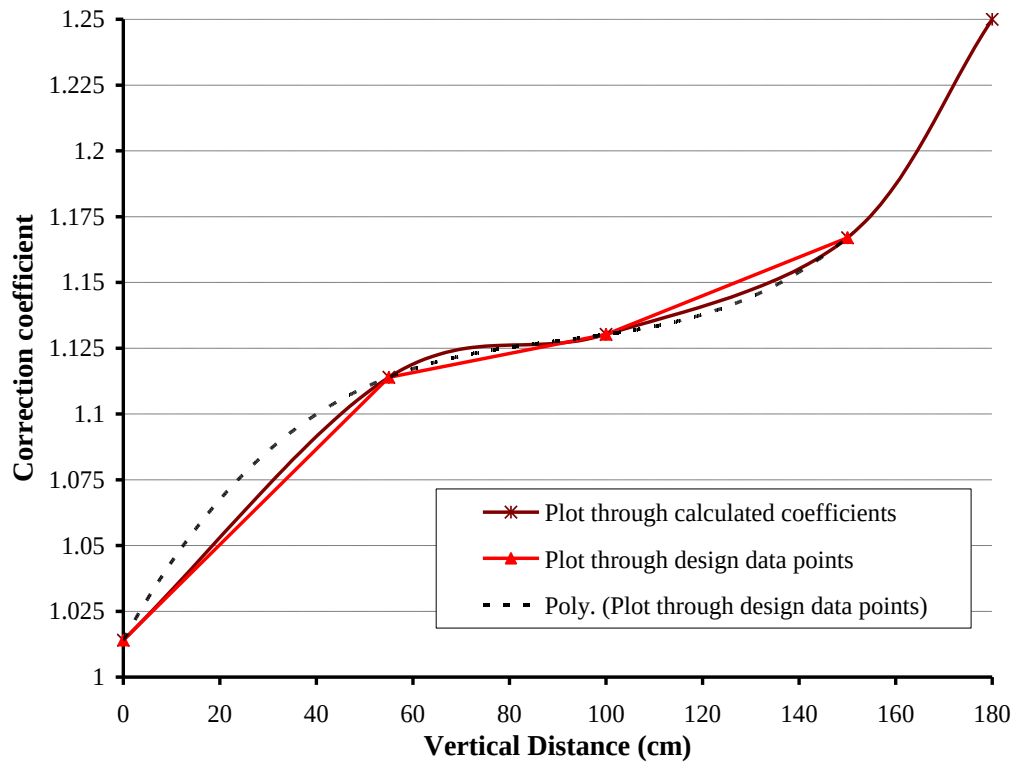
Since the PHR equation uses the resting HR as the base parameter, the value of the correction coefficients for the three factors as well as  $\epsilon$  should be 1 in the resting state. The methodology used for obtaining correction coefficients for the three significant factors has been discussed in this section. Light and mild lifting task requirements were identified by interacting with industry experts and users and were assumed to be (Load < 5kg; lifting frequency < 2 lifts/min.; and vertical distance: 0 at ground level). The operators who participated in this study were asked to replicate these task parameters to obtain a mean HR as described in earlier sections. Mean HR for mild lifting tasks during summer was obtained as 75 beats/min and in winter was 85 beats/min. By substituting this value in equation (4.3), the starting correction coefficient (1.014 for summer and 1.06 for winter) for load, lifting frequency and vertical distance were obtained assuming all three being equal at this lowest level. The correction coefficients for the three levels were thereafter obtained using the mean HR data (from Table 4.10) at each level of the three factors. The four data points thus obtained for each factor were plotted and a third degree polynomial equation was fitted to calculate the correction coefficients of the entire range (load 5-23 kg; lift frequency 2-12 lifts/min; and vertical distance 0 to 180 cm). The plots are shown in Figure 4.18(a), 4.18(b) and 4.18(c). The x and the y axis on the plots show the level settings for the three factors and the corresponding correction coefficient during summer. As discussed earlier, the mean HR increased during winter compared to summer. The increase was observed to even higher at higher lifting frequency. Figure 4.18(a) also shows the polynomial curve for winter data to obtain a correction coefficient for ambient temperature. The two curves show three different slopes (1<sup>st</sup> for load < 13kg showing a percentage increase in HR by 12.5 percent; 2<sup>nd</sup> for load between 13 & 18 kg showing percentage increase in HR by 13 percent ; and 3<sup>rd</sup> for load > 18 kg showing a percentage increase in HR by 11.5 percent). Based on this discussion, the correction factor for ambient temperature was set at 1 for summer and a corresponding increase in the coefficient by 12.5 percent for winter data.



(a)



(b)



(c)

Figure 4.18: Correction coefficients plot for three significant factors over the entire range; (a) for load, (b) for lift frequency and (c) for vertical distance

The calculated correction coefficients for the three factors are shown in Table 4.25. The PHR can be calculated for any combination of the three factors; load, lifting frequency and vertical distance using the correction coefficients given in Table 4.25 and the multiplicative equation along with a correction coefficient for ambient temperature. The PHR can serve as an indicator of perceived exertion in a lifting task by comparing it to the acceptable level of the working HR which is approximately 65% of the maximum working HR (Bridger [18]).

#### 4.7.2 Sample PHR Calculation for Load of 20 kg at a Frequency of 7 lifts/min up to a Height 100 cm for Winter

The correction coefficients for load, lifting frequency and vertical distance are 1.135, 1.127 and 1.1302 respectively (from Table 4.26). The correction coefficient for ambient condition has been taken as 1.125 for winter.

$$\begin{aligned} \text{PHR} &= \text{RestingHR} \times \alpha(\text{Load}) \times \beta(\text{Lift frequency}) \times \gamma(\text{Vertical Distance}) \times \delta(\text{Ambient}) \\ &= 71 \times 1.135 \times 1.127 \times 1.1302 \times 1.125 = 115.47 \text{ beats/minute (winter)} \end{aligned}$$

Table 4.25: Correction Coefficients (CC) for the different levels of the significant factors and ambient temperature

| Load (kg) | $\alpha$ (CC for load) | Frequency (lift/min) | $\beta$ (CC for frequency) | Vertical distance (cm) | $\gamma$ (CC for VD) | Ambient condition | $\delta$ (CC for ambient condition) |
|-----------|------------------------|----------------------|----------------------------|------------------------|----------------------|-------------------|-------------------------------------|
| 5         | 1.014                  | 2                    | 1.014                      | 0 (ground)             | 1.014                | Summer            | 1                                   |
| 6         | 1.040                  | 3                    | 1.073                      | 55 (knee)              | 1.1139               | Winter            | 1.125                               |
| 7         | 1.057                  | 4                    | 1.105                      | 110 (waist)            | 1.1302               |                   |                                     |
| 8         | 1.072                  | 5                    | 1.119                      | 150 (shoulder)         | 1.167                |                   |                                     |
| 9         | 1.085                  | 6                    | 1.124                      | 180 (overhead)         | 1.25                 |                   |                                     |
| 10        | 1.095                  | 7                    | 1.127                      |                        |                      |                   |                                     |
| 11        | 1.102                  | 8                    | 1.138                      |                        |                      |                   |                                     |
| 12        | 1.106                  | 9                    | 1.164                      |                        |                      |                   |                                     |
| 13        | 1.111                  | 10                   | 1.215                      |                        |                      |                   |                                     |
| 14        | 1.114                  | 11                   | 1.297                      |                        |                      |                   |                                     |
| 15        | 1.115                  | 12                   | 1.421                      |                        |                      |                   |                                     |
| 16        | 1.117                  |                      |                            |                        |                      |                   |                                     |
| 17        | 1.121                  |                      |                            |                        |                      |                   |                                     |
| 18        | 1.124                  |                      |                            |                        |                      |                   |                                     |
| 19        | 1.127                  |                      |                            |                        |                      |                   |                                     |
| 20        | 1.135                  |                      |                            |                        |                      |                   |                                     |
| 21        | 1.142                  |                      |                            |                        |                      |                   |                                     |
| 22        | 1.153                  |                      |                            |                        |                      |                   |                                     |
| 23        | 1.167                  |                      |                            |                        |                      |                   |                                     |

#### 4.7.3 PHR Index

In order to provide a quick guide to assess a lifting task, a PHR index has been proposed. The PHR index is the ratio of calculated PHR value to the safe/accepted limit of HR (65 percent of the maximum working HR) and is given by equation 4.4.

$$\text{PHR} = \frac{\text{Calculated PHR}}{\text{Acceptable HR}} \quad \text{.....Equation (4.4)}$$

If the PHR index is less than 1, it can be considered as a safe task and for a value of greater than 1, it would be a potentially unsafe task. A study sheet for quick evaluation of a lifting task using HR has been designed and is given in Figure 4.19.

| Assessment chart for determination of safe lifting task using heart rate measurement                                                                                         |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|-------------------------------------|--|---------------------------|----------------------|
| Plant:                                                                                                                                                                       |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           | Location:                           |  |                           |                      |
| Brief task Description                                                                                                                                                       |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
| Names of workmen involved:                                                                                                                                                   |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
| Resting heart rate, RHR (beats/min)                                                                                                                                          |                           |                                   |                                                                                                                                                                                               | $\text{Mean resting heart rate, RHR}_{\text{mean}} = \frac{\sum_{j=1}^N a_j}{N}$ <p>Where, <math>a_j</math> is the resting heart rate of the individual workman, N= total number of persons measured</p> |                           |                                     |  |                           |                      |
| Predicated Heart Rate (PHR) = $\text{RHR}_{\text{mean}} \times \text{CC (Load)} \times \text{CC (Freq)} \times \text{CC (Vertical. D)} \times \text{CC (Ambient condition)}$ |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
| Load<br>(Kg)                                                                                                                                                                 | Correction<br>Coefficient | Load<br>(Kg)                      | Correction<br>Coefficient                                                                                                                                                                     | Lift<br>Freq.                                                                                                                                                                                            | Correction<br>Coefficient | Vertical<br>Distance                |  | Correction<br>Coefficient | Ambient<br>condition |
| 5                                                                                                                                                                            | 1.014                     | 14                                | 1.114                                                                                                                                                                                         | 2                                                                                                                                                                                                        | 1.014                     | 0                                   |  | 1.014                     | Summer<br>1.0        |
| 6                                                                                                                                                                            | 1.040                     | 15                                | 1.115                                                                                                                                                                                         | 3                                                                                                                                                                                                        | 1.073                     | 55                                  |  | 1.1139                    |                      |
| 7                                                                                                                                                                            | 1.057                     | 16                                | 1.117                                                                                                                                                                                         | 4                                                                                                                                                                                                        | 1.105                     | 110                                 |  | 1.1302                    | Winter<br>1.125      |
| 8                                                                                                                                                                            | 1.072                     | 17                                | 1.121                                                                                                                                                                                         | 5                                                                                                                                                                                                        | 1.119                     | 150                                 |  | 1.167                     |                      |
| 9                                                                                                                                                                            | 1.085                     | 18                                | 1.124                                                                                                                                                                                         | 6                                                                                                                                                                                                        | 1.124                     | 180                                 |  | 1.25                      |                      |
| 10                                                                                                                                                                           | 1.095                     | 19                                | 1.127                                                                                                                                                                                         | 7                                                                                                                                                                                                        | 1.127                     |                                     |  |                           |                      |
| 11                                                                                                                                                                           | 1.102                     | 20                                | 1.135                                                                                                                                                                                         | 8                                                                                                                                                                                                        | 1.138                     |                                     |  |                           |                      |
| 12                                                                                                                                                                           | 1.106                     | 21                                | 1.142                                                                                                                                                                                         | 9                                                                                                                                                                                                        | 1.164                     |                                     |  |                           |                      |
| 13                                                                                                                                                                           | 1.111                     | 22                                | 1.153                                                                                                                                                                                         | 10                                                                                                                                                                                                       | 1.215                     |                                     |  |                           |                      |
|                                                                                                                                                                              |                           | 23                                | 1.167                                                                                                                                                                                         | 11                                                                                                                                                                                                       | 1.297                     |                                     |  |                           |                      |
|                                                                                                                                                                              |                           |                                   |                                                                                                                                                                                               | 12                                                                                                                                                                                                       | 1.421                     |                                     |  |                           |                      |
| PHR Index Calculation                                                                                                                                                        |                           |                                   | $\text{PHR}_{\text{index}} = \frac{\text{Calculated PHR}}{\text{Safe HR}} = \frac{\text{PHR}}{0.65 \text{ MWHR}}$ <p>Where Safe HR is considered 65% of maximum working heart rate (MWHR)</p> |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
| Decision                                                                                                                                                                     |                           | PHR <sub>index</sub> ≤ 1 (Accept) |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           | PHR <sub>index</sub> > 1 (Redesign) |  |                           |                      |
| Remarks (if any)                                                                                                                                                             |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           |                                     |  |                           |                      |
| Date of study:                                                                                                                                                               |                           |                                   |                                                                                                                                                                                               |                                                                                                                                                                                                          |                           | Assessed by:                        |  |                           |                      |

Figure 4.19: Assessment chart for determination of safe lifting task using heart rate measurement

#### 4.7.4 Confirmation Experiment

A confirmation experiment to validate the theoretically calculated PHR with the actual HR was undertaken for some sample combinations of load, lifting frequency and vertical distance. The results of this test validated the theoretical calculation of PHR made using equation 4.4 as the difference in the results was found to be insignificant using the standard t-test.

## CHAPTER 5

### PREDICTED OXYGEN UPTAKE

The effect of lifting parameters and their interactions on the oxygen uptake of Indian male workers involved in manual lifting tasks was investigated without consideration of ambient temperature conditions. The factors and their associated levels were chosen on the basis of a pilot experiment by varying one factor at a time and are given in Table 5.1. After completing a pilot study, factors: load, frequency of lift, asymmetric angle, vertical distance and travel distance were identified using the Taguchi experimental design. The COSMED pulmonary function equipment was used to measure the principal response oxygen uptake. Resting metabolic rate of all the eight workers was measured to ensure that no one had very high or low metabolism. The maximum aerobic capacity in terms of maximum oxygen uptake was also measured for each worker using the standard treadmill test. The workers were made to run on the treadmill to their maximum capacity until a clear plateau of the oxygen uptake versus time was obtained. The point after which the oxygen uptake remained unchanged is defined as  $VO_{2max}$ . The demographic details and metabolic capacity of the workers were recorded as per the requirement of the experimental study. As all workers had similar resting metabolic rate, the same was not normalized after they completed the task as per the various trial conditions of the experiment.

Table 5.1: Factors studied with their levels in second part of the study of first phase

| Factors                            | Levels    |             |                |
|------------------------------------|-----------|-------------|----------------|
|                                    | Level – 1 | Level – 2   | Level – 3      |
| Travel distance, A (cm)            | 25        | 45          | 60             |
| Load, B (kg)                       | 13        | 18          | 23             |
| Lifting frequency, C (lifts/min)   | 5         | 7           | 9              |
| Asymmetric angle, D ( $^{\circ}$ ) | 0         | 40          | 60             |
| Vertical distance, E (cm)          | 55 (Knee) | 110 (Waist) | 150 (Shoulder) |

#### 5.1 EXPERIMENTAL DESIGN

There are five factors varied during second part of the study of first phase. With each factor varied at three levels, two degrees of freedom (degree of freedom) is associated with each factor. Also, some interactions between the main factors were believed to be significant as per

the results of pilot study and were analyzed. Three interactions namely (i) load and frequency ( $B \times C$ ), (ii) load and vertical distance ( $B \times E$ ) and (iii) frequency and vertical distance ( $C \times E$ ) were studied to evaluate the effect on responses. A total of 12 degrees of freedom were associated with interactions. With five factors, each varied at three levels and interactions between these factors to be studied, the degrees of freedom required for designing an orthogonal experiment were calculated to be 22. In this experimental situation with three levels for each factor, a possible design matrix was a 27 trial Orthogonal Array (OA) labeled as  $L_{27}$  matrix. The 27 trials provide 26 degree of freedom for the entire experiment allocated to 13 columns of three levels with each column having two degree of freedom. The remaining four degrees of freedom available in the  $L_{27}$  array were utilized for calculating the unknown error that creeps in an experimental study and was measured by analyzing the unassigned columns in the  $L_{27}$  design matrix.

Each worker carried out asymmetrical free style continuous lifting of load from the ground position for all trial conditions for a period of 20 minutes. A rectangular shaped container with handle was used for lifting the load. At least one hour break was given between two trials to allow workers to fully recover from the fatigue. The pulmonary oxygen uptake (ml/kg-min) was considered as the principal response parameter.

The COSMED pulmonary function equipment was used to measure the principal responses oxygen uptake and heart rate simultaneously. It plots two curves for each of the two responses against time span. The oxygen uptake measurements were taken by putting the face oxygen mask on the workers with the help of belt. A heart rate probe (Polar belt) was clamped to the belt with the end of the probe connected to the main unit to measure the variation in heart rate versus time. The experimental time was noted using a stop watch. Measuring tape was used to setup the experimental layout viz horizontal distance, vertical distance etc. and anthropometrical data of subjects. The experimental setup is shown in Figure 5.1.

## **5.2 ANALYSIS OF OXYGEN UPTAKE**

Taguchi's  $L_{27}$  matrix was completed to measure oxygen uptake with two repetitions for each of the 27 trial conditions. Output from COSMED pulmonary function equipment had been collected for each trial to measure oxygen uptake. Two such plots have been shown in Figure 5.2 (a) and (b) corresponding to Trial 1 (where a low exertion was noticed) and Trial 12 (where a high exertion was noticed) respectively. The statistical calculations and the plots were completed using the MINITAB15 software. The mean oxygen uptake of eight workers for each

trial is shown in Table 5.2. The results were analyzed using Analysis of Variance (ANOVA) for identifying the significant factors and interactions affecting the response. The ANOVA data for the mean oxygen uptake is given in Table 5.3. The ANOVA table shows the F-value, p-value and percent contribution of each factor to identify the significance in affecting the response. As per the F-values, p-values and percent contribution load, lift frequency and vertical distance were found to be significant factors affecting oxygen uptake (for a confidence level of 99%). The other two factors asymmetric angle and travel distance as well as all the interactions were observed to be insignificant. The mean values (at each level) for all the five factors for oxygen uptake with their significance rank are shown in Table 5.4.



Figure 5.1: Worker involved in manual lifting task using COSMED pulmonary equipment

Table 5.2: Mean oxygen uptake of workers with L<sub>27</sub> experimental design

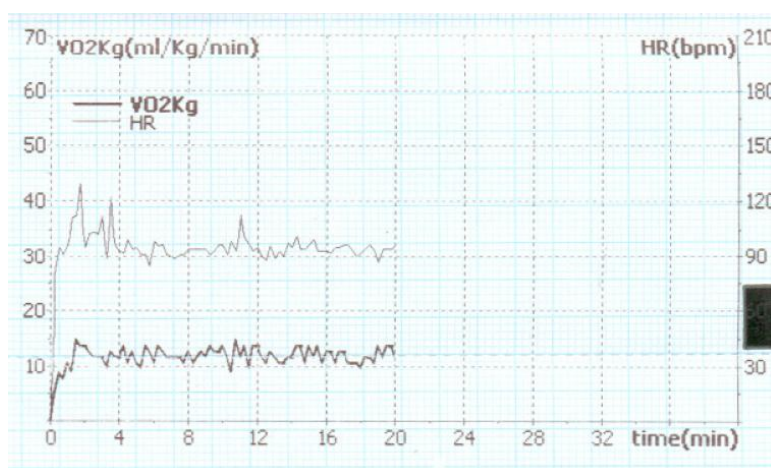
| Trial No. | Travel Distance (cm) | Load (kg) | Frequency (lifts/min) | Asymmetric Angle (°) | Vertical Distance (cm) | Mean oxygen uptake of eight workers (ml/kg-min) |                 |       |
|-----------|----------------------|-----------|-----------------------|----------------------|------------------------|-------------------------------------------------|-----------------|-------|
|           |                      |           |                       |                      |                        | One repetitions                                 | Two repetitions | Mean  |
| 1         | 25                   | 13        | 5                     | 0                    | 55                     | 6.9                                             | 7.3             | 7.1   |
| 2         | 25                   | 13        | 7                     | 40                   | 110                    | 7.4                                             | 7.88            | 7.64  |
| 3         | 25                   | 13        | 9                     | 60                   | 150                    | 13.91                                           | 13.12           | 13.51 |
| 4         | 45                   | 18        | 5                     | 0                    | 110                    | 8.3                                             | 7.9             | 8.1   |
| 5         | 45                   | 18        | 7                     | 40                   | 150                    | 12.11                                           | 12.59           | 12.3  |
| 6         | 45                   | 18        | 9                     | 60                   | 55                     | 12.9                                            | 13.3            | 13.1  |
| 7         | 60                   | 23        | 5                     | 0                    | 150                    | 11.3                                            | 11.1            | 11.2  |
| 8         | 60                   | 23        | 7                     | 40                   | 55                     | 12.1                                            | 12.7            | 12.4  |
| 9         | 60                   | 23        | 9                     | 60                   | 110                    | 16.3                                            | 15.4            | 15.85 |
| 10        | 45                   | 23        | 5                     | 60                   | 55                     | 9.35                                            | 9.48            | 9.41  |
| 11        | 45                   | 23        | 7                     | 0                    | 110                    | 13.23                                           | 14.05           | 13.64 |
| 12        | 45                   | 23        | 9                     | 40                   | 150                    | 15.98                                           | 16.47           | 16.23 |
| 13        | 60                   | 13        | 5                     | 60                   | 110                    | 8.9                                             | 8.3             | 8.6   |
| 14        | 60                   | 13        | 7                     | 0                    | 150                    | 10.75                                           | 10.86           | 10.8  |
| 15        | 60                   | 13        | 9                     | 40                   | 55                     | 11.27                                           | 11.34           | 11.3  |
| 16        | 25                   | 18        | 5                     | 60                   | 150                    | 10.19                                           | 10.21           | 10.2  |
| 17        | 25                   | 18        | 7                     | 0                    | 55                     | 10.52                                           | 10.68           | 10.6  |
| 18        | 25                   | 18        | 9                     | 40                   | 110                    | 13.78                                           | 13.82           | 13.8  |
| 19        | 60                   | 18        | 5                     | 40                   | 55                     | 8.89                                            | 8.91            | 8.90  |
| 20        | 60                   | 18        | 7                     | 60                   | 110                    | 10.62                                           | 10.58           | 10.6  |
| 21        | 60                   | 18        | 9                     | 0                    | 150                    | 15.15                                           | 15.51           | 15.3  |
| 22        | 25                   | 23        | 5                     | 40                   | 110                    | 10.46                                           | 10.67           | 10.56 |
| 23        | 25                   | 23        | 7                     | 60                   | 150                    | 15.64                                           | 16.21           | 15.9  |
| 24        | 25                   | 23        | 9                     | 0                    | 55                     | 14.08                                           | 15.12           | 14.6  |
| 25        | 45                   | 13        | 5                     | 40                   | 150                    | 8.18                                            | 8.6             | 8.4   |
| 26        | 45                   | 13        | 7                     | 60                   | 55                     | 8.82                                            | 9.37            | 9.1   |
| 27        | 45                   | 13        | 9                     | 0                    | 110                    | 13.12                                           | 13.73           | 13.4  |

Table 5.3: ANOVA table for oxygen uptake

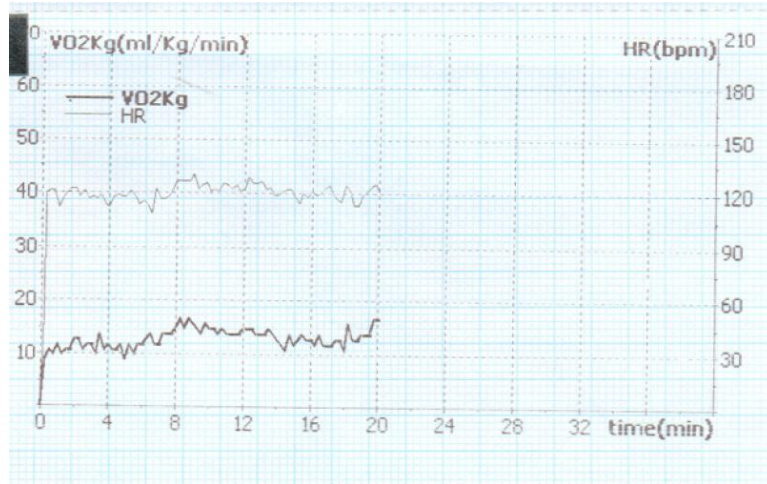
| Source                               | DOF | SS      | Variance | F-value | p-value | Percent contribution |
|--------------------------------------|-----|---------|----------|---------|---------|----------------------|
| Travel distance                      | 2   | 0.091   | 0.0455   | 0.08    | 0.926   | 0.08                 |
| Load                                 | 2   | 49.643  | 24.8216  | 42.52   | 0.002   | 24.99                |
| Frequency                            | 2   | 110.998 | 55.4991  | 95.08   | 0.000   | 57.03                |
| Asymmetric Angle                     | 2   | 1.305   | 0.6526   | 1.12    | 0.411   | 0.24                 |
| Vertical distance                    | 2   | 17.535  | 8.7676   | 15.02   | 0.014   | 8.23                 |
| Load $\times$ Frequency              | 4   | 5.242   | 1.3104   | 2.25    | 0.226   | 1.81                 |
| Load $\times$ Vertical distance      | 4   | 1.302   | 0.3254   | 0.56    | 0.707   | 0.24                 |
| Frequency $\times$ Vertical distance | 4   | 3.066   | 0.7664   | 1.31    | 0.399   | 0.67                 |
| Residual Error                       | 4   | 2.335   | 0.5887   |         |         | 0.29                 |
| Total                                | 26  | 191.516 |          |         |         | 100                  |

Table 5.4: Response table for means of oxygen uptake

| Level | Travel distance | Load   | Frequency | Asymmetric Angle | Vertical distance |
|-------|-----------------|--------|-----------|------------------|-------------------|
| 1     | 11.553          | 9.991  | 9.162     | 11.638           | 10.722            |
| 2     | 11.519          | 11.433 | 11.442    | 11.281           | 11.349            |
| 3     | 11.656          | 13.303 | 14.123    | 11.809           | 12.657            |
| Delta | 0.137           | 3.312  | 4.961     | 0.528            | 1.934             |
| Rank  | 5               | 2      | 1         | 4                | 3                 |



(a)



(b)

Figure 5.2: Fitmate Pro output for low and high exertion Trial condition (a) for Trial 1 and (b) for Trial 12

### 5.2.1 Main Effect and Interaction Plots

The main effect and interaction plots for oxygen uptake are shown in Figures 5.3 and 5.4 respectively. Main effect plots show the variation of oxygen uptake for each factor. The x-axis represents the three levels of factor and y-axis shows the resultant response value. The mean response has been indicated by a horizontal line. It can be observed from Figures 5.3 and 5.4, the oxygen uptake increases with the increase in lifting frequency, load and vertical distance. This increase is most prominent with increased lifting frequency. The plots for oxygen uptake also indicated that travel distance and asymmetric angle factors have no significant affect on the responses. The review of the interaction plots shows that none of the interactions were found to be significant for these trial conditions. Interaction plots are in agreement with the results obtained in Table 5.3 after ANOVA.

### 5.3 OPTIMAL DESIGN FOR OXYGEN UPTAKE

Three control factors namely (i) load, (ii) lifting frequency and (iii) vertical distance were identified as significant after ANOVA for oxygen uptake and their plots were used to establish their most appropriate level which will result in lower exertion and improved work conditions. The optimal design for the response would be meaningless in the traditional way defined by Taguchi wherein those levels are chosen which would lower the oxygen uptake thus causing least exertion to the workers. By using this method, if the oxygen uptake is to be minimized then keep the load, lifting frequency and vertical distance at the lowest level. However, such a solution will not be optimal as this would result in low labor productivity. An ideal solution will be to balance the task requirements and the setting of oxygen uptake.

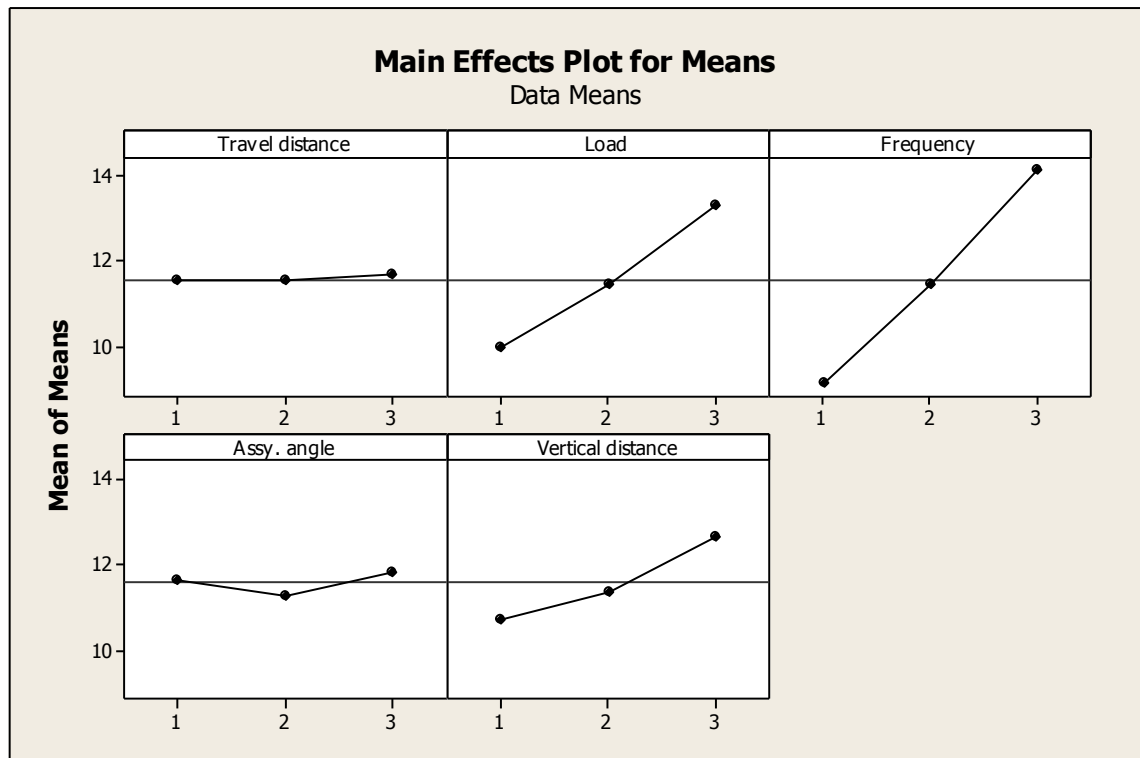


Figure 5.3: Main effects plot for mean oxygen uptake

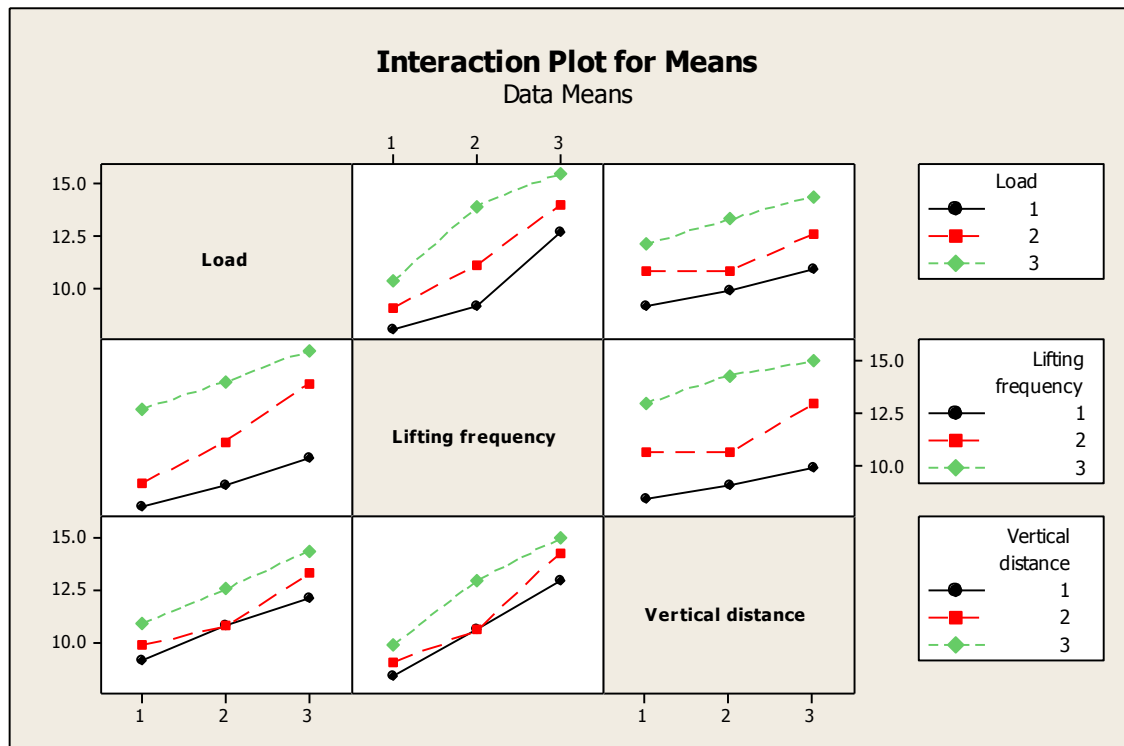


Figure 5.4: Interaction plot for mean oxygen uptake

In order to search for an optimal solution, the oxygen uptake values should be set at a level which would cause low to moderate exertion and then appropriately select the settings for the

three significant factors. The optimal setting for oxygen uptake is a measure of the maximum aerobic capacity of the workers and should not exceed 33% of an individual's maximum VO<sub>2</sub> uptake (maximum aerobic capacity over an 8-hour shift) (Bridger [18]). The mean aerobic capacity of the all workers was calculated to be 41.33 ml/kg-min. To prevent risks related to cardiovascular or musculoskeletal system, the energy expenditure should not exceed 33% of this value for work performed over a period of 8 hours. Using this as a benchmark, the oxygen uptake which would cause acceptable exertion to the workers is 13.64 ml/kg-min (33% of 41.33).

Three factors, load, lift frequency and vertical distance significantly affected the oxygen uptake as per ANOVA. All the 27 different combinations of these factors with three levels were obtained to calculate estimate mean oxygen uptake and are given in Table 4.27. The sample calculation is given in equation 5.1.

$$Oxy_{B_2C_2E_3} = \bar{B}_2 + \bar{C}_2 + \bar{E}_3 - 2\bar{T} = 11.433 + 11.442 + 12.657 - 2 \times 11.576 = 12.38 \text{ ml/kg-min.}$$

.....Equation (5.1)

Where  $Oxy_{B_2C_2E_3}$  is the estimated mean oxygen uptake when factor B (load) taken at level 2 (18 kg), factor C (lifting frequency) taken at level 2 (7 lifts/min), factor E (vertical distance) taken at level 3 (shoulder level, 152 cm) and  $\bar{T}$  is the mean of all responses.

As per the results obtained in Table 5.5, all the combinations of load lift frequency and vertical distance where the oxygen uptake is less than 13.64 ml/kg-min would be acceptable during manual lifting. All such combinations can be considered as safe tasks which would cause low to moderate exertion. The conditions in which the task becomes unacceptable are when the load to be lifted is 23 kg coupled with a frequency of more than 9 lifts/min and vertical distance is more than waist level high. Consequently, 4 different combinations of the three factors would cause high amount of exertion. All the remaining combinations would cause low to moderate exertion. The Figure 5.5 shows the bar chart of optimum mean oxygen uptake of 27 different combinations of the three significant factors namely (i) Factor B, load; (ii) Factor C, lift frequency and (iii) Factor E, vertical distance described in Table 5.5. Each trial on horizontal axis indicates one combination. For example, B1 C2 E3 to be read as: factor B (load) set at level 1 (13 kg), factor C (lift frequency) set at level 2 (7 lift/min) and factor E (vertical distance) set at level 3 (shoulder height) and so on. All the trials beyond the safe limit of oxygen uptake @ 13.64 ml/kg-min would cause high exertion to the workers and should be

treated as unsafe in the long run. All trials that are beyond the horizontal bold line in bar chart in Figure 5.5 depict the unsafe combinations of load, frequency and vertical distance.

Table 5.5: Mean and normalized oxygen uptake for different levels of three significant factors

| Load | Frequency | Vertical distance | Mean VO <sub>2</sub> | Normalized VO <sub>2</sub> |
|------|-----------|-------------------|----------------------|----------------------------|
| 13   | 5         | 55                | 6.723                | 0                          |
|      |           | 110               | 7.35                 | 0.06                       |
|      |           | 150               | 8.658                | 0.19                       |
|      | 7         | 55                | 9.003                | 0.22                       |
|      |           | 110               | 9.63                 | 0.28                       |
|      |           | 150               | 10.938               | 0.41                       |
|      | 9         | 55                | 11.684               | 0.49                       |
|      |           | 110               | 12.311               | 0.54                       |
|      |           | 150               | 13.619               | 0.68                       |
| 18   | 5         | 55                | 8.165                | 0.14                       |
|      |           | 110               | 8.792                | 0.20                       |
|      |           | 150               | 10.1                 | 0.33                       |
|      | 7         | 55                | 10.445               | 0.36                       |
|      |           | 110               | 11.072               | 0.42                       |
|      |           | 150               | 12.38                | 0.55                       |
|      | 9         | 55                | 13.126               | 0.62                       |
|      |           | 110               | 13.753               | 0.68                       |
|      |           | 150               | 15.061               | 0.81                       |
| 23   | 5         | 55                | 10.035               | 0.32                       |
|      |           | 110               | 10.662               | 0.38                       |
|      |           | 150               | 11.97                | 0.51                       |
|      | 7         | 55                | 12.315               | 0.54                       |
|      |           | 110               | 12.942               | 0.60                       |
|      |           | 150               | 14.25                | 0.73                       |
|      | 9         | 55                | 14.996               | 0.81                       |
|      |           | 110               | 15.623               | 0.87                       |
|      |           | 150               | 16.931               | 1                          |

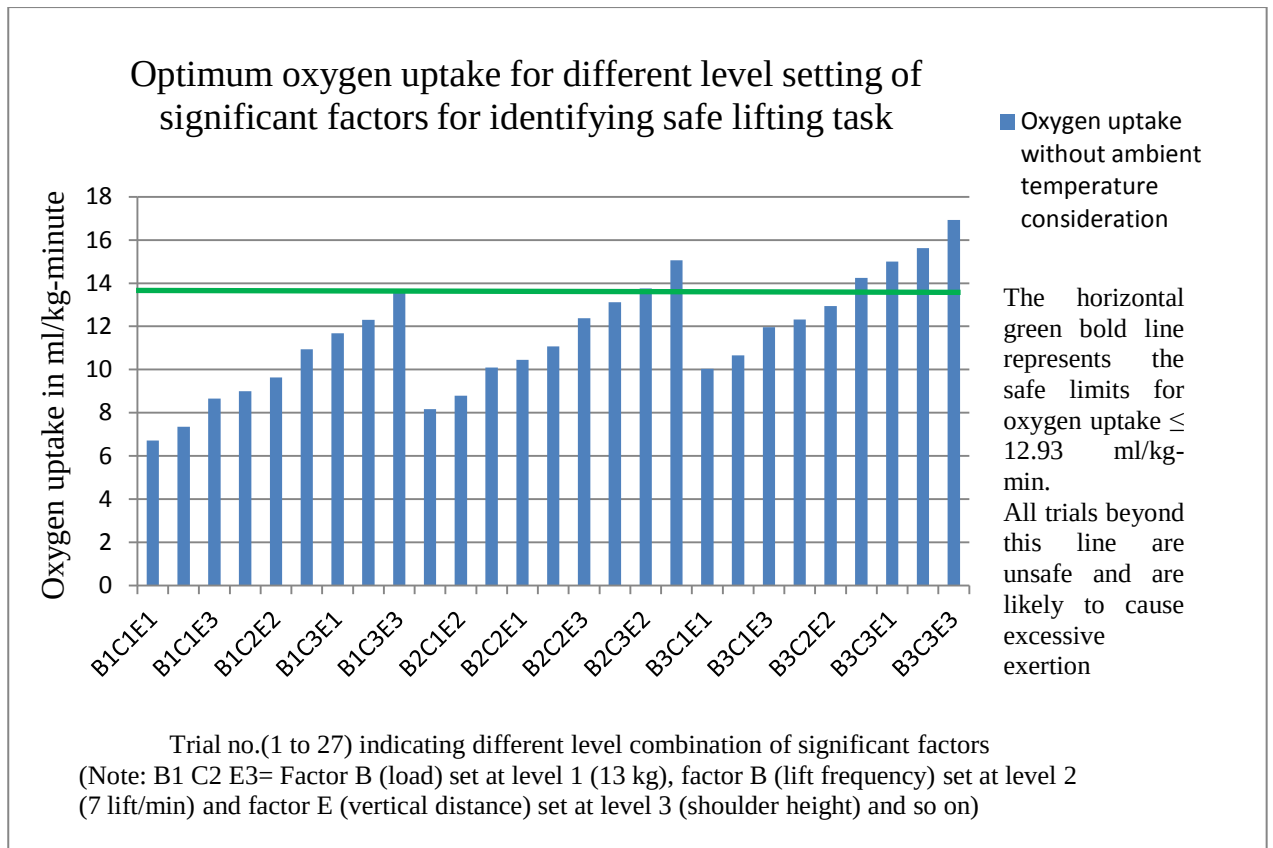


Figure 5.5: Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task

#### 5.4 DEVELOPMENT OF A MULTIPLICATIVE EQUATION TO CALCULATE PREDICTED OXYGEN UPTAKE (POU)

The optimal results obtained in Section 5.4 above are valid for this experimental study. A generalized multiplicative equation has been developed to calculate the Predicted Oxygen Uptake (POU) as likely to be NIOSH lifting equation (NIOSH [128]). The safe or unsafe lifting task can be evaluated using this POU value. The multiplicative equation uses the maximum aerobic capacity of the workers which is corrected by settings for the three significant parameters load, lifting frequency and vertical distance. In the worst case, when each multiplier is 1, the POU will be equal to the maximum aerobic capacity. The POU can thus be given by equation (5.2).

$$\text{POU} = \text{MAC} \times \text{CC}(\text{Load}) \times \text{CC}(\text{Lift frequency}) \times \text{CC}(\text{Vertical distance}) \dots \text{Equation (5.2)}$$

Where MAC is the mean maximum aerobic capacity of a group of workmen of a region/ country and CC is the correction coefficient for the three significant factors affecting the oxygen uptake ranging between 0 and 1.

### **Determining the Correction Coefficients**

The correction coefficient settings for the three factors have been obtained by using the following methodology as discussed here in this section.

The mean oxygen uptake values were linearly normalized using Equation 5.3 to obtain values between 0 and 1 and are given in last column of Table 5.5.

$$n_i = \frac{r_i - \min r_i}{\max r_i - \min r_i} \quad \dots\dots\dots \text{Equation (5.3)}$$

Where  $r_i$  is the response value of oxygen uptake for  $i^{\text{th}}$  trial. For the present case,  $i = 1, 2, 3 \dots\dots\dots 27$  (for 27 combinations). The purpose of normalization is to convert the oxygen uptake into an equivalent response scale where  $n_i$  will be unity for maximum oxygen uptake and zero for minimum oxygen uptake.

The mean normalized values of optimal oxygen uptake (at each level) for all the three significant factors are given in Table 5.6. These normalized values were plotted and is shown in Figure 5.6. The x and the y-axis on the plots show the level settings for the three factors and the corresponding normalized oxygen uptake. A polynomial curve was fitted through the three points thus obtained on the plots for each factor to interpolate or extrapolate the normalized oxygen uptake for the purpose of generalizing the results. The polynomial relation obtained after curve fitting are given in equations (5.4) to (5.6) for load, lifting frequency and vertical distance.

For load:  $y = 0.0007x^2 + 0.0047x + 0.1391 \quad \dots\dots\dots \text{Equation (5.4)}$

For lifting frequency:  $y = 0.00536x^2 + 0.0608x + 0.0002 \quad \dots\dots\dots \text{Equation (5.5)}$

For vertical distance:  $y = 1 \times 10^{-5}x^2 + 0.0002x + 0.3065 \quad \dots\dots\dots \text{Equation (5.6)}$

Where  $y$  is the estimated normalized oxygen uptake,  $x$  is the level setting for each factor and varies from 8 kg to 23 kg for load, 5 lifts/min to 12 lifts/min for lifting frequency and 0 to 180 cm for vertical distance. Thus, the generalization of results is possible in this range for the three significant factors during manual lifting. The generalized oxygen uptake after interpolation or extrapolation for the three factors is given in Table 5.7. A quick look at the

table shows that the normalized oxygen uptake varies between 0.22 (at 8 kg) to 0.61 (at 23 kg) for load, 0.23 (at 5 lifts/min) to 1.15 (12 lifts/min) for lift frequency and 0.32 (at floor level) to 0.67 (at overhead, 180 cm) for vertical distance.

Table 5.6: Response table of mean normalized oxygen uptake

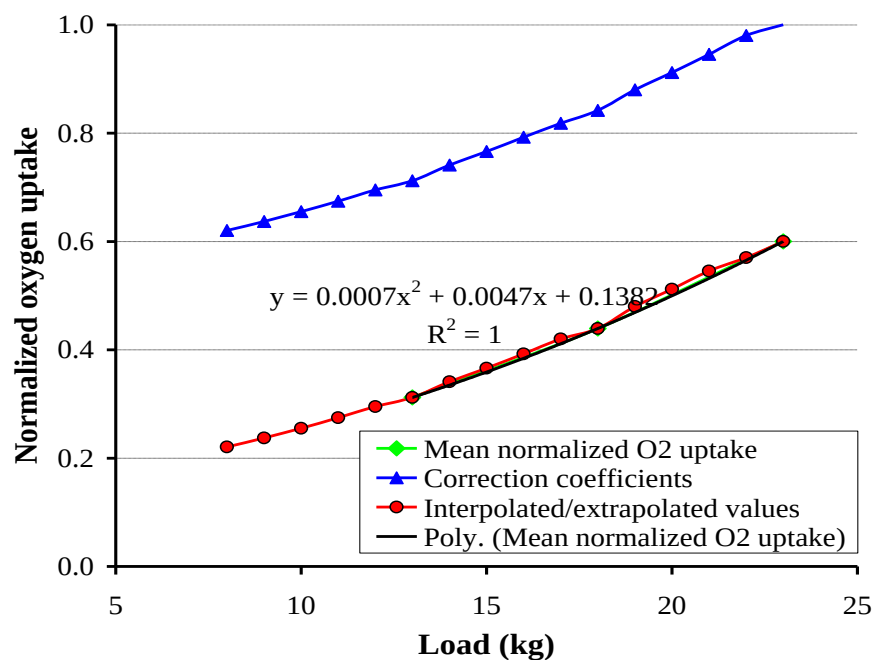
| Level | Load   | Frequency | Vertical Distance |
|-------|--------|-----------|-------------------|
| 1     | 0.3189 | 0.2366    | 0.3888            |
| 2     | 0.45   | 0.4566    | 0.4477            |
| 3     | 0.612  | 0.7222    | 0.5788            |

Table 5.7: Interpolated and extrapolated values of normalized oxygen uptake

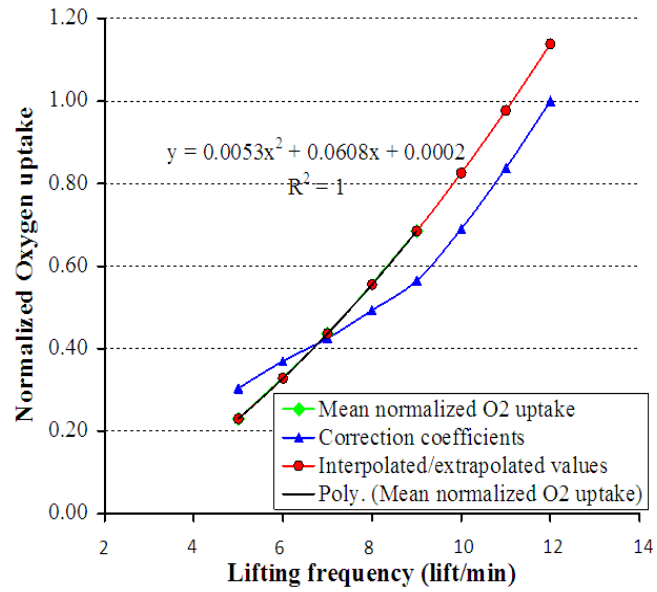
| Load (kg) | Interpolated/<br>extrapolated<br>values | Frequency (lifts/min) | Interpolated/<br>extrapolated<br>values | Vertical distance (cm) | Interpolated/<br>extrapolated<br>values |
|-----------|-----------------------------------------|-----------------------|-----------------------------------------|------------------------|-----------------------------------------|
| 23        | 0.612                                   | 12                    | 1.1492                                  | Overhead (180)         | 0.6665                                  |
| 22        | 0.591                                   | 11                    | 0.9926                                  | Shoulder (150)         | 0.57                                    |
| 21        | 0.553                                   | 10                    | 0.8434                                  | Waist (110)            | 0.44                                    |
| 20        | 0.529                                   | 9                     | 0.723                                   | Knee (55)              | 0.38                                    |
| 19        | 0.487                                   | 8                     | 0.5658                                  | Floor (0)              | 0.326                                   |
| 18        | 0.449                                   | 7                     | 0.451                                   |                        |                                         |
| 17        | 0.4284                                  | 6                     | 0.329                                   |                        |                                         |
| 16        | 0.4016                                  | 5                     | 0.2366                                  |                        |                                         |
| 15        | 0.3692                                  |                       |                                         |                        |                                         |
| 14        | 0.3462                                  |                       |                                         |                        |                                         |
| 13        | 0.3189                                  |                       |                                         |                        |                                         |
| 12        | 0.2961                                  |                       |                                         |                        |                                         |
| 11        | 0.2748                                  |                       |                                         |                        |                                         |
| 10        | 0.2551                                  |                       |                                         |                        |                                         |
| 9         | 0.2370                                  |                       |                                         |                        |                                         |
| 8         | 0.2203                                  |                       |                                         |                        |                                         |

The normalized oxygen uptake obtained in Table 5.5 has been translated in a way that the most exerting task (maximum load and lifting frequency and highest level of vertical distance) is given a correction coefficient of 1 which would result in POU equal to maximum aerobic capacity. The lowest level of the three parameters with this logic should be set at 0. However, with 0 as correction coefficient for the lower levels of three contributing factors, the POU will be equal to zero which means nothing. As the resting metabolic rate is about 3.5 ml/kg-min, the correction coefficient for the least exerting task (minimum load and lifting frequency and lowest level of vertical distance) should be greater than zero and should attain a certain value for the three factors so that POU is equal to 5.0 ml/kg-min which is little more than the resting metabolic rate. This was confirmed by conducting a study with load of 8 kg lifted at a frequency of 5 lifts per minute at the floor level.

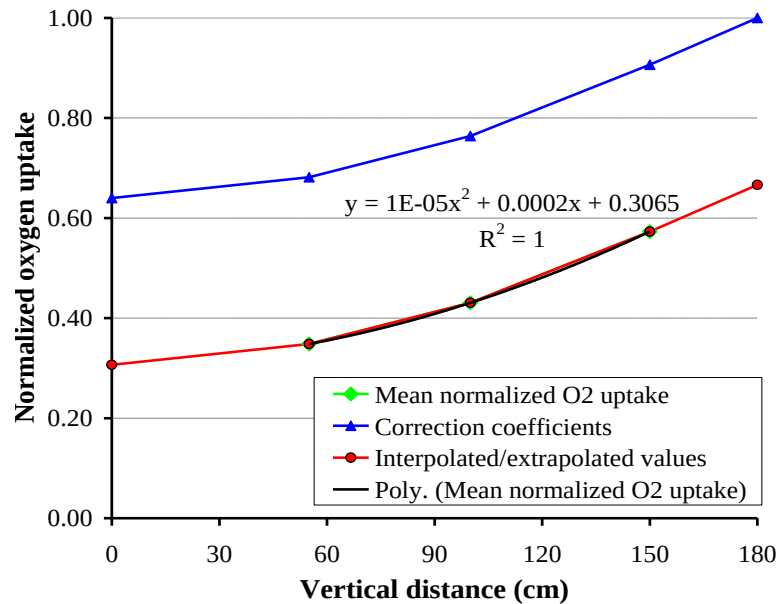
The modified correction coefficients for the three factors are given in Table 5.8 and have also been plotted as the modified curve on the plots shown in Figures 5.6 (a), (b) and (c). The modified curve shown in blue color has been used to calculate the correction coefficients for the three factors. The POU can be calculated for any combination of the three factors; load, lifting frequency and vertical distance using the correction coefficients given in Table 5.8 and the multiplicative equation (5.2). The POU can serve as an indicator of extent of exertion in a lifting task by comparing it to the acceptable level of the pulmonary oxygen uptake. The acceptable value of the oxygen uptake is 33% of the maximum aerobic capacity.



(a)



(b)



(c)

Figures 5.6 (a), (b) and (c): Plots of normalized oxygen uptake and correction coefficients for the three significant factors

#### 5.4.1 POU Calculation for Different Combination of Load, Frequency, Vertical Distance (one sample example)

Finding correction coefficients for load of 15 kg as 0.766, for frequency 7 lifts/min as 0.425 and for vertical distance 150 cm as 0.91 (from Table 5.8), POU can be calculated as under

$$\begin{aligned} \text{POU} &= \text{Maximum Aerobic Capacity} \times \text{CC}(\text{Load}) \times \text{CC}(\text{Freq}) \times \text{CC}(\text{VD}) \\ &= 41.33 \times 0.766 \times 0.425 \times 0.91 = 12.24 \text{ ml/kg} - \text{min} \end{aligned}$$

Where load 15 kg, frequency 7 lifts per minute and vertical distance shoulder height 150 cm for particular worker.

Table 5.8: Correction coefficients for the different levels of the three significant factors

| Load (kg) | Correction coefficient | Frequency (lifts/min) | Correction coefficient | Vertical distance (cm) | Correction coefficient |
|-----------|------------------------|-----------------------|------------------------|------------------------|------------------------|
| 23        | 1.000                  | 12                    | 1.000                  | 180                    | 1.00                   |
| 22        | 0.980                  | 11                    | 0.837                  | 150                    | 0.91                   |
| 21        | 0.946                  | 10                    | 0.690                  | 110                    | 0.76                   |
| 20        | 0.912                  | 9                     | 0.565                  | 55                     | 0.68                   |
| 19        | 0.880                  | 8                     | 0.493                  | 0                      | 0.64                   |
| 18        | 0.842                  | 7                     | 0.425                  |                        |                        |
| 17        | 0.818                  | 6                     | 0.369                  |                        |                        |
| 16        | 0.793                  | 5                     | 0.304                  |                        |                        |
| 15        | 0.766                  |                       |                        |                        |                        |
| 14        | 0.741                  |                       |                        |                        |                        |
| 13        | 0.712                  |                       |                        |                        |                        |
| 12        | 0.695                  |                       |                        |                        |                        |
| 11        | 0.675                  |                       |                        |                        |                        |
| 10        | 0.655                  |                       |                        |                        |                        |
| 9         | 0.637                  |                       |                        |                        |                        |
| 8         | 0.621                  |                       |                        |                        |                        |

#### 5.4.2 POU Index

A POU index has been evaluated to quick assess a lifting task. The POU index is the ratio of theoretical calculated POU value to the accepted limit of oxygen uptake (33% of the maximum aerobic capacity). A safe task and a potentially unsafe task can be identified as POU index is less than 1 and greater than 1 respectively.

An assessment chart designed to evaluate the task has been proposed for industry application and is given in Figure 5.7.

#### 5.4.3 Validation

The standard t-test (statistical tool) was used to validate the theoretical calculation of POU (from equation 5.2) for some sample combinations of load, lifting frequency and vertical

distance. It can be observed from results that theoretical value and the actual oxygen uptake are very much correlated.

| Assessment chart for determination of safe lifting task using oxygen uptake measurement |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
|-----------------------------------------------------------------------------------------|--------------------|----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------------|---------|
| Plant:                                                                                  |                    |                                                                                                                            |                                                                                                                                                                                     | Location:    |                        |         |
| Brief Task Description                                                                  |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
| Names of workmen involved:                                                              |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
| Maximum Aerobic Capacity (Mean) (MAC)                                                   |                    |                                                                                                                            | $\text{Mean Aerobic capacity} = \frac{\sum_{i=1}^N a_i}{N} = \dots\dots\dots$ Where, $a_i$ is the aerobic capacity of the individual workman, N = total number of persons involved. |              |                        |         |
| Predicted Oxygen Uptake (POU)                                                           |                    |                                                                                                                            | $\text{POU} = \text{MAC} \times \text{CC}(\text{Load}) \times \text{CC}(\text{Freq}) \times \text{CC}(\text{VD}) = \dots\dots\dots$                                                 |              |                        |         |
| Correction Coefficients (CC)                                                            |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | Load (kg)          | CC (Load)                                                                                                                  | Frequency (lifts/min)                                                                                                                                                               | CC (Freq)    | Vertical Distance (cm) | CC (VD) |
|                                                                                         | 23                 | 1.000                                                                                                                      | 12                                                                                                                                                                                  | 1.000        | 180                    | 1.00    |
|                                                                                         | 22                 | 0.980                                                                                                                      | 11                                                                                                                                                                                  | 0.8375       | 150                    | 0.91    |
|                                                                                         | 21                 | 0.946                                                                                                                      | 10                                                                                                                                                                                  | 0.69         | 110                    | 0.76    |
|                                                                                         | 20                 | 0.912                                                                                                                      | 9                                                                                                                                                                                   | 0.565        | 55                     | 0.68    |
|                                                                                         | 19                 | 0.880                                                                                                                      | 8                                                                                                                                                                                   | 0.493        | 0                      | 0.64    |
|                                                                                         | 18                 | 0.842                                                                                                                      | 7                                                                                                                                                                                   | 0.425        |                        |         |
|                                                                                         | 17                 | 0.818                                                                                                                      | 6                                                                                                                                                                                   | 0.3695       |                        |         |
|                                                                                         | 16                 | 0.793                                                                                                                      | 5                                                                                                                                                                                   | 0.304        |                        |         |
|                                                                                         | 15                 | 0.766                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 14                 | 0.741                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 13                 | 0.712                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 12                 | 0.695                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 11                 | 0.675                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 10                 | 0.655                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 9                  | 0.637                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | 8                  | 0.621                                                                                                                      |                                                                                                                                                                                     |              |                        |         |
| POU Index Calculation                                                                   |                    | $\text{POU}_{\text{index}} = \frac{\text{Calculated POU}}{\text{Safe VO}_2} = \frac{\text{POU}}{0.33 \times \text{MAC}} =$ |                                                                                                                                                                                     |              |                        |         |
|                                                                                         |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
| Decision                                                                                | POU ≤ 1 (Accept)   |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
|                                                                                         | POU > 1 (Redesign) |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
| Remarks (if any)                                                                        |                    |                                                                                                                            |                                                                                                                                                                                     |              |                        |         |
| Date of study:                                                                          |                    |                                                                                                                            |                                                                                                                                                                                     | Assessed by: |                        |         |

Figure 5.7: Assessment chart for determination of safe lifting task using oxygen uptake measurement

## CHAPTER 6

### SAFE LIMITS OF MANUAL LIFTING TASK PARAMETERS USING BIOMECHANICS PRINCIPLE

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Manual Material Handling (MMH) exposures are complex in nature. Manual lifting activities account for majority of back disorders or related health issues. Measurement of ground reaction forces in different planes is a good measure of the musculoskeletal stresses being exerted on the workers performing such tasks. Due to different environmental conditions (for example hot and humid weather) in India, such lifting tasks cause excessive exertion to the workers involved in such tasks. In this chapter, the details of experimentation related to the effect of lifting parameters (weight, frequency of lift, coupling (grip), posture (asymmetry), vertical distance, horizontal and travel distance) on vertical ground reaction forces and loading rate of human body in different dynamic manual lifting and carrying activities have been presented. The chapter also covers the determination of safe limits of significant factors for optimality of performance of the manual lifting task.

#### 6.1 EXPERIMENTAL DESIGN

Based on the results of a pilot study as well as of the first phase of the study, the factors namely load weight, frequency of lift, coupling (grip), posture (asymmetry), vertical and horizontal distance from load, travel distance were identified as control factors.

**Levels of Weight:** The maximum level for weight was set at 23 kg as given by NIOSH, Waters et al. [175]. Also, not much variation in  $F_z$  was observed with weight below 13 kg and lifting frequency of 5 lifts/min during the pilot study. The lower level of weight and frequency were selected which started to affect the  $F_z$  significantly. 13 kg weight and 5 lifts/min lifting frequency were thus selected as the lower level for these factors. Three levels of weight varied at equal intervals (i.e., 13 kg, 18 kg and 23 kg) were selected.

**Lift Frequency:** The lift frequency was varied at three levels set 5, 7 and 9 lifts/min.

**Vertical Distance:** The most extreme task parameter related to vertical distance is placing weight at the shoulder height. Mean shoulder height of the workmen participating in the study was taken as the highest level for vertical distance. To measure the effect of vertical distance, the vertical distance was set at shoulder, waist and knee levels, which correspond to 150 cm, 110 cm and 55 cm respectively.

**Horizontal Distance:** The maximum arm reach (horizontal distance) was observed to be 55 cm and the most comfortable horizontal position was 25 cm. To study the effect of horizontal distance, three levels for horizontal distance were selected as 15, 30 and 55 cm.

**Travel Distance:** Since the laboratory has only two force platforms, the maximum travel distance (or carrying distance) that could be studied was 60 cm. Two other levels, 25 cm and 45 cm were selected to represent the three levels for travel distance.

**Asymmetrical Angle (a measure of posture):** The posture of the workmen represented by the asymmetric angle was selected as 0° (Neutral Position), 40° and 60°.

**Coupling:** The coupling on the weight tray was considered as another factor and was varied at three levels, i.e. ‘without gloves’, ‘with gloves’ and ‘with cushioning’.

The factors and their respective levels used in the study are given in Table 6.1.

Table 6.1: Factors studied with their levels in first part of study of second phase

| Factors (unit)                      | Levels      |              |            |
|-------------------------------------|-------------|--------------|------------|
|                                     | Level – 1   | Level – 2    | Level – 3  |
| Weight, A (kg)                      | 13          | 18           | 23         |
| Lifting frequency, B<br>(lifts/min) | 5           | 7            | 9          |
| Coupling Grip, C                    | With Gloves | With Cushion | W/o Gloves |
| Assy. Angle, D (in °)               | 0           | 40           | 60         |
| Vertical distance, E (cm)           | 55          | 110          | 150        |
| Horizontal distance, F (cm)         | 15          | 30           | 55         |
| Travel Distance, G (cm)             | 25          | 45           | 60         |

### Subject Details

Ten Male workers (age 27±5 years) routinely engaged in material handling tasks that included lifting of loads were invited to participate in the study with their consent. Each of them had no prior medical history and was in good health. All the subjects were trained for the task before the start of actual experimentation. Each worker was trained to lift a container from its initial position on the floor to the desired position in one continuous motion. An open rectangular shaped galvanized iron (GI) sheet container (45 cm × 30 cm) with handles on each side was used for lifting the load. The weight consisting of steel weights were placed at the middle of the container to ease lifting. Before the beginning of the study, the resting heart rate

(beats/min), resting metabolic rate (kcal/day), resting oxygen uptake (ml/kg-m) and maximum aerobic capacity (ml/kg-m) were recorded for each subject.

### Measurement Equipment

Two force platforms (Kistler 9286AA, 200 Hz) were used to measure the vertical, anterior/posterior, and medial/lateral ground reaction forces (GRF) and moments under feet produced during lifting. The setup arrangement is shown in Figure 6.1. A stop watch and measuring tape were used for measuring the work/rest periods and distances varied in the study respectively.

In the present experimental situation, there are seven factors that are believed to affect ground reaction forces and moments. Taguchi's Fractional Factorial Experiments (FEEs) Ross [142] were used to complete the experiment design. A three level array  $L_{27}$  was used for this study and was used for conducting the trials (see left columns of Table 6.3). The assignment of factors was completed using the Taguchi Linear Graphs and Triangular Tables Ross [142] in combination with MINITAB 16, a statistical software to aid the analysis. The trials were completely randomized meaning that each trial had an equal opportunity to be the first trial.

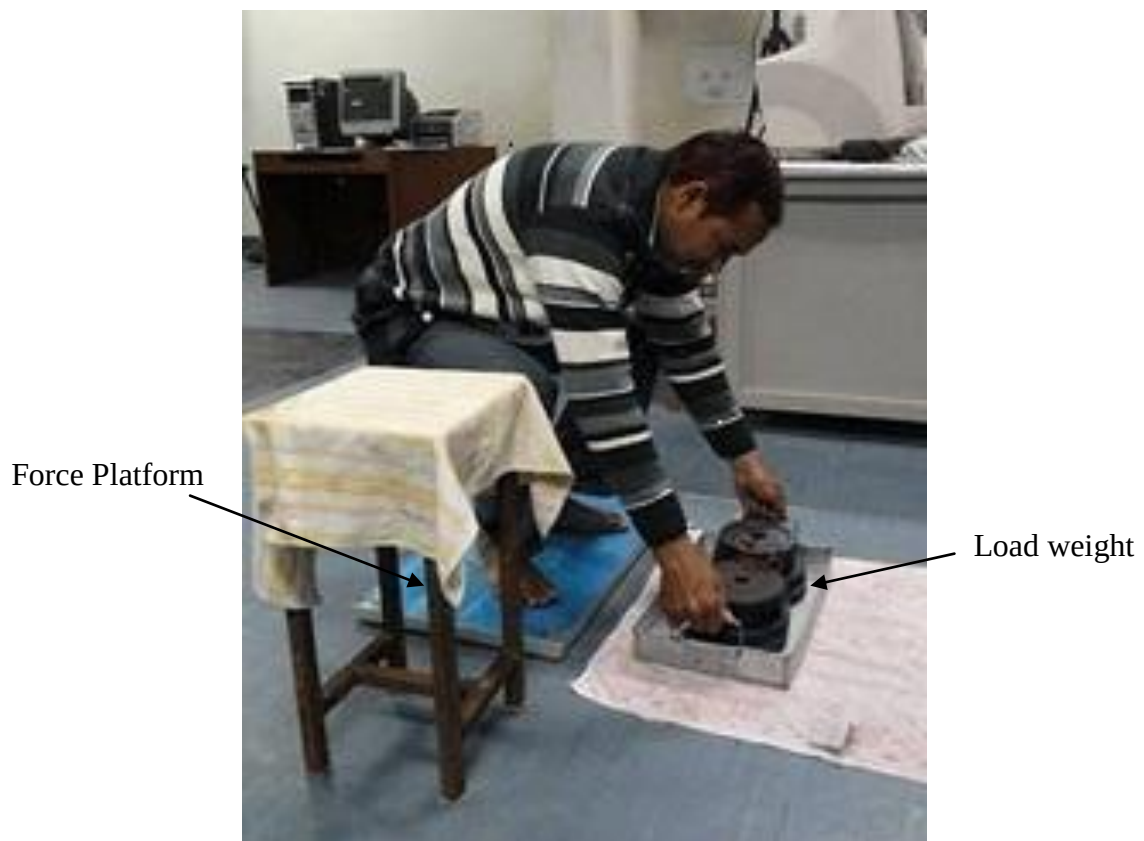


Figure 6.1: worker involved in lifting task with Kistler force platform (9286AA)

## 6.2 GROUND REACTION FORCE

The ground reaction force (GRF) is equal in magnitude and opposite in direction to the force that the body exerts on the supporting surface through the foot during human activities and is measured by force plate. The GRF has three components:  $F_x$ ,  $F_y$  &  $F_z$ . Among these,  $F_x$  is in transverse direction and  $F_y$  is along the direction of the motion and  $F_z$  is along the vertical direction.  $F_x$  and  $F_y$  are low in magnitude in comparison to  $F_z$  during lifting and carrying task.  $F_z$  always thrusts the body upward through feet. The vertical component of GRF is normally denoted as  $F_z$ , and the two horizontal components are denoted as  $F_x$  and  $F_y$ . The Vertical Ground Reaction Force (VGRF) is primarily generated by vertical acceleration of the body (bending and stretching) and is higher than  $F_x$  and  $F_y$ .  $M_x$ ,  $M_y$  and  $M_z$  are the moments around x, y and z directions respectively. The free moment ( $T_z$ ) is the turning force or moment around a vertical axis through the center of pressure (C of P). The C of P is the position of the resultant GRF vector in a plane that is parallel to surface of the plate. In the present study, the GRF refers to the vertical component ( $F_z$ ) only as other forces and moments value are of low magnitude and thus do not impact the responses. Vertical ground reaction force was considered as the principal response parameters.

### 6.2.1 Measurement of Ground Reaction Force

Each subject carried out asymmetrical free style lifting of weight from the ground position for all trial conditions. Each worker carried out free style lifting of weight from standing position in front of the container as per the experimental trial conditions for ten minutes. Sufficient break was given after each lifting to recover from the fatigue. The  $F_z$  was measured after each trial and for each worker and recorded on a data sheet for further analysis. The data was extracted from a graphical output for GRF (in Newton) plotted against a time scale (in seconds). Vertical Reaction Force ( $F_z$ ) was measured for all the ten workers for all trials over an experimental period of ten minutes. One such plot for one minute is shown in Figure 6.2 (a) for trial 15. The mean value of  $F_z$  for worker 3 for trial 15 was then calculated for the above said period of ten minutes. It can be noticed that the trial was conducted using a frequency of seven lifts/min which is equivalent to 70 lifts in ten minutes. Each lift is thus equivalent to a time period of 8.5 sec approximately.

Since it is not feasible to show a plot for ten minute study here, a 60 sec run, out of the ten minutes study for this trial, was extracted to show the variation of  $F_z$  with time and is shown in Figure 6.2 (a). Seven trials during the 60 seconds period can be easily seen in this plot. To

further elaborate on the lifting task, one lift represented by duration of about 8.5 seconds is shown in Figure 6.2 (b). The lifting task in this plot is divided into four time spans and the GRF or  $F_z$  can be measured for each span. The four time spans identified on the plot are defined as under:

**Position I:** Initial stationary position when the  $F_z$  is equal to body weight marked by position I on the plots.

**Position II:** Just before the lift when the worker has bent for lifting from ground position. In this position,  $F_z$  is observed to be lower than the body weight of the worker. Also,  $F_z$  decreases even more with increased frequency and vertical distance primarily because of the jerking action required to initiate the lift.

**Position III:** This time span represents the lifting phase and  $F_z$  gets larger in magnitude in comparison to body weight and is obtained by measuring the instantaneous force rate from tangential gradient.

**Position IV:** This is the final stationary position where  $F_z$  is again equal to body weight. This is the time between two successive lifts.

All the positions listed above are also identified in Figure 6.2 (b). This plot was used to calculate the lower, peak and mean value of  $F_z$  for this trial. A plot of  $F_z$  for one minute for each trial was used to calculate mean  $F_{z \min}$  (Position II), mean  $F_{z \max}$  (Position III), and their mean represented by  $F_{z \text{ mean}}$  using the following data points.

- Mean  $F_{z \min} = (\text{Sum of all } F_{z \min}) / \text{Number of lifts (at position II, lower most value)}$
- Mean  $F_{z \text{ mean}} = (\text{Sum of all } F_{z \text{ mean}}) / \text{Number of lifts}$
- Mean  $F_{z \max} = (\text{Sum of all } F_{z \max}) / \text{Number of lifts (at position III, peak value)}$

Similar approach was used to calculate the vertical ground reaction force ( $F_z$ ), lower, peak and mean values of each worker and each trial. These values are given in Table 6.2. Force –time vertical reaction force graphs for different trials for workers involved in lifting task are shown in Figures 6.3,6.4,6.5,6.6,6.7,6.8,6.9 and 6.10.

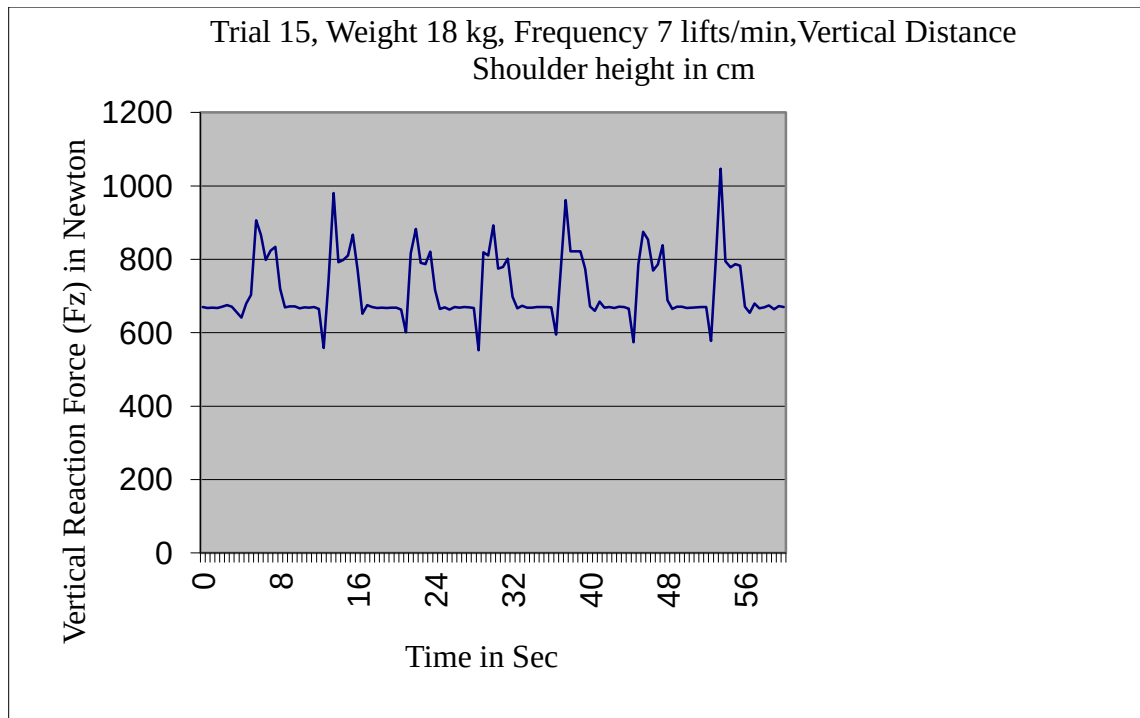


Figure 6.2 (a): Force –time vertical reaction force graph for workers involved in lifting task (Trial no 15, weight 18 kg, frequency 7 lifts in 60 seconds, vertical distance shoulder height in cm)

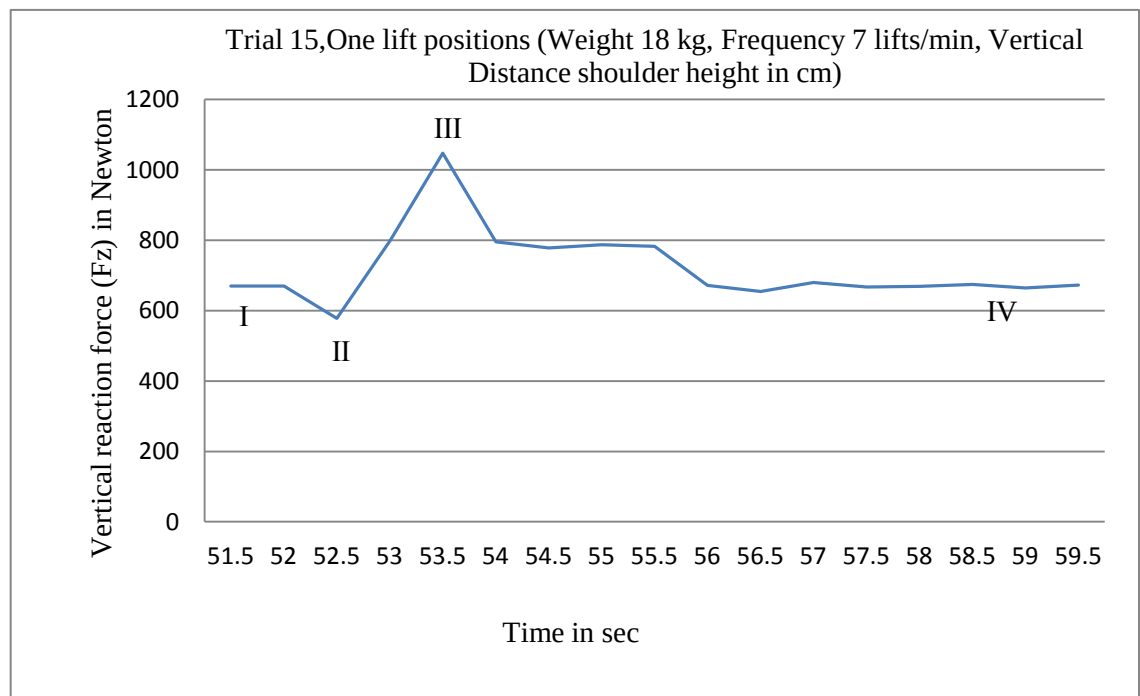


Figure 6.2 (b): Force –time vertical reaction force graph for workers involved in lifting task (Trial no 15, weight 18 kg, frequency 7 lifts/min, vertical distance shoulder height in cm for one lift (7<sup>th</sup>, in this case) in 8.5sec) Vertical reaction force ( $F_z$ ) in Newton)

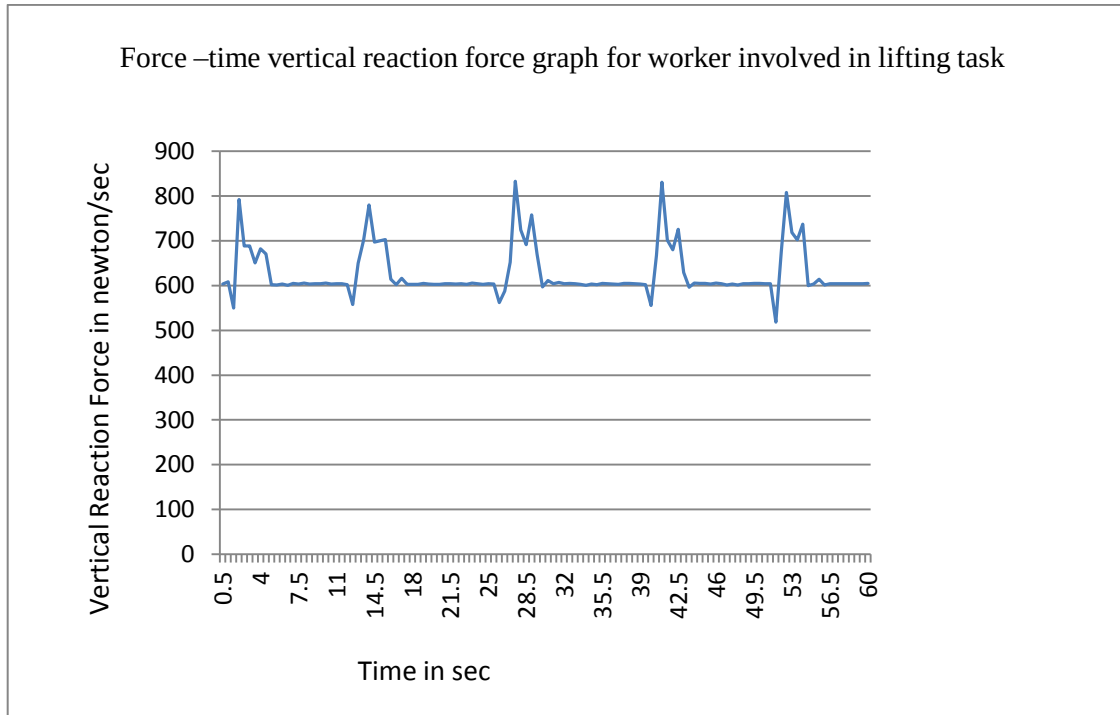


Figure 6.3: Graphical output of vertical ground reaction force of trial no. 3

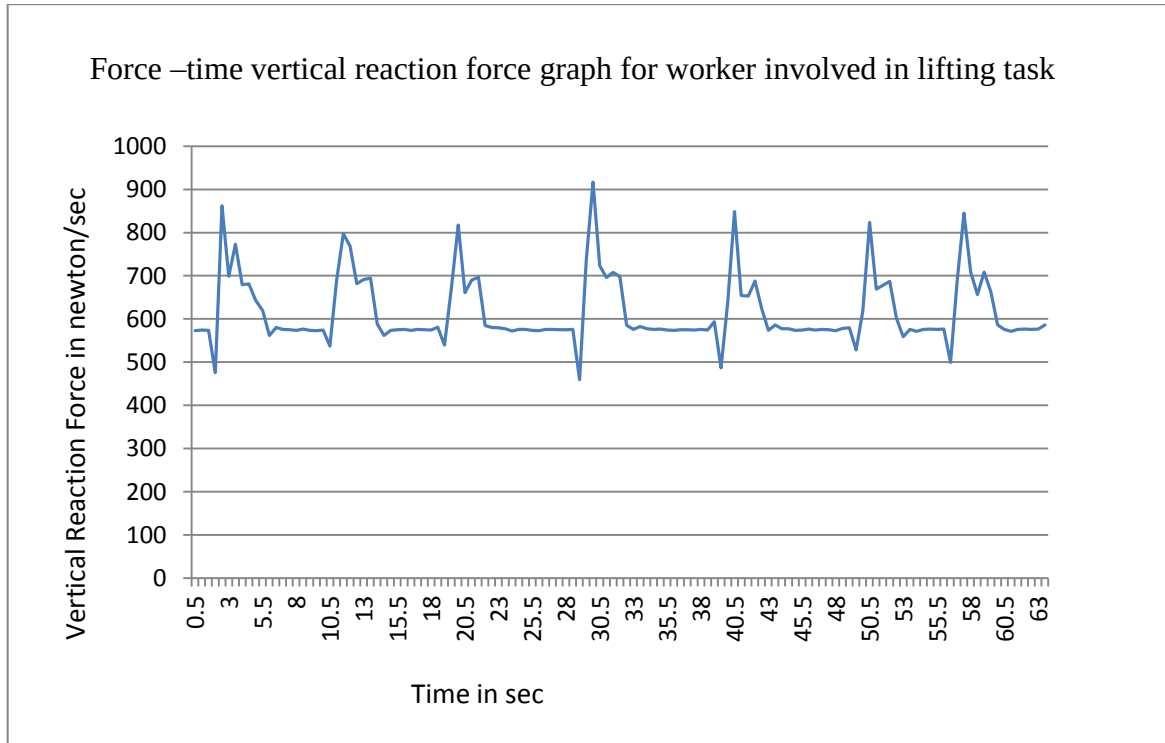


Figure 6.4: Graphical output of vertical ground reaction force of trial no. 6

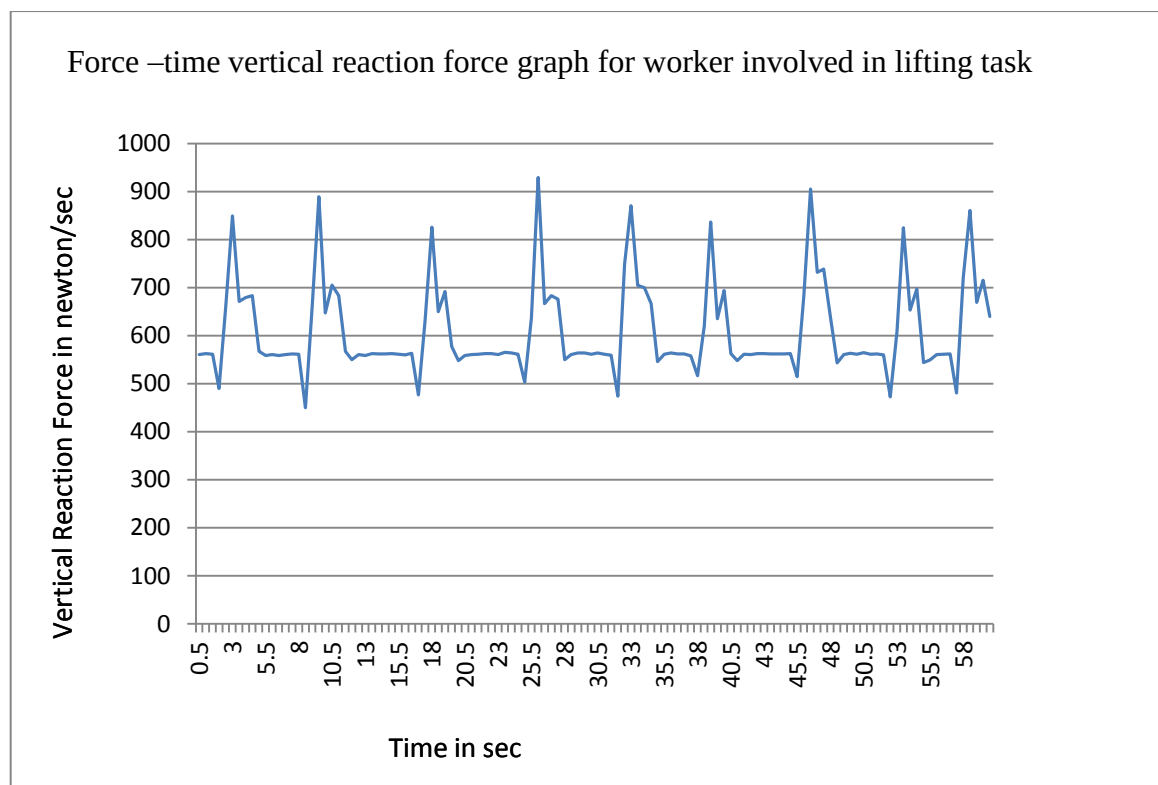


Figure 6.5: Graphical output of vertical ground reaction force of trial no. 9

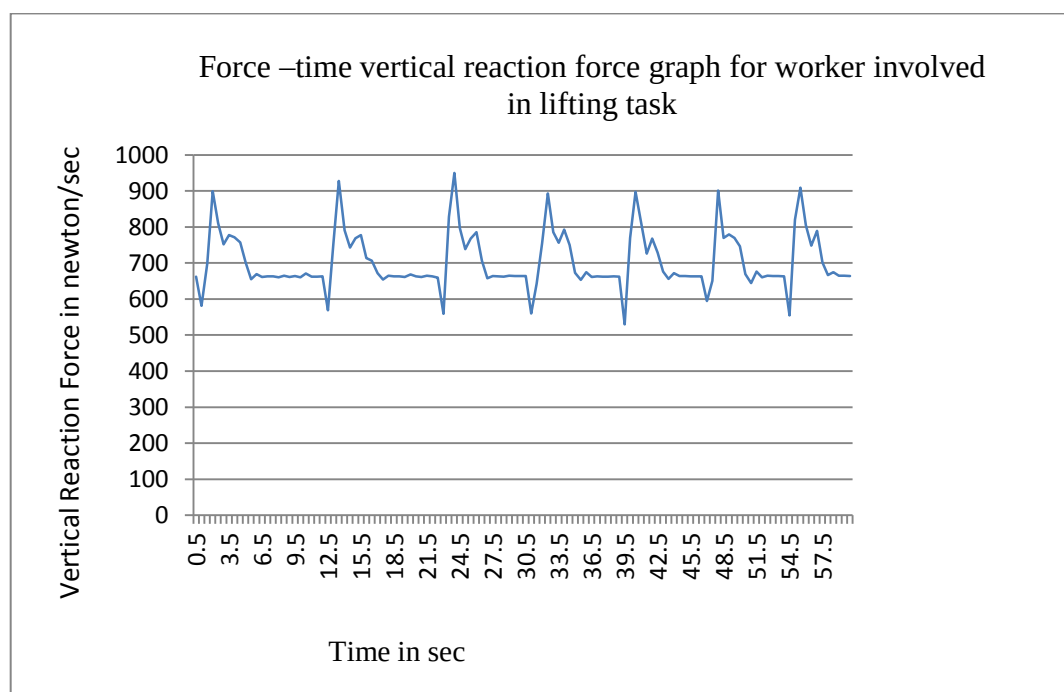


Figure 6.6: Graphical output of vertical ground reaction force of trial no. 13

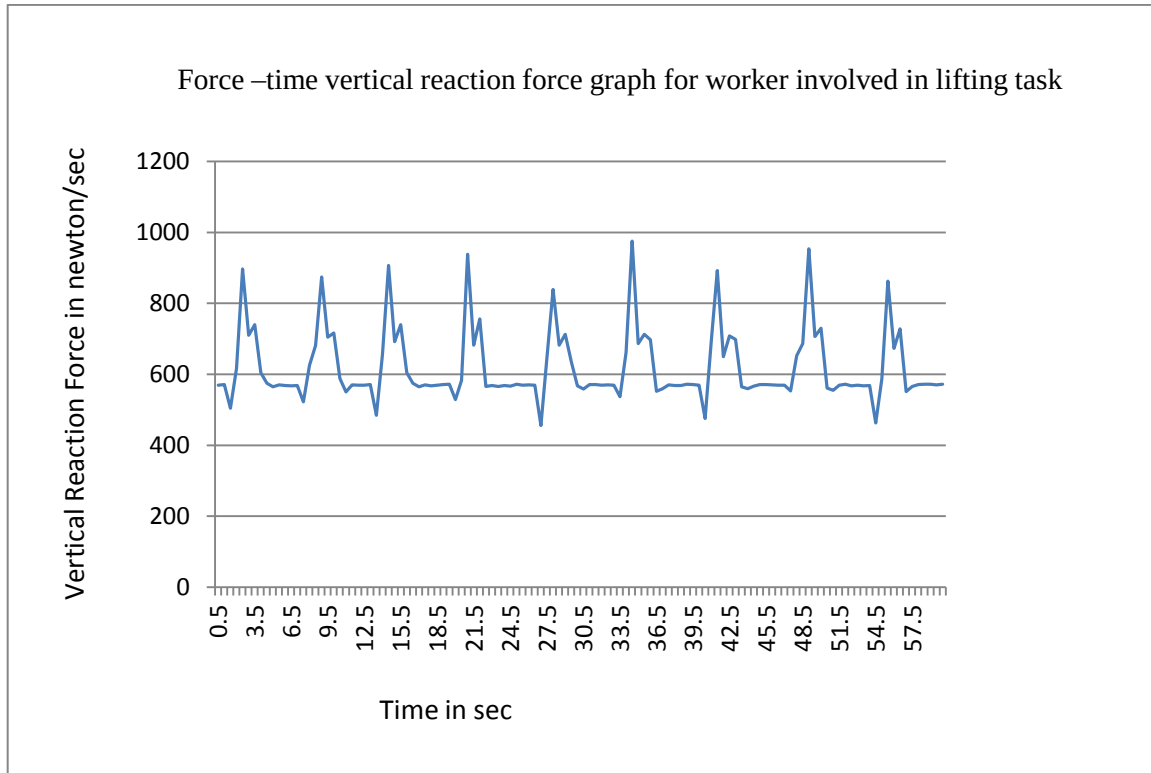


Figure 6.7: Graphical output of vertical ground reaction force of trial no.18

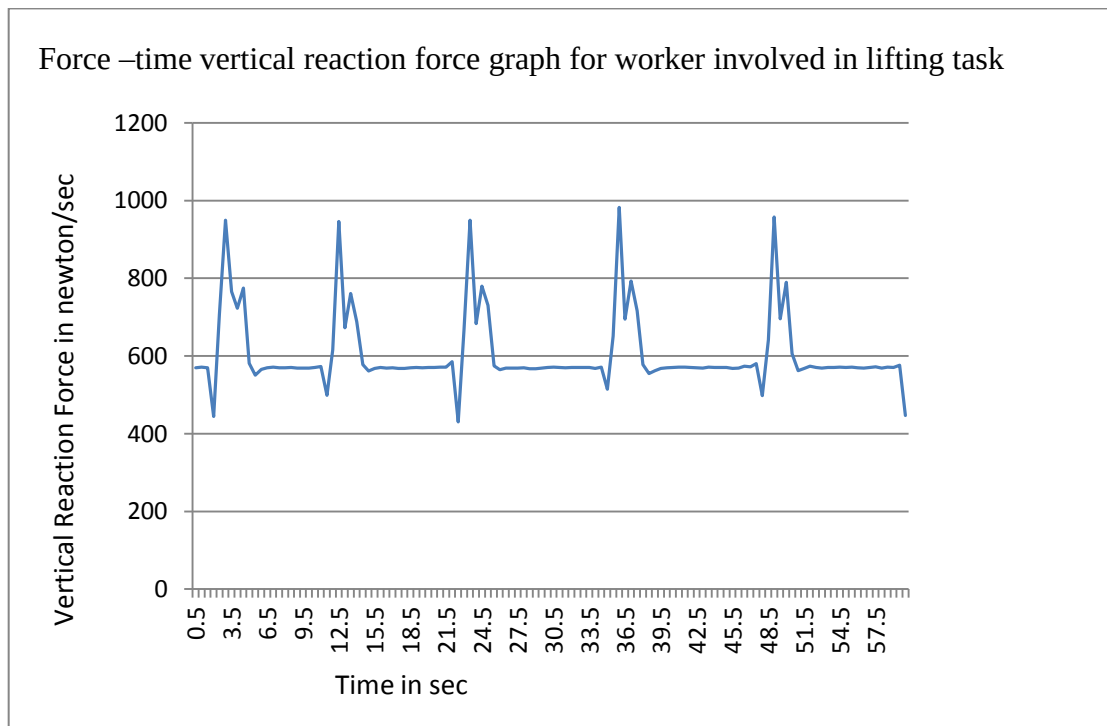


Figure 6.8: Graphical output of vertical ground reaction force of trial no. 21

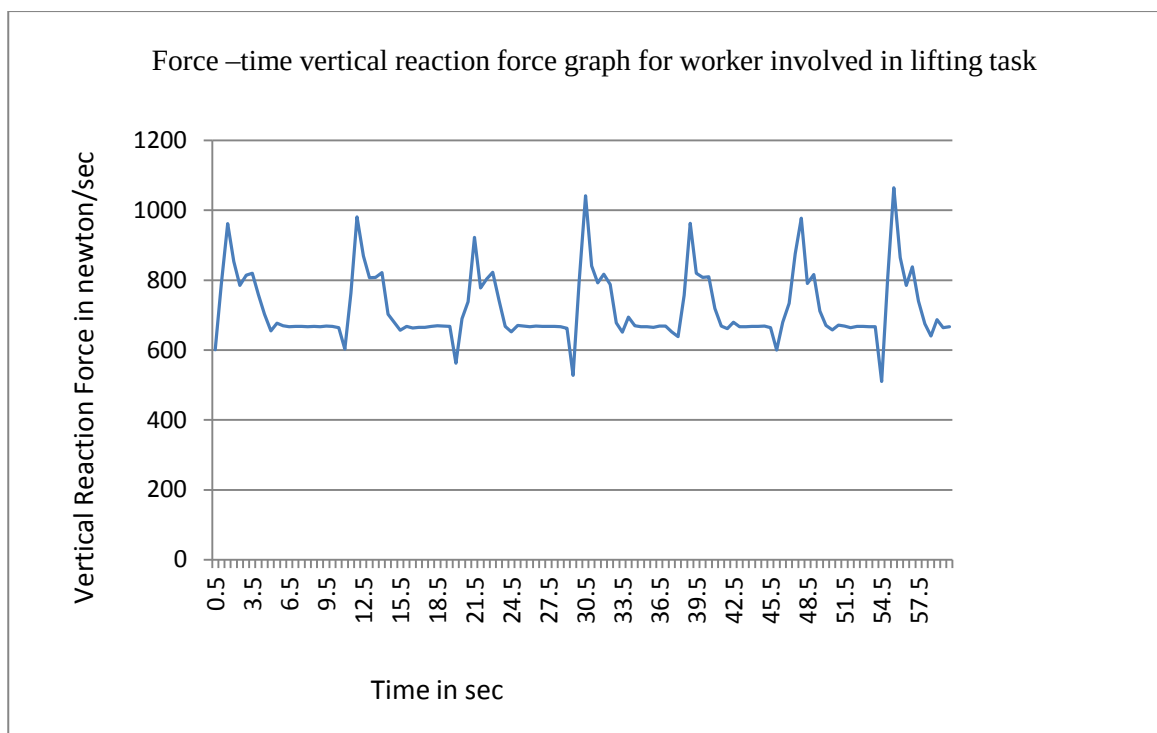


Figure 6.9: Graphical output of vertical ground reaction force of trial no. 24

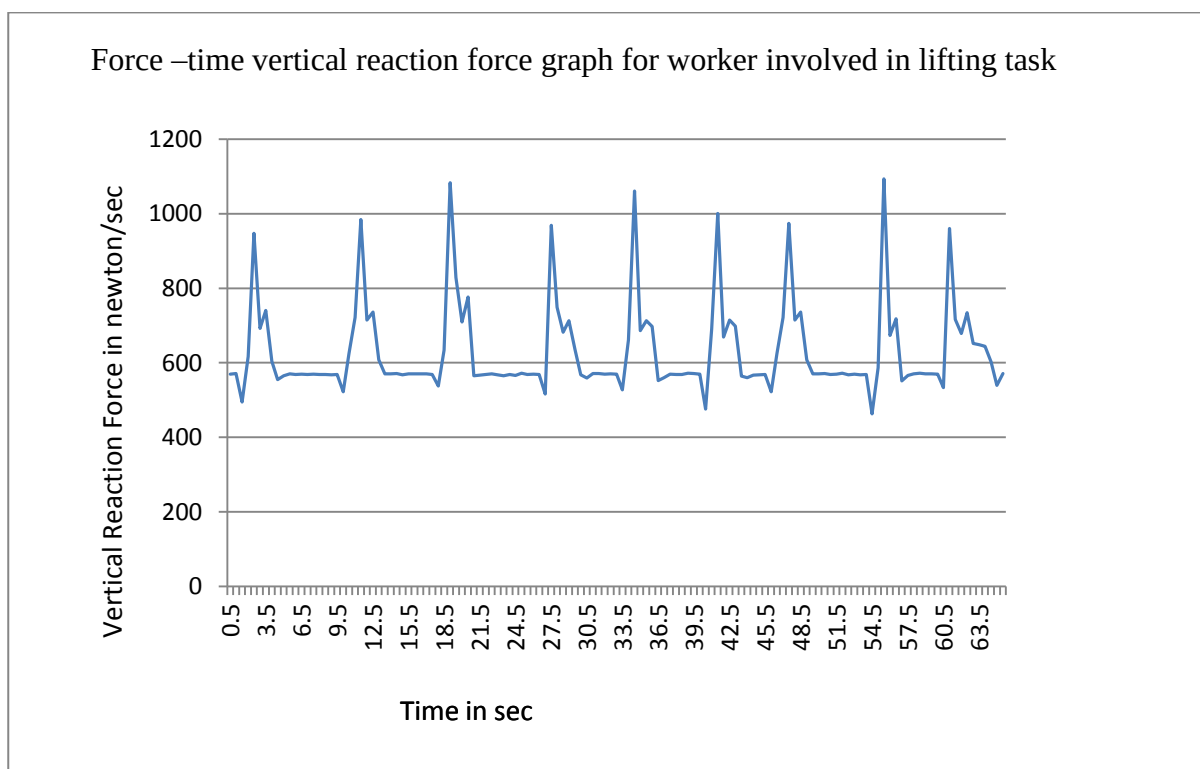


Figure 6.10: Graphical output of vertical ground reaction force of trial no. 27

Table 6.2: Vertical ground reaction force ( $F_z$ ), lower, mean and peak values

| Trial<br>no | Vertical ground reaction force ( $F_z$ ) Value |        |        |                         |        |        |        |        |                         |        |         |        |        |                         |        |
|-------------|------------------------------------------------|--------|--------|-------------------------|--------|--------|--------|--------|-------------------------|--------|---------|--------|--------|-------------------------|--------|
|             | Lower                                          |        |        |                         |        | Mean   |        |        |                         |        | Peak    |        |        |                         |        |
|             | W 1                                            | W 2    | W 3    | Average<br>W 4 to<br>10 | Mean   | W 1    | W 2    | W 3    | Average<br>W 4 to<br>10 | Mean   | W 1     | W 2    | W 3    | Average<br>W 4 to<br>10 | Mean   |
| 1           | 435.01                                         | 468.67 | 623.87 | 496.43                  | 506.00 | 575.27 | 614.64 | 689.32 | 587.55                  | 616.70 | 861.17  | 787.63 | 843.24 | 818.48                  | 827.63 |
| 2           | 417.89                                         | 511.01 | 610.63 | 543.99                  | 520.88 | 590.34 | 621.23 | 698.14 | 598.23                  | 626.99 | 845.18  | 814.34 | 872.23 | 847.96                  | 844.93 |
| 3           | 455.07                                         | 495.97 | 588.67 | 510.78                  | 512.62 | 607.23 | 632.50 | 706.65 | 608.78                  | 638.79 | 851.56  | 873.04 | 897.62 | 872.67                  | 873.72 |
| 4           | 433.97                                         | 608.84 | 598.35 | 503.87                  | 536.26 | 602.32 | 618.32 | 692.35 | 596.21                  | 627.30 | 821.17  | 801.23 | 861.71 | 827.67                  | 827.95 |
| 5           | 395.44                                         | 560.67 | 568.66 | 478.76                  | 500.88 | 598.57 | 624.78 | 703.46 | 604.75                  | 632.89 | 817.57  | 822.25 | 881.68 | 856.51                  | 844.50 |
| 6           | 460.84                                         | 580.76 | 574.21 | 464.55                  | 520.09 | 616.87 | 637.54 | 713.12 | 614.56                  | 645.52 | 844.63  | 880.76 | 912.12 | 886.92                  | 881.11 |
| 7           | 442.88                                         | 510.89 | 580.75 | 435.57                  | 492.52 | 611.02 | 621.31 | 701.42 | 602.38                  | 634.03 | 836.67  | 830.98 | 890.45 | 833.49                  | 847.90 |
| 8           | 437.54                                         | 521.23 | 574.48 | 381.48                  | 478.68 | 613.69 | 630.11 | 708.83 | 622.13                  | 643.69 | 856.12  | 851.76 | 906.65 | 881.53                  | 874.02 |
| 9           | 448.45                                         | 544.54 | 568.67 | 401.65                  | 490.83 | 619.23 | 643.77 | 722.77 | 627.89                  | 653.42 | 865.68  | 891.21 | 923.83 | 909.33                  | 897.51 |
| 10          | 398.00                                         | 497.24 | 583.76 | 432.43                  | 477.86 | 609.39 | 629.65 | 705.87 | 607.19                  | 638.03 | 883.27  | 898.31 | 886.85 | 894.39                  | 890.71 |
| 11          | 389.77                                         | 513.27 | 594.33 | 454.02                  | 487.85 | 612.94 | 632.48 | 717.99 | 624.27                  | 646.92 | 895.78  | 917.92 | 920.82 | 901.78                  | 909.08 |
| 12          | 458.29                                         | 527.43 | 590.43 | 438.12                  | 503.57 | 616.38 | 647.46 | 719.79 | 637.74                  | 655.34 | 909.56  | 937.89 | 941.85 | 919.28                  | 927.15 |
| 13          | 443.23                                         | 522.36 | 573.99 | 426.34                  | 491.48 | 610.56 | 631.29 | 708.48 | 612.98                  | 640.83 | 903.86  | 909.53 | 915.45 | 904.43                  | 908.32 |
| 14          | 437.56                                         | 484.44 | 582.32 | 457.86                  | 490.55 | 618.81 | 639.71 | 724.73 | 633.74                  | 654.25 | 907.54  | 923.67 | 947.76 | 915.75                  | 923.68 |
| 15          | 493.54                                         | 489.67 | 597.35 | 436.13                  | 504.17 | 620.13 | 654.57 | 728.24 | 642.22                  | 661.29 | 930.68  | 940.31 | 971.87 | 939.29                  | 945.54 |
| 16          | 423.65                                         | 433.34 | 544.65 | 449.43                  | 462.77 | 608.56 | 635.84 | 710.22 | 619.84                  | 643.61 | 921.67  | 915.76 | 929.76 | 875.15                  | 910.59 |
| 17          | 437.95                                         | 442.93 | 523.14 | 417.14                  | 455.29 | 622.28 | 641.16 | 727.45 | 638.29                  | 657.30 | 980.49  | 926.45 | 951.41 | 916.73                  | 943.77 |
| 18          | 419.56                                         | 421.33 | 590.18 | 413.65                  | 461.18 | 624.56 | 659.21 | 739.15 | 650.88                  | 668.45 | 1017.45 | 943.88 | 989.19 | 945.69                  | 974.05 |
| 19          | 412.70                                         | 396.54 | 484.56 | 463.98                  | 439.45 | 609.99 | 638.27 | 712.98 | 621.54                  | 645.69 | 910.68  | 920.95 | 950.44 | 927.89                  | 927.49 |
| 20          | 390.35                                         | 414.88 | 464.94 | 444.42                  | 428.65 | 615.56 | 649.49 | 736.21 | 649.68                  | 662.74 | 925.43  | 931.38 | 969.74 | 942.74                  | 942.32 |

|    |        |        |        |        |        |        |        |        |        |        |         |         |         |         |         |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|
| 21 | 403.76 | 393.87 | 468.52 | 428.10 | 423.56 | 621.34 | 656.33 | 741.88 | 663.33 | 670.72 | 945.84  | 955.79  | 995.53  | 948.46  | 961.41  |
| 22 | 427.18 | 416.49 | 456.23 | 442.22 | 435.53 | 614.68 | 644.12 | 718.87 | 629.61 | 651.82 | 915.63  | 934.77  | 957.46  | 935.38  | 935.81  |
| 23 | 409.12 | 409.24 | 489.33 | 452.11 | 439.95 | 620.14 | 654.89 | 742.48 | 655.67 | 668.29 | 959.34  | 947.19  | 976.83  | 966.46  | 962.46  |
| 24 | 374.66 | 398.18 | 477.34 | 432.79 | 420.74 | 629.69 | 663.68 | 749.63 | 672.22 | 678.81 | 1002.32 | 970.82  | 1017.18 | 947.99  | 984.58  |
| 25 | 382.80 | 432.75 | 512.75 | 469.07 | 449.34 | 623.35 | 647.76 | 723.36 | 634.93 | 657.35 | 997.12  | 954.66  | 1026.59 | 880.22  | 964.65  |
| 26 | 369.05 | 401.67 | 494.65 | 474.54 | 434.98 | 636.77 | 665.35 | 747.11 | 667.91 | 679.28 | 1021.79 | 985.26  | 1045.87 | 1016.44 | 1017.34 |
| 27 | 378.67 | 389.56 | 503.64 | 443.67 | 428.89 | 645.23 | 676.99 | 760.36 | 685.43 | 692.00 | 1069.46 | 1027.89 | 1111.95 | 1057.65 | 1066.74 |

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### 6.2.2 Calculation of Loading Rate from Vertical Reaction Force Fz

The rate at which the vertical component of the GRF is applied to the body is often measured during running, landing, walking, dynamic lifting and so on. The peak rate of vertical ground reaction force (loading rate) is an indication of the risk of chronic injury due to such activities, (Miller and Nigg [120, 130]). Loading rate (LR) is defined as the quotient of the peak loading and time to peak loading during human activities. The instantaneous loading rate obtained by measuring the gradient of a tangent that is drawn at the point on the Fz–time curve where the rate of change is considered to be greatest (Figure-6.2 (b)). Alternatively, an average loading rate can be obtained by measuring the rate at which Fz rises. One sample calculation for loading rate for trial 15, (worker 3, load 18 kg, frequency of 7 lifts/min, lifted from floor to shoulder level) is given in equation 6.1.

$$LR = \frac{F_{z \max} - F_{z \min}}{t_2 - t_1} = \frac{1047 - 578}{53.5 - 52.5} = 469 \text{ N / sec} \quad \dots \text{Equation (6.1)}$$

$F_{z \max}$  &  $F_{z \min}$  are the peak and lower value of  $F_z$  of one lift and  $(t_2 - t_1)$  is time span between peak and lower  $F_z$  value. The loading rate was calculated for all the trial conditions using the same method. The mean loading rate of each trial of each worker with lifting parameters is given in Table 6.3. Average vertical ground reaction force and mean loading rate of all workers are given in Table 6.4.

### 6.3 ANALYSIS OF GROUND REACTION FORCE

Using Taguchi's  $L_{27}$  array trial conditions, ground reaction forces ( $F_z$ ) and loading rate were measured. The lower, mean and peak values of  $F_z$  and mean loading rate of workers are given under the response column of Table 6.2. The results were analyzed using Analysis of Variance (ANOVA) for identifying the significant factors affecting the performance measures. The pooled ANOVA results for ground reaction forces,  $F_z$  and loading rate are given in Table 6.5. From the percentage contribution values calculated in last column of Table 6.5, weight, frequency, vertical distance were identified as significant factors. All the remaining factors had no or minimal effect on the response. From the mean effects plots shown in Figure 6.11, it was observed that the parameters of weight, vertical distance and lifting frequency majorly affected the vertical ground reaction force ( $F_z$ ) which increases when higher weight was lifted (23 kg) from floor to the shoulder level at high lifting frequency. Highest value of  $F_z$  was measured for Trial 27.

Table 6.3: Mean loading rate (LR) of workers

| Trial No. | Wt (kg)<br>A | Freq (lifts/min)<br>B | Grip (coupling)<br>C | Ass. Angle (°)<br>D | V.D (cm)<br>E | H.D (cm)<br>F | T.D (cm)<br>G | Loading rate(N/S) |     |     |                      |                     |
|-----------|--------------|-----------------------|----------------------|---------------------|---------------|---------------|---------------|-------------------|-----|-----|----------------------|---------------------|
|           |              |                       |                      |                     |               |               |               | W1                | W2  | W3  | Average of W4 to W10 | Mean of all workers |
| 1         | 13           | 5                     | With Gloves          | 0                   | 55            | 15            | 25            | 223               | 209 | 259 | 246                  | 234.25              |
| 2         | 13           | 5                     | With Cushion         | 40                  | 110           | 30            | 45            | 259               | 247 | 309 | 279                  | 273.5               |
| 3         | 13           | 5                     | W/o Gloves           | 60                  | 150           | 55            | 60            | 326               | 314 | 368 | 344                  | 338                 |
| 4         | 13           | 7                     | With Gloves          | 0                   | 55            | 55            | 60            | 257               | 239 | 294 | 271                  | 265.25              |
| 5         | 13           | 7                     | With Cushion         | 40                  | 110           | 15            | 25            | 291               | 278 | 333 | 309                  | 302.75              |
| 6         | 13           | 7                     | W/o Gloves           | 60                  | 150           | 30            | 45            | 360               | 327 | 385 | 358                  | 357.5               |
| 7         | 13           | 9                     | With Gloves          | 0                   | 55            | 30            | 45            | 299               | 287 | 329 | 318                  | 308.25              |
| 8         | 13           | 9                     | With Cushion         | 40                  | 110           | 55            | 60            | 331               | 319 | 358 | 353                  | 340.25              |
| 9         | 13           | 9                     | W/o Gloves           | 60                  | 150           | 15            | 25            | 388               | 362 | 412 | 394                  | 389                 |
| 10        | 18           | 5                     | With cushion         | 60                  | 55            | 30            | 60            | 334               | 326 | 343 | 329                  | 333                 |
| 11        | 18           | 5                     | W/o Gloves           | 0                   | 110           | 55            | 25            | 363               | 354 | 372 | 358                  | 361.75              |
| 12        | 18           | 5                     | With Gloves          | 40                  | 150           | 15            | 45            | 403               | 382 | 409 | 394                  | 397                 |
| 13        | 18           | 7                     | With cushion         | 60                  | 55            | 15            | 45            | 358               | 349 | 361 | 353                  | 355.25              |
| 14        | 18           | 7                     | W/o Gloves           | 0                   | 110           | 30            | 60            | 407               | 378 | 387 | 381                  | 388.25              |
| 15        | 18           | 7                     | With Gloves          | 40                  | 150           | 55            | 25            | 442               | 406 | 468 | 439                  | 439                 |
| 16        | 18           | 9                     | With cushion         | 60                  | 55            | 55            | 25            | 393               | 371 | 399 | 388                  | 387.75              |
| 17        | 18           | 9                     | W/o Gloves           | 0                   | 110           | 15            | 45            | 457               | 409 | 433 | 422                  | 430.25              |
| 18        | 18           | 9                     | With Gloves          | 40                  | 150           | 30            | 60            | 523               | 457 | 528 | 489                  | 499.25              |
| 19        | 23           | 5                     | W/o Gloves           | 40                  | 55            | 55            | 45            | 414               | 381 | 427 | 401                  | 405.75              |
| 20        | 23           | 5                     | With Gloves          | 60                  | 110           | 15            | 60            | 438               | 408 | 442 | 416                  | 426                 |
| 21        | 23           | 5                     | With cushion         | 0                   | 150           | 30            | 25            | 488               | 449 | 471 | 443                  | 462.75              |
| 22        | 23           | 7                     | W/o Gloves           | 40                  | 55            | 30            | 25            | 427               | 403 | 452 | 405                  | 421.75              |
| 23        | 23           | 7                     | With Gloves          | 60                  | 110           | 55            | 45            | 479               | 451 | 469 | 453                  | 463                 |
| 24        | 23           | 7                     | With cushion         | 0                   | 150           | 15            | 60            | 523               | 503 | 534 | 498                  | 514.5               |
| 25        | 23           | 9                     | W/o Gloves           | 40                  | 55            | 15            | 60            | 439               | 395 | 441 | 418                  | 423.25              |
| 26        | 23           | 9                     | With Gloves          | 60                  | 110           | 30            | 25            | 528               | 478 | 489 | 481                  | 494                 |
| 27        | 23           | 9                     | With cushion         | 0                   | 150           | 55            | 45            | 611               | 559 | 603 | 574                  | 586.75              |

(Note: Wt: weight, freq: frequency, Ass. Angle: Asymmetric angle, V.D: Vertical Distance, H.D: Horizontal Distance, T.D: Travel Distance, W1: Worker no. one)

Table 6.4: Lower, peak and mean values of Vertical ground reaction force (VGRF,  $F_z$ ) and mean loading rate of all workers with experiment design trials

| Trial No. | Wt (kg)<br>A | Freq (lift/min)<br>B | Grip (coupling)<br>C | Ass. Angle ( $^{\circ}$ )<br>D | V.D (cm)<br>E | H.D (cm)<br>F | T.D (cm)<br>G | Average Vertical Ground Reaction Force $F_z$ in N, For all ten workers |        |         | Mean Loading Rate of all workers (N/s) |
|-----------|--------------|----------------------|----------------------|--------------------------------|---------------|---------------|---------------|------------------------------------------------------------------------|--------|---------|----------------------------------------|
|           |              |                      |                      |                                |               |               |               | Lower                                                                  | Mean   | Peak    |                                        |
| 1         | 13           | 5                    | With Gloves          | 0                              | Knee          | 15            | 25            | 506.09                                                                 | 616.81 | 827.72  | 234.25                                 |
| 2         | 13           | 5                    | With Cushion         | 40                             | Waist         | 30            | 45            | 521.03                                                                 | 627.1  | 845.13  | 273.5                                  |
| 3         | 13           | 5                    | W/o Gloves           | 60                             | Shoulder      | 55            | 60            | 512.77                                                                 | 638.91 | 873.91  | 338                                    |
| 4         | 13           | 7                    | With Gloves          | 0                              | Knee          | 55            | 60            | 536.3                                                                  | 627.41 | 828.12  | 265.25                                 |
| 5         | 13           | 7                    | With Cushion         | 40                             | Waist         | 15            | 25            | 500.13                                                                 | 632.92 | 844.71  | 302.75                                 |
| 6         | 13           | 7                    | W/o Gloves           | 60                             | Shoulder      | 30            | 45            | 520.15                                                                 | 645.7  | 881.41  | 357.5                                  |
| 7         | 13           | 9                    | With Gloves          | 0                              | Knee          | 30            | 45            | 492.61                                                                 | 634.22 | 848.23  | 308.25                                 |
| 8         | 13           | 9                    | With Cushion         | 40                             | Waist         | 55            | 60            | 478.76                                                                 | 643.73 | 874.29  | 340.25                                 |
| 9         | 13           | 9                    | W/o Gloves           | 60                             | Shoulder      | 15            | 25            | 491                                                                    | 653.66 | 897.83  | 389                                    |
| 10        | 18           | 5                    | With cushion         | 60                             | Knee          | 30            | 60            | 477.93                                                                 | 638.18 | 890.9   | 333                                    |
| 11        | 18           | 5                    | W/o Gloves           | 0                              | Waist         | 55            | 25            | 487.97                                                                 | 647.01 | 909.28  | 361.75                                 |
| 12        | 18           | 5                    | With Gloves          | 40                             | Shoulder      | 15            | 45            | 503.72                                                                 | 655.3  | 927.41  | 397                                    |
| 13        | 18           | 7                    | With cushion         | 60                             | Knee          | 15            | 45            | 491.54                                                                 | 640.97 | 908.49  | 355.25                                 |
| 14        | 18           | 7                    | W/o Gloves           | 0                              | Waist         | 30            | 60            | 490.68                                                                 | 654.42 | 923.89  | 388.25                                 |
| 15        | 18           | 7                    | With Gloves          | 40                             | Shoulder      | 55            | 25            | 504.36                                                                 | 661.51 | 945.8   | 439                                    |
| 16        | 18           | 9                    | With cushion         | 60                             | Knee          | 55            | 25            | 462.83                                                                 | 643.79 | 910.78  | 387.75                                 |
| 17        | 18           | 9                    | W/o Gloves           | 0                              | Waist         | 15            | 45            | 455.4                                                                  | 657.58 | 943.97  | 430.25                                 |
| 18        | 18           | 9                    | With Gloves          | 40                             | Shoulder      | 30            | 60            | 461.33                                                                 | 668.7  | 974.45  | 499.25                                 |
| 19        | 23           | 5                    | W/o Gloves           | 40                             | Knee          | 55            | 45            | 439.51                                                                 | 645.8  | 927.71  | 405.75                                 |
| 20        | 23           | 5                    | With Gloves          | 60                             | Waist         | 15            | 60            | 428.82                                                                 | 662.88 | 942.6   | 426                                    |
| 21        | 23           | 5                    | With cushion         | 0                              | Shoulder      | 30            | 25            | 423.75                                                                 | 670.91 | 961.87  | 462.75                                 |
| 22        | 23           | 7                    | W/o Gloves           | 40                             | Knee          | 30            | 25            | 435.68                                                                 | 651.98 | 936.01  | 421.75                                 |
| 23        | 23           | 7                    | With Gloves          | 60                             | Waist         | 55            | 45            | 440.12                                                                 | 668.37 | 962.67  | 463                                    |
| 24        | 23           | 7                    | With cushion         | 0                              | Shoulder      | 15            | 60            | 420.97                                                                 | 679.06 | 984.9   | 514.5                                  |
| 25        | 23           | 9                    | W/o Gloves           | 40                             | Knee          | 15            | 60            | 449.46                                                                 | 657.48 | 964.79  | 423.25                                 |
| 26        | 23           | 9                    | With Gloves          | 60                             | Waist         | 30            | 25            | 435.13                                                                 | 679.47 | 1017.61 | 494                                    |
| 27        | 23           | 9                    | With cushion         | 0                              | Shoulder      | 55            | 45            | 429.19                                                                 | 692.39 | 1067.49 | 586.75                                 |

Note: (Wt: weight, freq: frequency, Ass. Angle: Asymmetric angle, V.D: Vertical Distance, H.D: Horizontal Distance, T.D: Travel Distance)

Table 6.5: Pooled ANOVA for Vertical ground reaction forces ( $F_z$ ) and Loading Rate (LR)

| Source                | DOF | SS      |        | V       |         | F      |        | PC    |      |
|-----------------------|-----|---------|--------|---------|---------|--------|--------|-------|------|
|                       |     | $F_z$   | LR     | $F_z$   | LR      | $F_z$  | LR     | $F_z$ | LR   |
| A (Weight)            | 2   | 4604.85 | 108424 | 2302.42 | 54212   | 220.98 | 262.46 | 53.8  | 61.6 |
| B(Frequency)          | 2   | 913.51  | 22046  | 456.75  | 11023   | 43.83  | 53.36  | 8.62  | 12.3 |
| E (Vertical Distance) | 2   | 2449.17 | 40805  | 1224.58 | 20402.5 | 117.53 | 98.78  | 27.4  | 23   |
| Residual Error        | 20  | 208.38  | 4131   | 10.419  | 206.55  |        |        |       |      |
| Total                 | 26  | 8175.93 | 175406 |         |         |        |        |       |      |

(Note : SS = Sum of square, DOF= Degrees of freedom, V = Variance, F= ratio, PC = Percent contribution,  $F_z$ =Vertical ground reaction force, LR = loading rate)

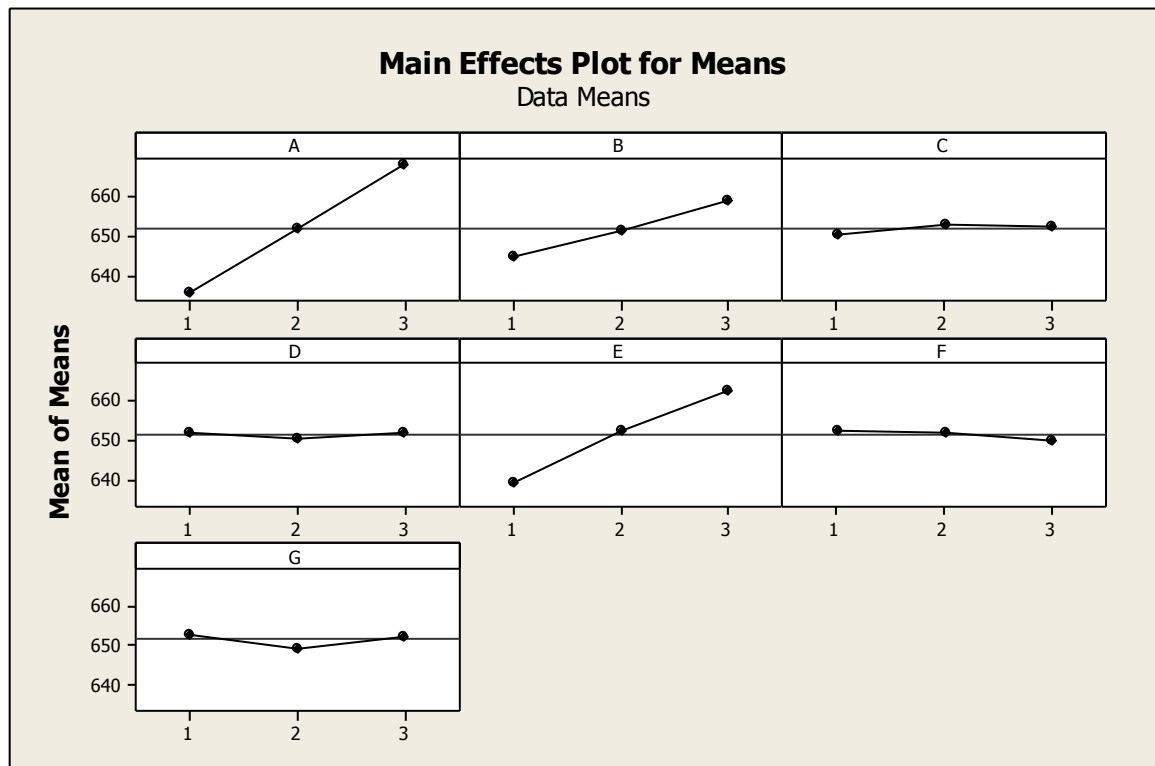


Figure 6.11: Main effects plot for Means (vertical ground reaction force  $F_z$ )

The ‘mean effects plots’ for loading rate are shown in Figure 6.12. These plots show the variation of loading rate for significant factors weight, vertical distance and lifting frequency. Loading rate increases when maximum weight (23 kg) was lifted from floor to shoulder level with maximum frequency. The mean loading rate was plotted for different vertical distance, weight and lifting frequency and is shown in Figure 6.13.

The plots clearly show that the loading rate increases almost linearly with increase in weight to be lifted and also with increased frequency of lifting. Also, loading rate increases with increased vertical distance. Even when the weight to be lifted is not increased, the loading rate increases with higher lifting frequency. The loading rate shows no considerable change when the vertical distance is increased from 55 cm (knee level) to 110 cm (waist height). However, there is a definite increase in loading rate when the vertical distance increases beyond this level to 150 cm (shoulder level). The increased loading rate signifies an increased exertion to the workers engaged in dynamic lifting tasks.

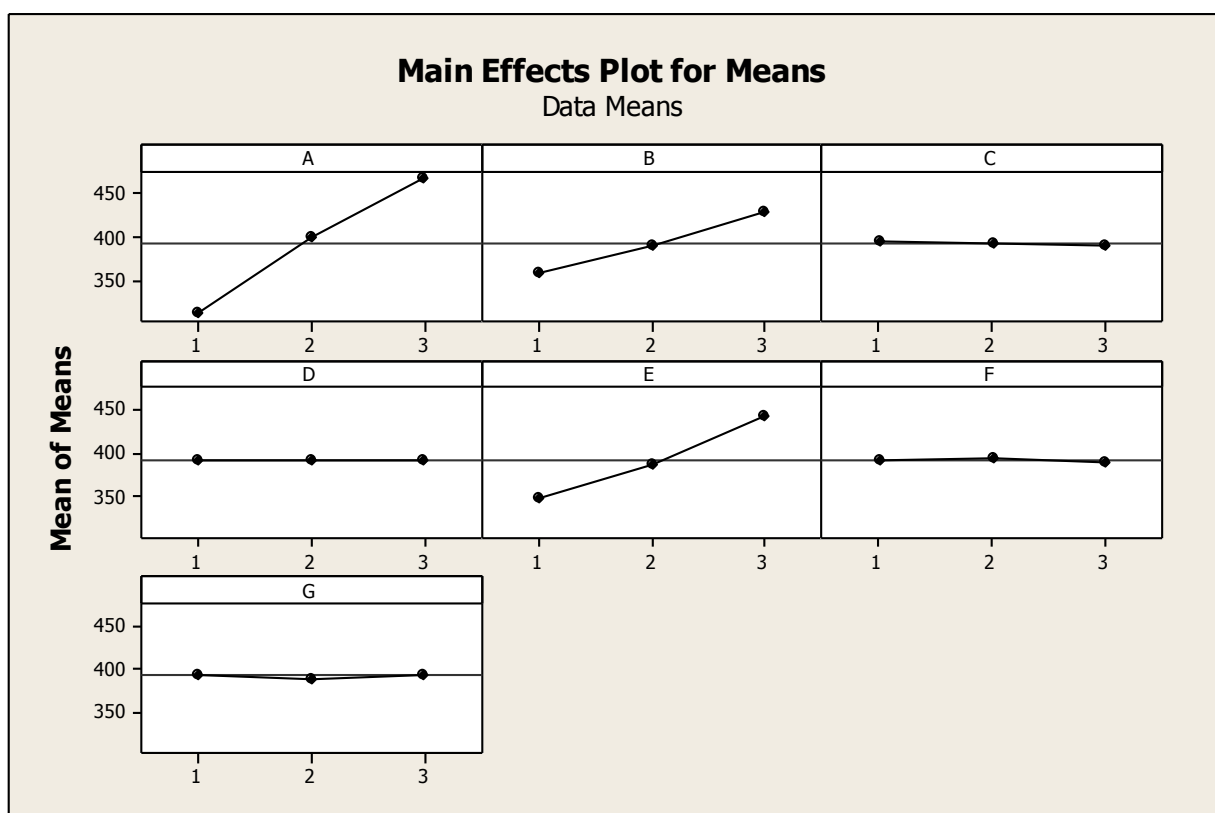


Figure 6.12: Main effects plot for Means (loading rate, LR)

Since weight, lifting frequency and vertical distance significantly affected the loading rate, different combinations of these factors were used to identify the least and the most exerting task conditions. For example, when the weight was increased from 13 to 23kg without altering the lifting frequency and vertical distance, the mean loading rate increased by 33.8 percent. Similarly, for the same weight and vertical distance, when the frequency was increased from 5 to 9 lifts per minute, the loading rate increased by 21.15 percent. On similar lines, when weight and lifting frequency were kept constant and the vertical distance was increased from floor to

the shoulder level, the loading rate increased by 27.9 percent. The results representing the resultant change in loading rate with the change in task parameters are compiled in Table 6.6.

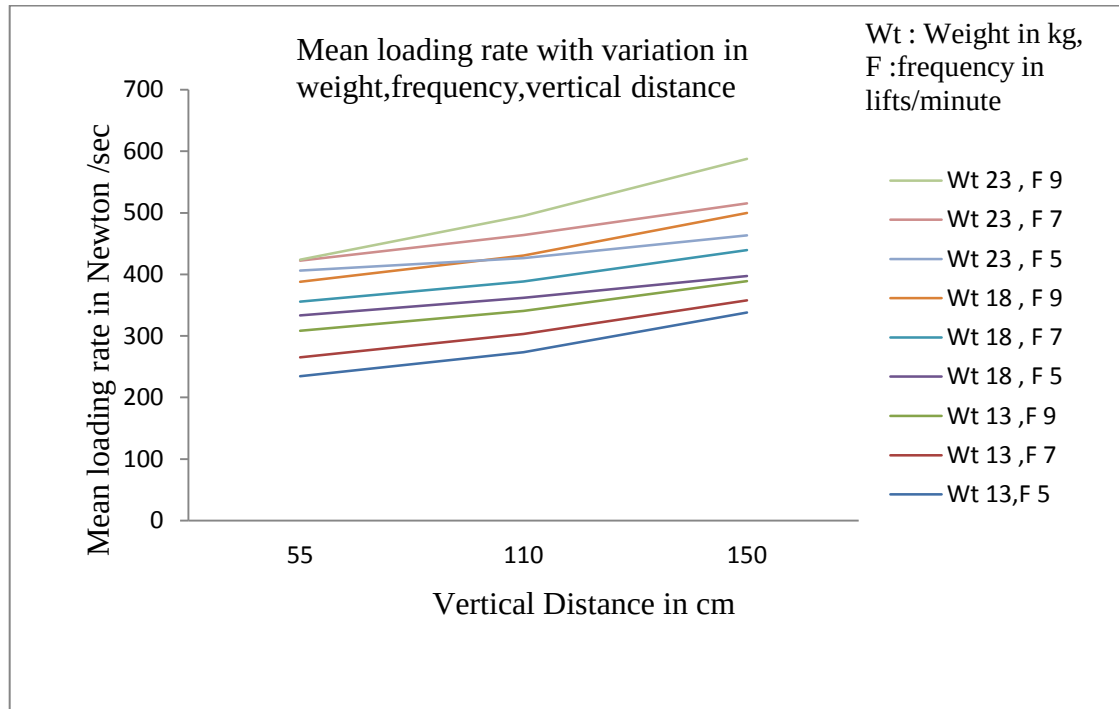


Figure 6.13: Mean loading rate plot with variation in weight, frequency and vertical distance.

(Mean loading rate in N/s, Weight (w) in kg, Frequency (f) in lifts/min and Vertical distance in cm)

#### 6.4 OPTIMAL DESIGN FOR LOADING RATE

To arrive at the optimal conditions that would cause lowest exertion to the workers, the lower most levels of the significant factors may be used. However, such a solution will mean that the weight, frequency and vertical distance should be at their lower most levels.

Table 6.6: Extra loading rate required with changing levels of significant factors

| Weight (A)                       |                      |                                | Frequency (B)                 |                               |                                | Vertical Distance (E)   |                            |                                |
|----------------------------------|----------------------|--------------------------------|-------------------------------|-------------------------------|--------------------------------|-------------------------|----------------------------|--------------------------------|
| Frequency & Vertical Dist. fixed | Weight Increase (Kg) | Percent change in loading rate | Weight & Vertical Dist. fixed | Frequency Increase per minute | Percent change in loading rate | weight, Frequency fixed | Vertical Distance Increase | Percent change in loading rate |
| 5,knee                           | 13 to 23             | 42.28                          | 13,knee                       | 5 to 9                        | 23.99                          | 13,5                    | knee to shoulder           | 30.71                          |
| 9,shoulder                       | 13 to 23             | 33.8                           | 23,shoulder                   | 5 to 9                        | 21.15                          | 23,9                    | knee to shoulder           | 27.9                           |

No purpose would be served by a solution that lift as little a weight as possible at one's own pace or reduce the distance of the destination at which the weight is to be placed, to reduce the

vertical distance. A solution involving keeping the weight, frequency and vertical distance at their lower most level, will not be optimal as very little work will be done. It is not possible to design tasks as per this solution. In actual production workshops, it may be desirable to handle as much weight as possible at high frequency of lifting at some particular vertical distance so that adequate output is obtained from the task/worker. It is desirable that such combinations of weight, lifting frequency and vertical distance are identified that increases work productivity and at the same time do not cause overly high exertion to the workers. This would mean that optimal levels for combination of weight, lifting frequency and vertical distance be arrived at. For an optimal solution, response values would be fixed at an appropriate level which would cause low to moderate exertion.

In the first phase of the study, experiments were conducted to evaluate the affect of lifting task parameters in different ambient temperature conditions on the heart rate and oxygen uptake of workers involved in manual lifting tasks. Three factors, i.e., weight, lifting frequency and vertical distance were found to significantly affect the two responses. Various combinations of the three significant factors were used to calculate the oxygen uptake and heart rate which were then compared with the safe limits as per the maximum aerobic capacity of the workers. Based on these comparisons, the safe combinations of the three factors were identified which can be used to design lifting tasks in varied ambient conditions. In order to find optimal solution for the loading rate, the safe limits of oxygen uptake and heart rate were used from the previous study. The best fit equation for the three responses loading rate, oxygen uptake and heart rate was obtained using a Mat Lab code (Annexure I) and is given by equation (6.2).

$$Z = -157.22 - 29.39 \times X + 2.55 \times X^2 + 4.46 \times Y \quad \text{.....Equation (6.2)}$$

Where Z, X and Y are loading rate (LR) in Newton/sec, oxygen uptake (VO<sub>2</sub>) in ml/kg/min and heart rate (HR) in beats per minute respectively. Numbers 157.22, 29.39, 2.55 and 4.46 are constants.

To solve equation (6.2), the safe limit for oxygen uptake and heart rate were used as 33% of the maximum aerobic capacity (Bridger [18]). This safe limit was calculated as 12.93 ml/kg/min (33% of the maximum aerobic capacity of the workers) for oxygen uptake and 110 beats per minute for heart rate (Astrand and Rhodahl, 1977 [4]). These values were taken from the first phase of the study. Using this data, the safe upper limit for loading rate was calculated to be 380 Newton/sec. Each of three responses is mutually predictable.

Figures 6.14 and 6.15 show the expected value of loading rate for different values of oxygen uptake and heart rate respectively. From the plot, it can be observed that the safe limit obtained for loading rate (380 Newton/sec) is in agreement with the safe limits for oxygen uptake (12.93 ml/kg/min) and heart rate 110 beats per minute. Each of the three responses is mutually predictable. Figure 6.19 shows the expected value of loading rate for different combinations of oxygen uptake and heart rate. For example, loading rate can be calculated if oxygen uptake and heart rate are known. Loading rate can then be used to estimate the ground reaction force ( $F_z$  in this case). To identify the optimal combinations of weight, lifting frequency and vertical distance the results of loading rate were used in conjunction with oxygen uptake and heart rate calculated from the first phase of the study.

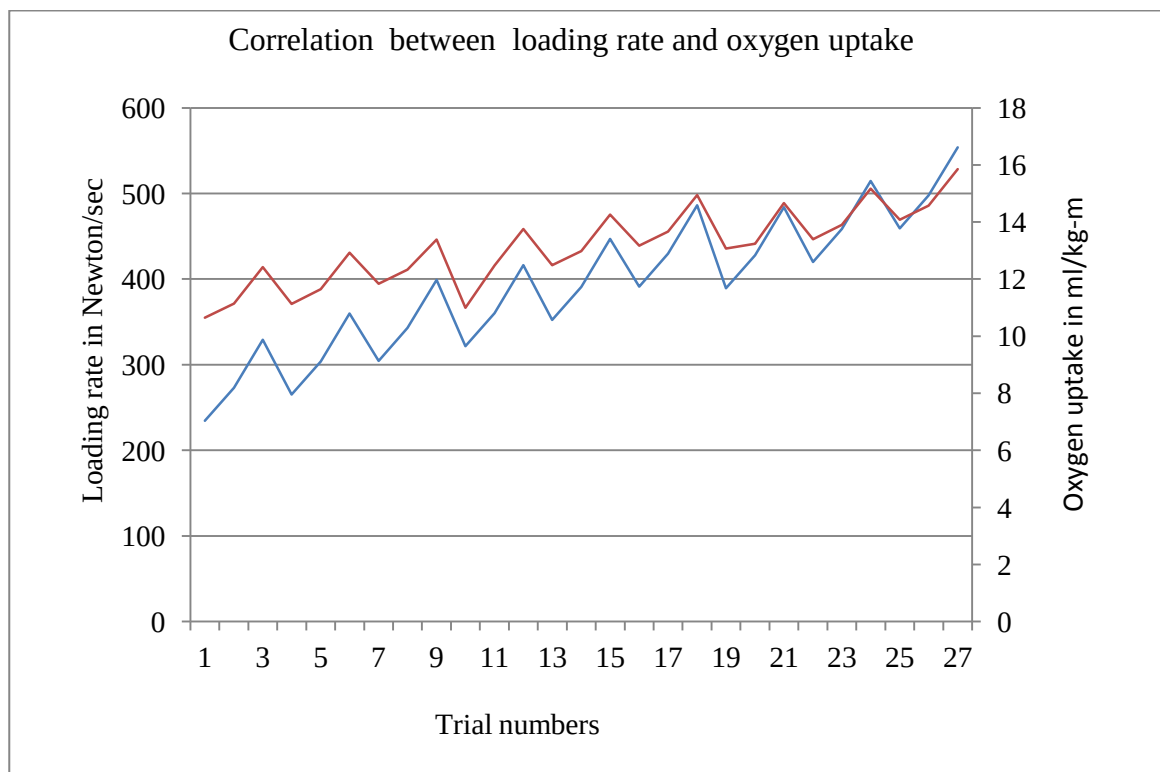


Figure 6.14: Correlation graph of loading rate and oxygen uptake for workers involved in lifting

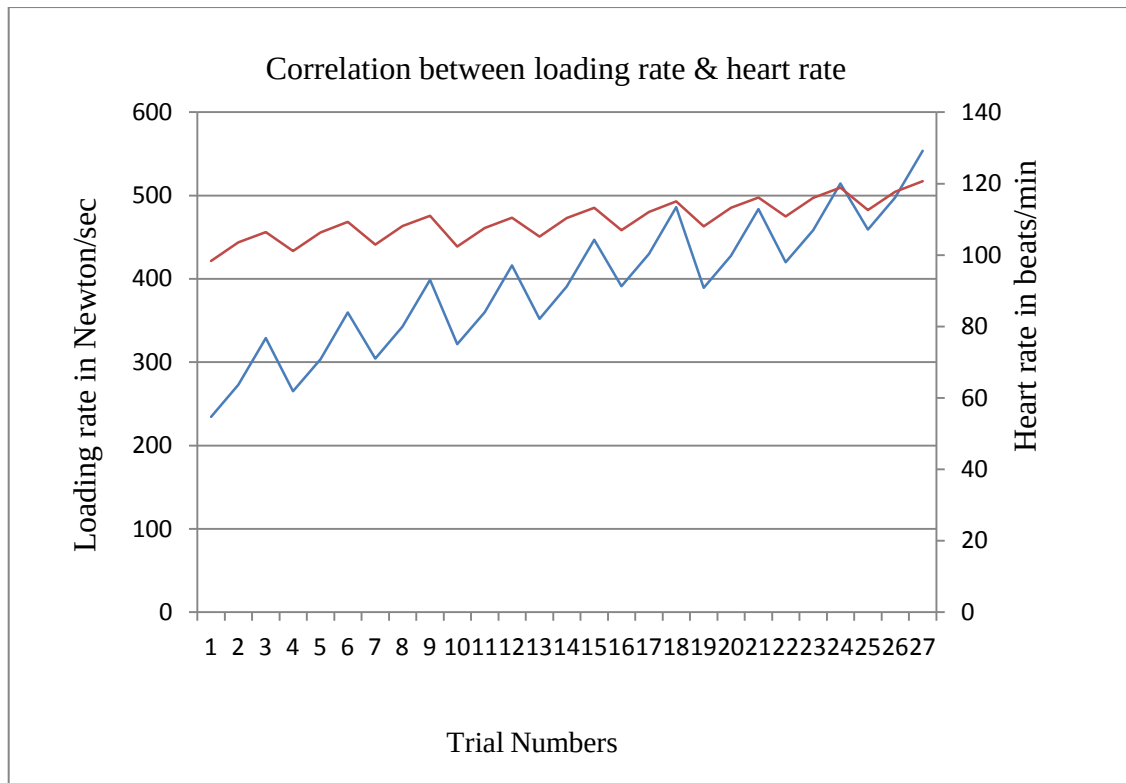


Figure 6.15: Correlation graph of loading rate and heart rate for workers involved in lifting

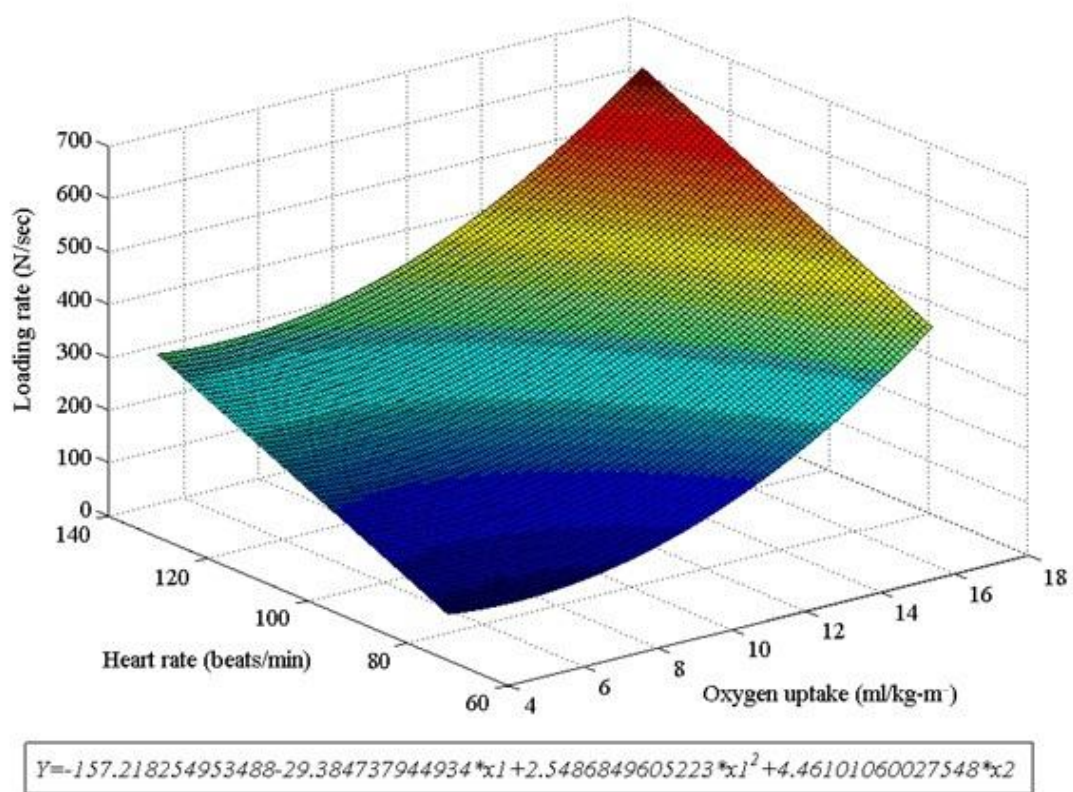


Figure 6.16: Correlation graph of loading rate, oxygen uptake and heart rate for workers involved in lifting

The ANOVA results show that three factors, weight, frequency and vertical distance significantly affected the loading rate. Same factors were also identified as significant in the first phase of the study. The optimal values of loading rate, oxygen uptake and heart rate were calculated using the Taguchi's additive model for all the 27 different combinations of the three significant factors and are given in Table 6.7. One sample calculation for optimum loading rate (trial no. 6) and oxygen uptake (trial no. 22) is given below.

$$LR_{A_1B_2E_3} = \bar{A}_1 + \bar{B}_2 + \bar{E}_3 - 2\bar{T} = 312.33 + 390.13 + 443.24 - 2 \times 392.96 = 359.78 \quad \text{Newton/sec}$$

$$VO2_{A_3B_2E_1} = \bar{A}_3 + \bar{B}_2 + \bar{E}_1 - 2\bar{T} = 14.2 + 13.1 + 12.4 - 2 \times 13.16 = 13.4 \quad \text{Ml/kg-min}$$

Where  $LR_{A_1B_2E_3}$  is the predicted loading rate when factor A (weight) is taken as level 1, factor B (lifting frequency) is taken as level 2 and factor E (vertical distance) is taken as level 3. Similarly,  $VO2_{A_3B_2E_1}$  is the predicted oxygen uptake when weight is taken as level 3, lifting frequency is taken as level 2 and vertical distance is taken as level 1.  $\bar{T}$  is the mean of all responses. The combined results for the three responses are given in Table 6.7

All the trials that exhibited a loading rate of less than the safe limit of 380 Newton/sec were considered as safe trials and the combinations used in these trials as safe factor settings for the three factors. All trials that had loading rate beyond this safe limit can be described as potentially hazardous and such combinations of the three factors should be avoided as these are likely to cause excessive exertion and musculoskeletal disorders. Another observation made from Table 6.7 is that the safe trials identified using the loading rate are in broad agreement with those identified with oxygen uptake and heart rate. Safe limit bar charts were plotted for loading rate, oxygen uptake and heart rate and are shown in Figures 6.17, 6.18 and 6.19. The bold horizontal line represents the safe limit of the response and any value over this limit represents a potentially hazardous trial condition. The weight, frequency and the vertical distance combination used in these trials should be avoided.

Table 6.7: Decision matrix for identifying safe lifting task (options for optimal designs)

| Trial No. | Wt (Kg)<br>A | Freq (lifts/min)<br>B | V.D (cm)<br>E | Optimum mean loading rate<br>Newton /sec | Decision with Safe limit $\leq 380$ Newton /sec | From First Phase study               |                                                 |                                   |                                               |
|-----------|--------------|-----------------------|---------------|------------------------------------------|-------------------------------------------------|--------------------------------------|-------------------------------------------------|-----------------------------------|-----------------------------------------------|
|           |              |                       |               |                                          |                                                 | Optimum mean oxygen uptake ml/kg-min | Decision with Safe limit $\leq 12.93$ ml/kg-min | Optimum mean heart rate beats/min | Decision with Safe limit $\leq 110$ beats/min |
| 1         | 13           | 5                     | E1            | 234.44                                   | Y                                               | 10.65                                | Y                                               | 98.38                             | Y                                             |
| 2         | 13           | 5                     | E2            | 272.95                                   | Y                                               | 11.145                               | Y                                               | 103.55                            | Y                                             |
| 3         | 13           | 5                     | E3            | 329.11                                   | Y                                               | 12.42                                | Y                                               | 106.455                           | Y                                             |
| 4         | 13           | 7                     | E1            | 265.11                                   | Y                                               | 11.13                                | Y                                               | 101.13                            | Y                                             |
| 5         | 13           | 7                     | E2            | 303.62                                   | Y                                               | 11.65                                | Y                                               | 106.345                           | Y                                             |
| 6         | 13           | 7                     | E3            | 359.78                                   | Y                                               | 12.925                               | Y                                               | 109.25                            | Y                                             |
| 7         | 13           | 9                     | E1            | 304.27                                   | Y                                               | 11.835                               | Y                                               | 102.915                           | Y                                             |
| 8         | 13           | 9                     | E2            | 342.78                                   | Y                                               | 12.33                                | Y                                               | 108.085                           | Y                                             |
| 9         | 13           | 9                     | E3            | 398.94                                   | N                                               | 13.385                               | N                                               | 110.99                            | N                                             |
| 10        | 18           | 5                     | E1            | 321.51                                   | Y                                               | 11                                   | Y                                               | 102.385                           | Y                                             |
| 11        | 18           | 5                     | E2            | 360.02                                   | Y                                               | 12.48                                | Y                                               | 107.555                           | Y                                             |
| 12        | 18           | 5                     | E3            | 416.18                                   | N                                               | 13.755                               | N                                               | 110.46                            | N                                             |
| 13        | 18           | 7                     | E1            | 352.18                                   | Y                                               | 12.49                                | Y                                               | 105.18                            | Y                                             |
| 14        | 18           | 7                     | E2            | 390.69                                   | N                                               | 12.985                               | N                                               | 110.35                            | N                                             |
| 15        | 18           | 7                     | E3            | 446.85                                   | N                                               | 14.26                                | N                                               | 113.255                           | N                                             |
| 16        | 18           | 9                     | E1            | 391.34                                   | N                                               | 13.17                                | N                                               | 106.92                            | Y                                             |
| 17        | 18           | 9                     | E2            | 429.85                                   | N                                               | 13.665                               | N                                               | 112.09                            | N                                             |
| 18        | 18           | 9                     | E3            | 486.01                                   | N                                               | 14.94                                | N                                               | 114.995                           | N                                             |
| 19        | 23           | 5                     | E1            | 389.26                                   | N                                               | 13.075                               | N                                               | 108.04                            | Y                                             |
| 20        | 23           | 5                     | E2            | 427.77                                   | N                                               | 13.24                                | N                                               | 113.21                            | N                                             |
| 21        | 23           | 5                     | E3            | 483.93                                   | N                                               | 14.665                               | N                                               | 116.115                           | N                                             |
| 22        | 23           | 7                     | E1            | 419.93                                   | N                                               | 13.4                                 | N                                               | 110.835                           | N                                             |
| 23        | 23           | 7                     | E2            | 458.44                                   | N                                               | 13.895                               | N                                               | 116.005                           | N                                             |
| 24        | 23           | 7                     | E3            | 514.6                                    | N                                               | 15.17                                | N                                               | 118.91                            | N                                             |
| 25        | 23           | 9                     | E1            | 459.09                                   | N                                               | 14.08                                | N                                               | 112.575                           | N                                             |
| 26        | 23           | 9                     | E2            | 497.6                                    | N                                               | 14.575                               | N                                               | 117.745                           | N                                             |
| 27        | 23           | 9                     | E3            | 553.76                                   | N                                               | 15.85                                | N                                               | 120.65                            | N                                             |

(Note: Wt: Weight, Freq: Frequency, V.D: Vertical distance, E<sub>i</sub>: Factor E set at i<sup>th</sup> level,

Y: Safe lifting task, N: Unsafe lifting task)

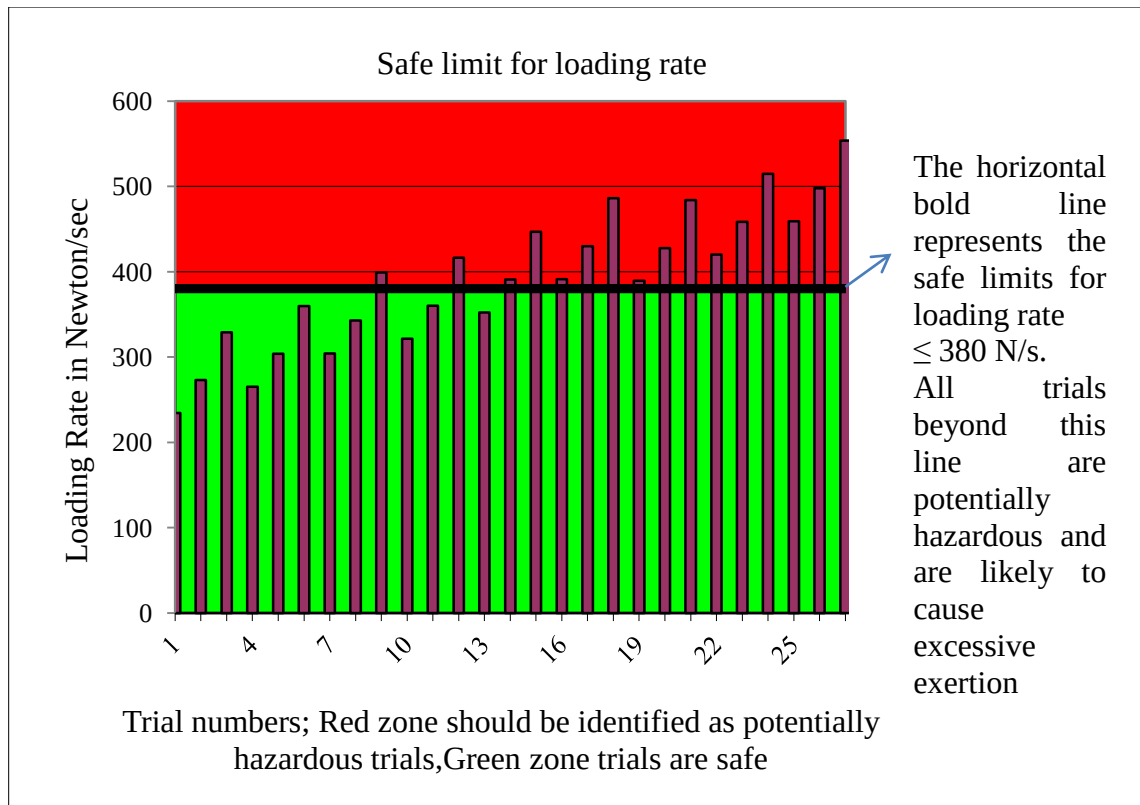


Figure 6.17: Safe optimum graph of loading rate for workers involved in lifting task

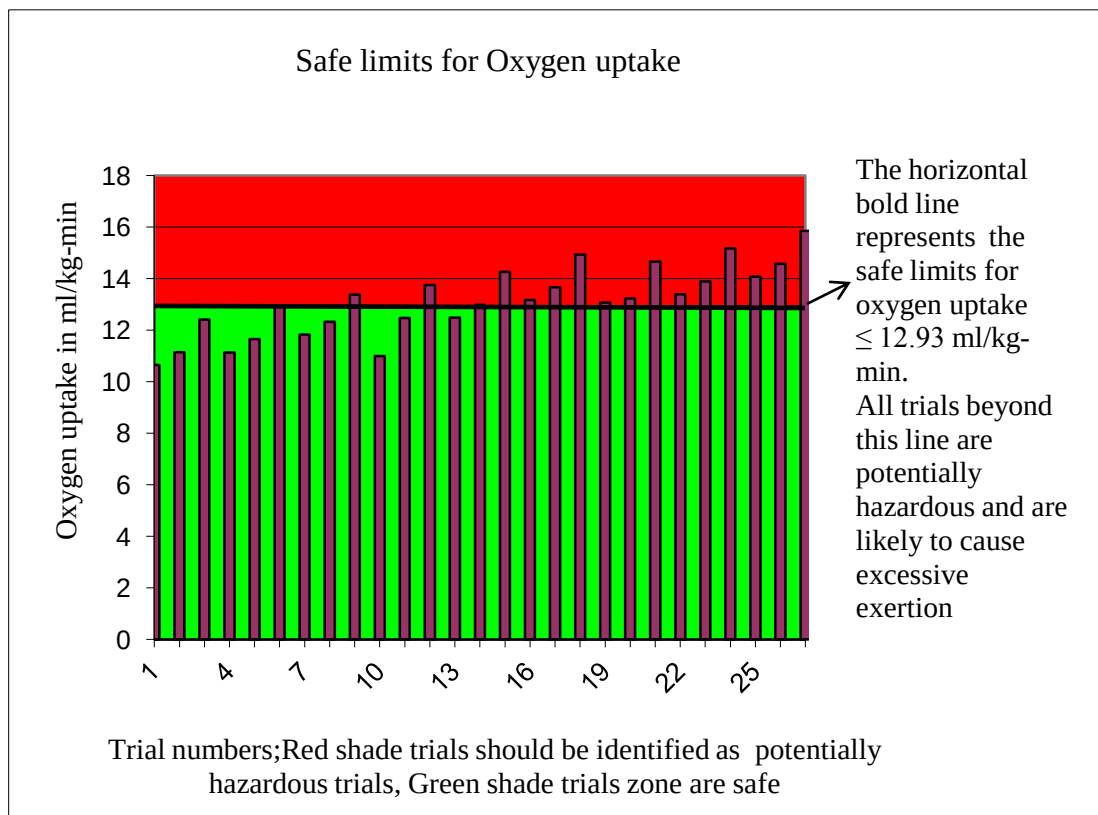


Figure 6.18: Safe optimum graph of oxygen uptake for workers involved in lifting task

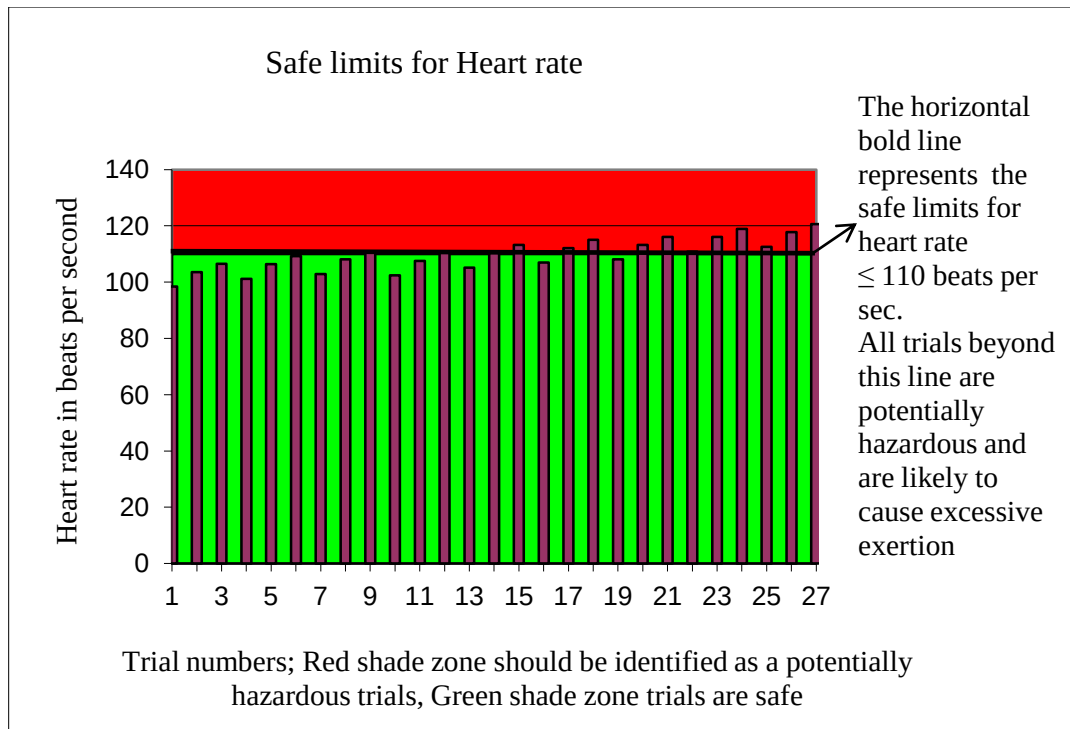


Figure 6.19: Safe optimum graph of heart rate for workers involved in lifting task

The safe limits for various task parameters were established to prevent/reduce injuries to workers engaged in lifting and carrying tasks. Three task parameters namely weight, lifting frequency and vertical distance were found to be significantly affecting the exertion caused to the worker. The safe limits were established in terms of loading rate and are the safe trials can be noted from Figure 6.17. The safe limits can also be established in terms of the significant parameters wherein various combinations of load, lifting frequency and vertical distance are presented to design a manual lifting task using the regression equation developed in the previous section. For example, if the weight to be lifted up to knee level is 20 kg, then the lifting frequency should not exceed 5 lifts per minute. Same way the safe combinations of the three parameters are presented in Table 6.8.

Table 6.8: Safe Limits for various combinations of weight, lifting frequency and vertical distance

| Sr. No. | Weight (kg) | Frequency (lifts per minute) | Vertical distance | Remarks |
|---------|-------------|------------------------------|-------------------|---------|
| 1       | 8 to 12     | 5 to 9                       | Knee to shoulder  | Safe    |
| 2       | 13 to 16    | 5                            | Knee to shoulder  | Safe    |
|         |             | 7                            | Knee to shoulder  | Safe    |

|   |          |        |                |        |
|---|----------|--------|----------------|--------|
|   |          | 9      | Knee and waist | Safe   |
|   |          | 5      | Knee and waist | Safe   |
| 3 | 16 to 18 | 7      | Knee only      | Safe   |
|   |          | 9      | -              | Unsafe |
|   |          | 5      | Knee only      | safe   |
| 4 | 18 to 20 | 7      | -              | Unsafe |
|   |          | 9      | -              | Unsafe |
| 5 | 21 to 23 | 5 to 9 | -              | Unsafe |

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## CHAPTER 7

### PREDICTION OF LOADING RATE USING NEURAL NETWORKS

This chapter presents development of a model using artificial neural networks for the results of the experimental study to estimate the ground reaction forces (loading rate) that cause exertion to workers during a manual lifting task.

An artificial neural network model was developed to predict the ground reaction forces. The artificial neural network model (ANN) accurately predicts the loading rate in a lifting task and is a reliable tool for predicting exertion caused to workers during a lifting task. The lifting task parameters; lifting frequency, load, vertical distance, horizontal and travel distances were used as inputs to develop the neural network model. The loading rate was calculated from the graphical output of ground reaction forces after the completion of the trials.

#### 7.1 EXPERIMENTAL DESIGN

On the basis of the pilot study, several parameters affecting the vertical reaction force were identified. These parameters were (i) lifting frequency, (ii) load, (iii) vertical distance and (iv) horizontal distance and travel distance and were varied at different levels for detailed study of their effect on ground reaction force (GRF). The experiments were conducted on fourteen healthy workers (age 21 to 32), with their consent and were routinely engaged in manual lifting tasks. Each worker was asked to lift a loaded container at different vertical lifting heights (from floor to knee height, knee to waist height and waist to shoulder height). The list of factors and their levels is given in Table 7.1.

Table 7.1: Factors involved with their levels in second part of study of second phase

| Factors (unit)                     | Levels    |           |           |
|------------------------------------|-----------|-----------|-----------|
|                                    | Level – 1 | Level – 2 | Level – 3 |
| Lifting frequency, A(lifts/minute) | 5         | 7         | 9         |
| Load, B (kg)                       | 13        | 18        | 23        |
| Vertical distance, C (cm)          | 55        | 110       | 150       |
| Horizontal distance, D(cm)         | 20        | 40        | -         |
| Travel Distance, G (cm)            | 25        | 45        | 60        |

The experiment design layout was made using Taguchi's Fractional Factorial Experiments (FfEs) for designing orthogonal trial conditions (Taguchi [168]; Ross [142]; Montgomery, [125]). Considering the degrees of freedom required from the array, a mixed level  $L_{18}$  (one column for assigning a two level factor and four columns for assigning three level factors) orthogonal array was selected. The factors were assigned in appropriate columns using MINITAB 16 (see Table 7.2). The experimental set up was completed using two Kistler force platforms (9286AA, 200 Hz). To measure trials time, rest periods and distances varied in the study, a stop watch and ruler were used respectively. Vertical ground reaction force was considered as the principal response parameter.



Figure 7.1: Experimental Set up with Kistler force platforms

## 7.2 CALCULATION OF LOADING RATE

Ground reaction forces (GRF) measured using a Force Platform, is equal in magnitude and opposite in direction to the action force that is applied to the force plate. GRF is represented in vertical, anterior- posterior and medial lateral planes. The two horizontal components of the GRF are denoted as  $F_x$  and  $F_y$  and the vertical component is denoted as  $F_z$ . The vertical component of force  $F_z$  is the most important measure related to this study and is obtained by bending and stretching of the body. Here, the GRF is the vertical component ( $F_z$ ) measured on the force platform.

In the present lifting task, the worker bends to lift the loaded container and then places it at the desired place. These motions create vertical acceleration of the body which can be measured

using the force platform. The vertical reaction force,  $F_z$  was measured as a graphical output for each trial and for all workers during continuous lifting for 15 minutes. One such plot for duration of one minute as per conditions laid in trial 10 is shown in Figure 7.2. The plot shows the variation of  $F_z$  against time. Data for complete 15 minutes of lifting was plotted but because of constraints of representing on the plot for this thesis a one minute duration plot is shown. As per the trial conditions used for trial 10, a load of 18 kg was lifted at a frequency of 5 lifts per minute. The five complete lifts can be seen in Figure 7.2 and time taken to complete one lift was 10.5 sec. For detailed analysis of the time taken for one lift, this time was divided in four time phases. Figure 7.3 shows the subset of the plot for trail 10 for one lift of 10.5 seconds.

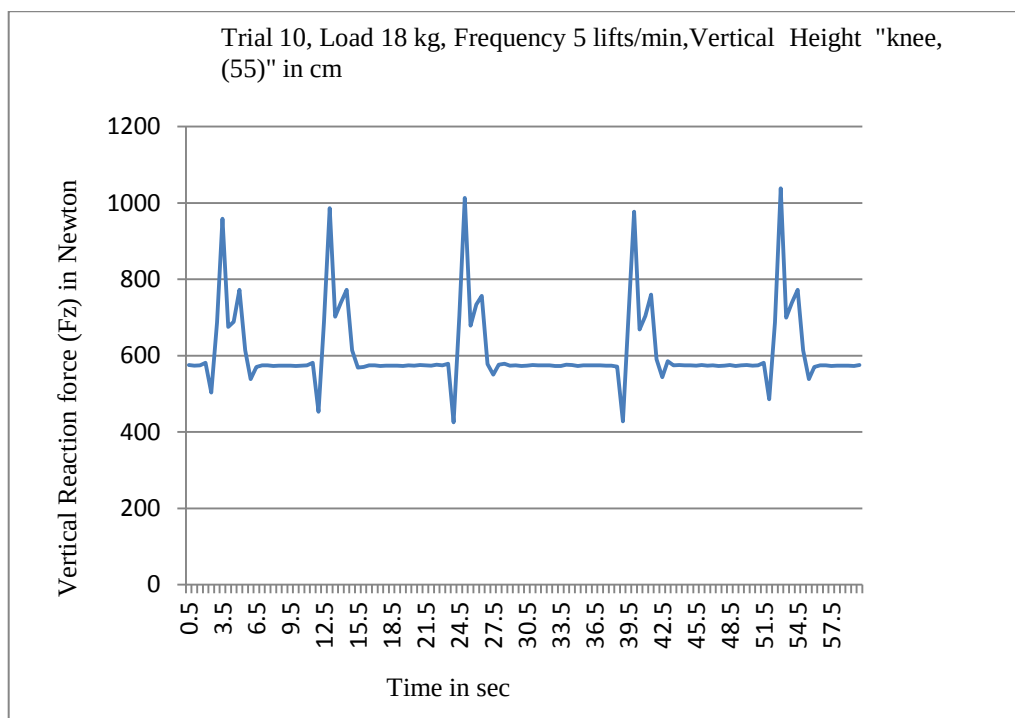


Figure 7.2: Force –time vertical reaction force graph for workers involved in lifting task  
(Trial no. 10, 5 lifts in 60 seconds)

Positions 1 represents the initial position of the worker at the beginning of the lift. At this position, the vertical reaction force,  $F_z$  is equal to the body weight of the worker. For the initiation of the lifting task, worker bends to lift the load this is represented as position 2.  $F_z$  at this position is less than the body weight of worker because of the jerking action required to initiate the lift. Position 3 shows the time phase when actual lifting is completed and is represented by an increase in magnitude of  $F_z$  in comparison to the body weight and is obtained by measuring the gradient of a tangent. Position 4 represents the final resting position

of the worker after the completion of the lift. In this position also,  $F_z$  is equal to the body weight. From these plots of  $F_z$  and time, average loading rate can be calculated as the rate at which  $F_z$  rises. Also, instantaneous loading rate can be evaluated by measuring the gradient of a tangent that is drawn at the point on the  $F_z$ –time curve where the rate of change is considered to be the highest. The main cause of the risk of chronic injury in such dynamic lifting activities is the peak rate of vertical ground reaction force and is defined as the loading rate (Miller and Nigg) [119, 128].

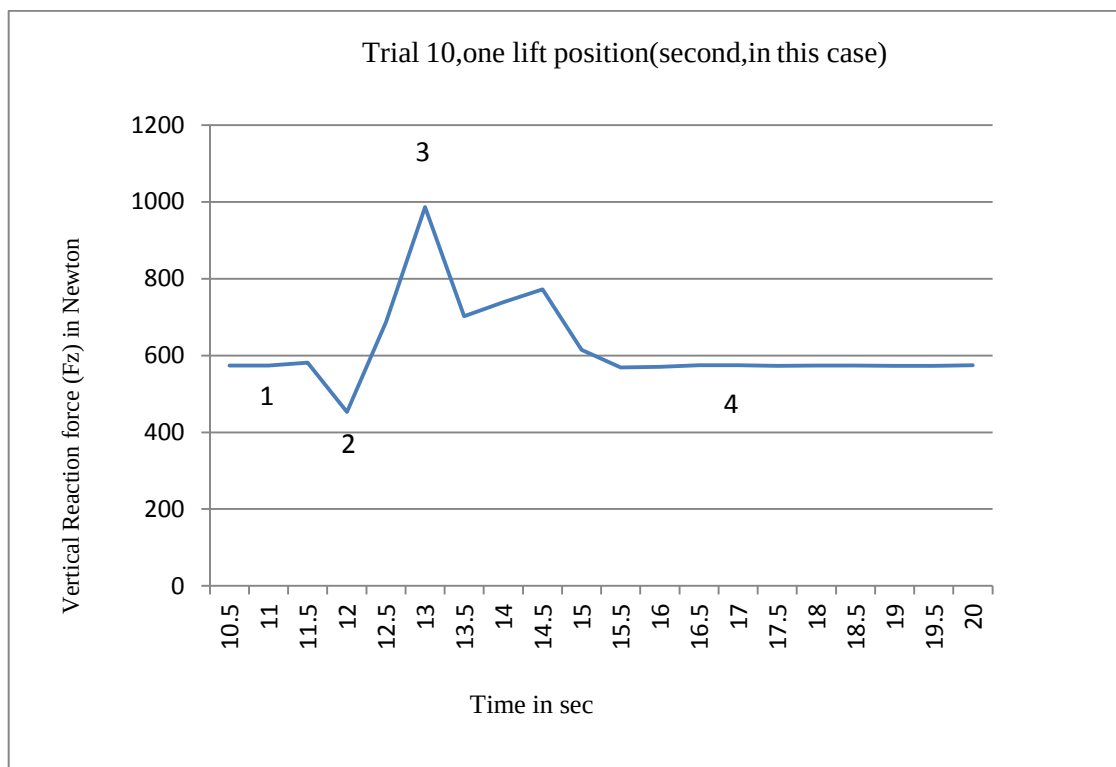


Figure 7.3: Force –time vertical reaction force graph for workers involved in lifting task (Trial no. 10, one lift (2<sup>nd</sup>, in this case) in 10.5 sec)

The loading rate was calculated from the graphical output of vertical ground reaction force after completion of each trial of experimental design layout. Mean loading rate of all workers and trials are shown in Table 7.2.

### 7.3 ANALYSIS OF LOADING RATE

The results for loading rate were analyzed using analysis of variance (ANOVA) and are given in Table 7.3. F-value and p-value given in Table 7.3 define the significance of each effect. Higher the magnitude of the F-test value for a particular factor, larger is the effect of that factor on the loading rate. The percentage contribution of each factor was calculated from sum of

squares and residual error and is given in the last column of Table 7.3. It can be observed from results that load followed by vertical distance and lifting frequency were the significant factors affecting loading rate and the other factors had either no or minimal effect. The rate of vertical ground reaction force (loading rate) increased linearly when higher load was lifted (23 kg) from floor to the shoulder level at high lifting frequency. For further iterative analysis, ANN was used to establish a relationship between input and output parameters and predict the loading rate.

Table 7.2: Mean loading rate of all workers with experiment design trials

| Trial. No.<br>n=(1-18) | Input Parameters           |              |                         |                          |                      | Output Response                 |
|------------------------|----------------------------|--------------|-------------------------|--------------------------|----------------------|---------------------------------|
|                        | Frequency<br>(lift/minute) | Load<br>(kg) | Vertical<br>Height (cm) | Horizontal<br>Dist. (cm) | Travel<br>Dist. (cm) | Mean<br>Loading rate<br>(N/sec) |
| 1                      | 5                          | 13           | 55                      | 20                       | 25                   | 242.3                           |
| 2                      | 7                          | 13           | 110                     | 20                       | 45                   | 301.5                           |
| 3                      | 9                          | 13           | 150                     | 20                       | 60                   | 379.2                           |
| 4                      | 5                          | 18           | 55                      | 20                       | 45                   | 296.1                           |
| 5                      | 7                          | 18           | 110                     | 20                       | 60                   | 360.4                           |
| 6                      | 9                          | 18           | 150                     | 20                       | 25                   | 461.7                           |
| 7                      | 7                          | 23           | 55                      | 20                       | 25                   | 376                             |
| 8                      | 9                          | 23           | 110                     | 20                       | 45                   | 479.8                           |
| 9                      | 5                          | 23           | 150                     | 20                       | 60                   | 441.1                           |
| 10                     | 9                          | 13           | 55                      | 40                       | 60                   | 300.6                           |
| 11                     | 5                          | 13           | 110                     | 40                       | 25                   | 268.2                           |
| 12                     | 7                          | 13           | 150                     | 40                       | 45                   | 340.3                           |
| 13                     | 7                          | 18           | 55                      | 40                       | 60                   | 319.4                           |
| 14                     | 9                          | 18           | 110                     | 40                       | 25                   | 400                             |
| 15                     | 5                          | 18           | 150                     | 40                       | 45                   | 370.9                           |
| 16                     | 9                          | 23           | 55                      | 40                       | 45                   | 405.5                           |
| 17                     | 5                          | 23           | 110                     | 40                       | 60                   | 397.1                           |
| 18                     | 7                          | 23           | 150                     | 40                       | 25                   | 510.8                           |

Table 7.3: Pooled ANOVA for loading rate

| Factors               | DOF | Sum of Squares | Variance | F-value | P-value | Percentage contribution |
|-----------------------|-----|----------------|----------|---------|---------|-------------------------|
| Lifting Frequency(A)  | 2   | 21723          | 10863.5  | 58.92   | 0.027*  | 15.11                   |
| Load (B)              | 2   | 80601          | 40300.5  | 218.60  | 0.003*  | 56.79                   |
| Vertical distance (C) | 2   | 35514          | 17757    | 96.32   | 0.041*  | 24.87                   |
| Pooled Error          | 20  | 3687           | 184.35   |         |         |                         |
| Total                 | 26  | 141269         |          |         |         |                         |

(Note : DOF= Degrees of freedom)

## 7.4 ARTIFICIAL NEURAL NETWORK

Artificial neural systems are mathematical models of the brain-like systems that function as parallel distributed computing networks that can be trained to learn new associations, functional dependencies and new patterns (Zurada [188,187]; Lin and Lee [106]; Fuller [54]). To predict the loading rate during manual lifting, a multilayer, fully connected, feed-forward network was used. The multilayer, feed forward networks are capable of generating arbitrarily close approximations to any continuous nonlinear mapping (Cybenko [33]; Hush [74]). A network is made up of a processing element or unit as a neuron and the connections between units are indicated by the arc. The flow of information is indicated by the arrowhead on the connections. Figure 7.4 shows the general processing element or neuron model.

After calculating the net input, the model produces final output and passes it on to a non-linear filter called activation function. There are many activation functions used in neural networks. An activation function continuous in nature that varies gradually between the asymptotic values 0 and 1 or -1 and +1 is generally used in multilayer network. Data enters at the inputs and passes layer by layer through the network till the outputs are arrived at. The outputs are compared to the desired outputs and an error signal is computed for output nodes and depending on the error signal, an updated connection weight is obtained through training using the Leven berg-Marquardt Back Propagation algorithm (LMBP). This comparison of the output from the network and the target is continuously made until the network output matches the target output. This procedure provides better generalization in trained networks.

For establishing a neural network model, the experimental data was divided into three sets namely (i) the training set (T), (ii) the testing set (S) and (iii) the validation set (V). The training set was used to compute the gradient and to determine the weight update. The test set was used to signal when to stop training. As per the modeling procedure, the training should be

terminated when the error on the test set starts to go up to avoid over fitting the network or when any of the stopping condition of the LMBP technique is satisfied. The validation set is used to compare the generalization abilities of different networks.

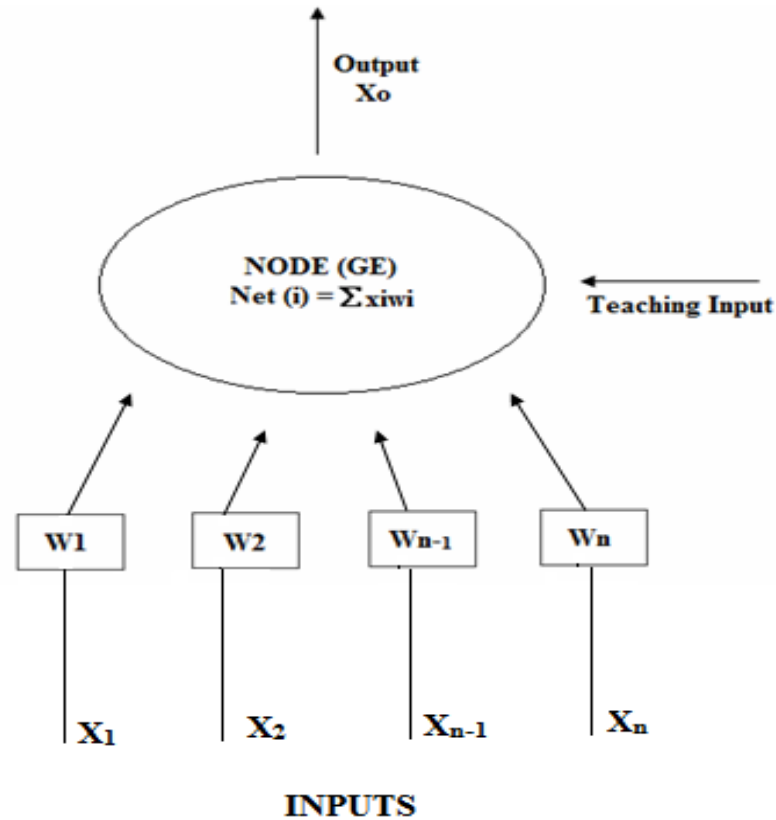


Figure 7.4: Schematic diagram of single neuron in a network model, showing how it was connected to other nodes and the each input connections with weight

All the input variables and output variable were normalized between 0.1 and 0.9 (0 and 1) because the logistic activation function was used in developing the network. The following loop was used for iteration of the network.

- Separate the experimental data in three sets as described above in appropriate percentages
- Train the network using training set (T) and test the resulting network using test set (S)
- Assess generalization performance using validation set (V)
- Revise one variable with weight update and continue from initial step.

The network consisted of one input layer (as many neurons as the number of inputs), the hidden layer (the number of units variables) and the output layer (a single neuron) and was assumed to be 5-N-1, where N are the number of neurons in the hidden layer. The experimental

data from Table 7.2 was used to train, test and validate the ANN predicted model. Five input parameters with their levels and one output response (loading rate) in this study as provided in Table 7.2. The experimental data obtained from the 18 trials were divided randomly in three subsets as (i) 12 for training, (ii) 3 for testing and (iii) 3 for validation and represent 67, 11.5 and 11.5 percent of the data respectively. The network was trained using LMBP algorithm of neural network tool box of Matlab 7.12.0 software. The error goal and learning rate were set as 0.001 and 0.1 respectively. A number of networks were constructed and the best network was identified based on Mean Squared Error (MSE) and Regression (Correlation) as the performance indices were utilized to understand the relation between predicted and desired output. These indices were then used as the criterion to measure the prediction accuracy of different networks. In the present study, twenty neurons in hidden layers were finally achieved from training algorithm for the best network and total neurons in network were (5+20+1=26). Training was repeated eight times with different network weights and biases to reduce the relative error. It was observed that the outcome of network directly depends upon the weight distribution done randomly. The best neural network architect that was selected for the prediction of loading rate is shown in Figure 7.5

The absolute percentage relative error between the network predicted value (output) and experimental value was calculated by the following equation 7.1.

$$\% \text{ Relative Error} = \left( \frac{\text{Experimental Results} - \text{ANN Predicted Results}}{\text{Experimental Results}} \right) \times 100 \quad \dots \text{Equation (7.1)}$$

The predicted results of neural network model are shown in Table 7.4 and it is clear that a the maximum variation of 3.26 percent and a minimum of 0.01 percent variations were observed between the experimental and predicted value represented for trial number 6 and 7 respectively and overall mean relative error was 0.852 percent which shows a close relationship.

The performance results of ANN predicted model for loading rate are shown in Figure 7.6. Best validation performance was obtained as 0.1641 at epoch 2. The plots of comparison of the experimental results with predicted results obtained by the neural network are shown in Figure 7.7. A very close relationship between both the results in verifying the network generalization capabilities is depicted in the plots. Table 7.5 shows the mean squared error and regression for training, testing and validation. Mean squared error is the average squared difference between outputs and targets and the lower values are considered better.

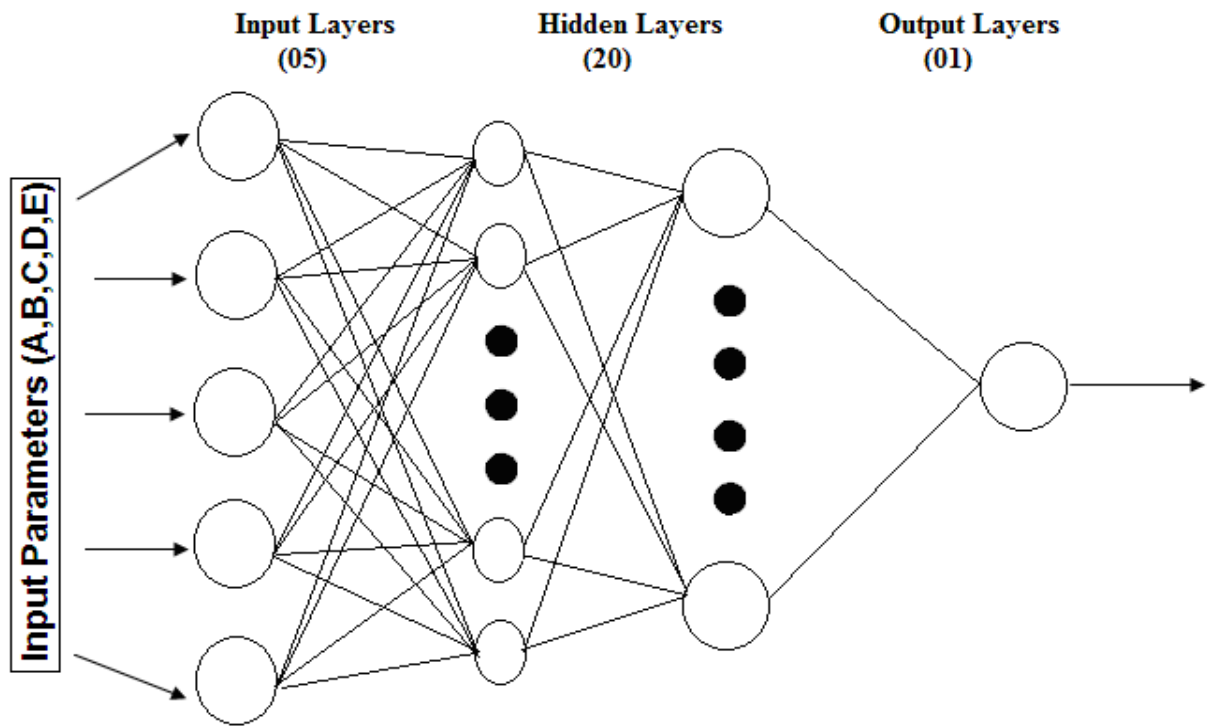


Figure 7.5: Neural network architect for predicted loading rate calculation

Table 7.4: Comparison of the experimental value and predicted value from ANN model

| Trial no.(1-18) | Output response (loading rate in Newton/sec) |                                | Percentage Relative Error |
|-----------------|----------------------------------------------|--------------------------------|---------------------------|
|                 | Experimental value                           | Predicted value from ANN model |                           |
| 1               | 242.3                                        | 245.52                         | 1.3345                    |
| 2               | 301.5                                        | 299.25                         | 0.7432                    |
| 3               | 379.2                                        | 379.35                         | 0.0318                    |
| 4               | 296.1                                        | 295.54                         | 0.1498                    |
| 5               | 360.4                                        | 364.38                         | 1.1067                    |
| 6               | 461.7                                        | 446.64                         | 3.2621                    |
| 7               | 376                                          | 375.23                         | 0.0124                    |
| 8               | 479.8                                        | 479.2                          | 0.1236                    |
| 9               | 441.1                                        | 434                            | 1.6089                    |
| 10              | 300.6                                        | 302.50                         | 0.0634                    |

|    |       |        |        |
|----|-------|--------|--------|
| 11 | 268.2 | 269.13 | 0.0421 |
| 12 | 340.3 | 342.43 | 0.6258 |
| 13 | 319.4 | 315.64 | 1.1743 |
| 14 | 400   | 401.27 | 0.3187 |
| 15 | 370.9 | 376.55 | 1.5112 |
| 16 | 405.5 | 396.40 | 2.2432 |
| 17 | 397.1 | 393.39 | 0.9324 |
| 18 | 510.8 | 510.52 | 0.0531 |

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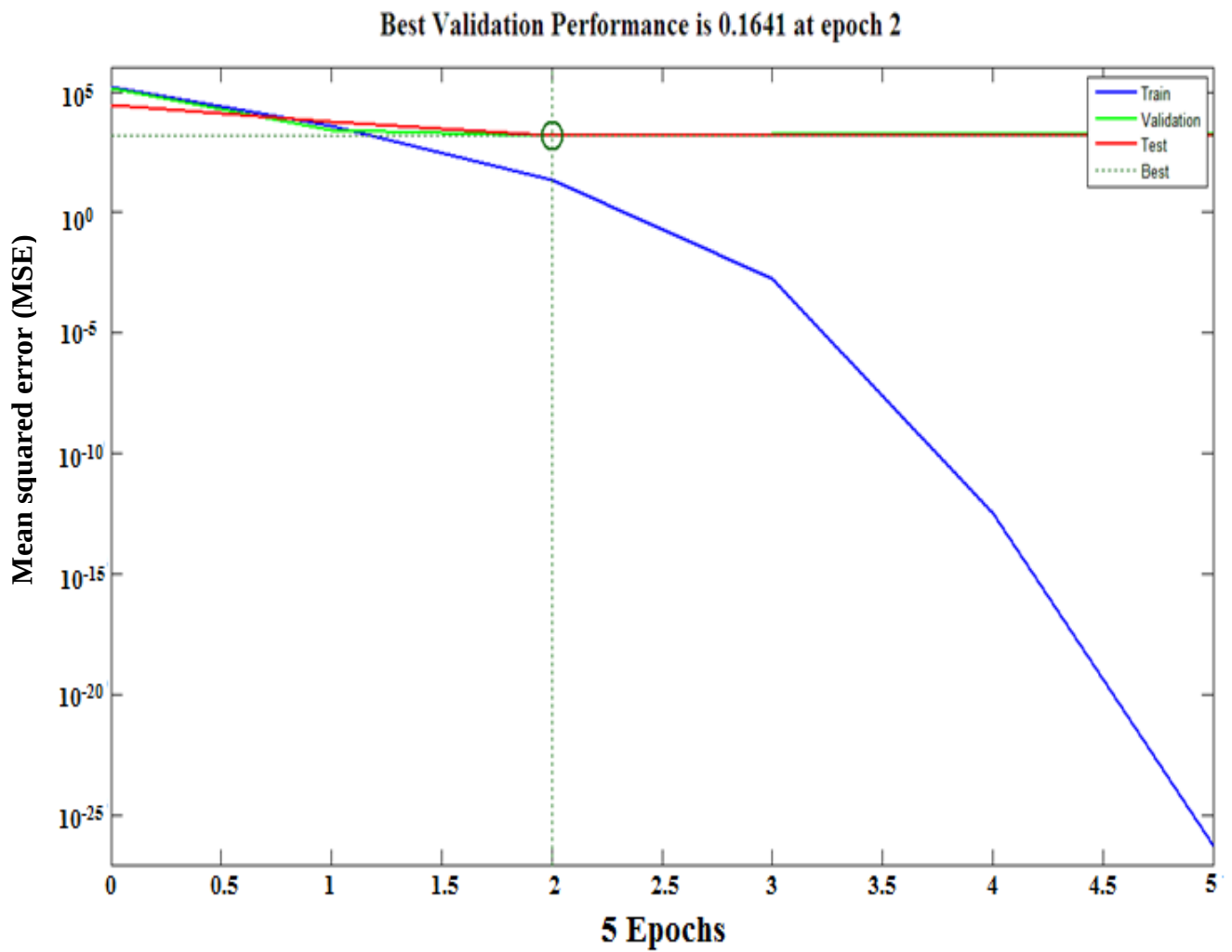


Figure 7.6: All performances result of ANN predicted model for loading rate

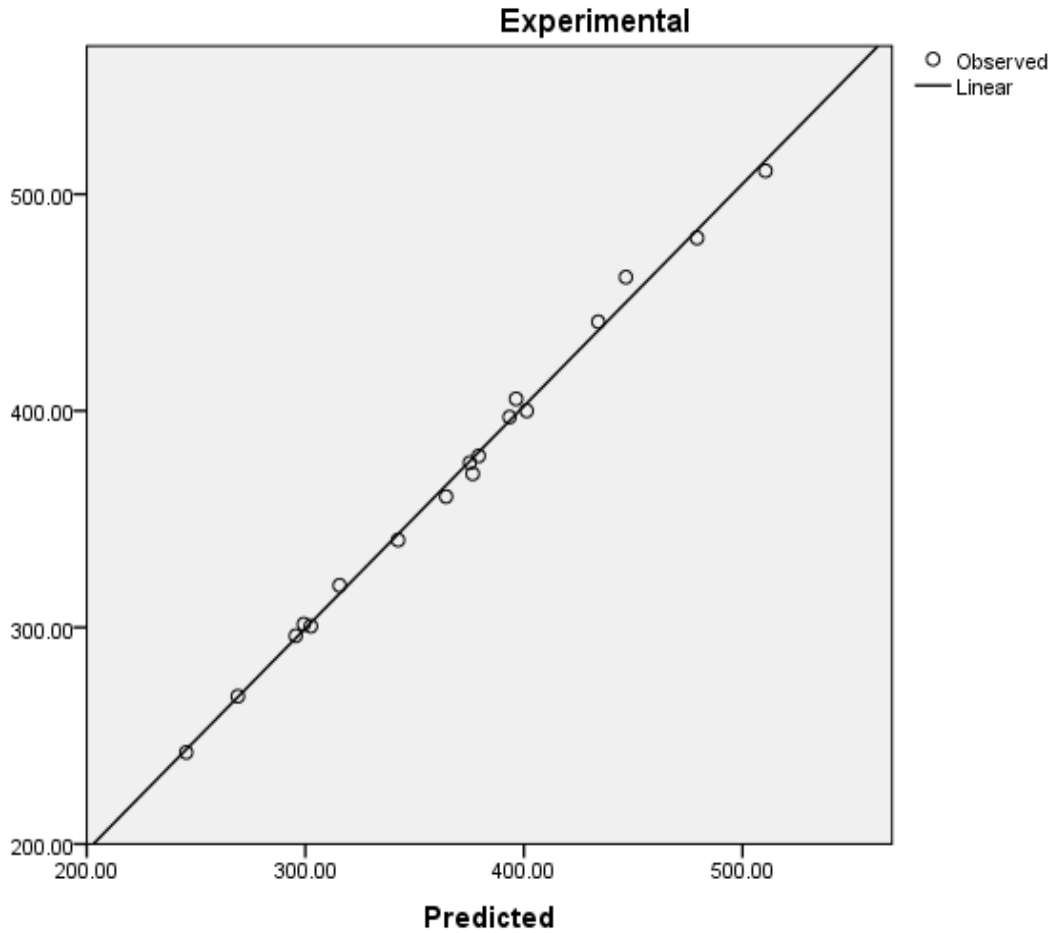


Figure 7.7: The comparison of the experimental results and predicted results obtained by the neural network

Table 7.5: Mean squared error and Regression error of predicted model results

| Results    | Samples | Mean squared error (MSE) | Regression error |
|------------|---------|--------------------------|------------------|
| Training   | 12      | 2.12125 e -1             | 9.98611e -1      |
| Validation | 3       | 1.64145 e -1             | 9.91660e -1      |
| Testing    | 3       | 3.72089 e- 0             | 6.87375e -1      |

The linear regression analysis was performed to check the capabilities of network for the network output and the experimental target value. Figure 7.8 shows the regression plot for training ( $R=1$ ), validation ( $R=0.93277$ ), testing ( $R=0.68738$ ) and overall ( $R=0.94705$ ). Regression  $R$  values measure the correlation between outputs and targets. An  $R$  value of 1 means a close relationship. Figure 7.9 shows the gradient, validation checks with the number of epochs during the training of the selected network.

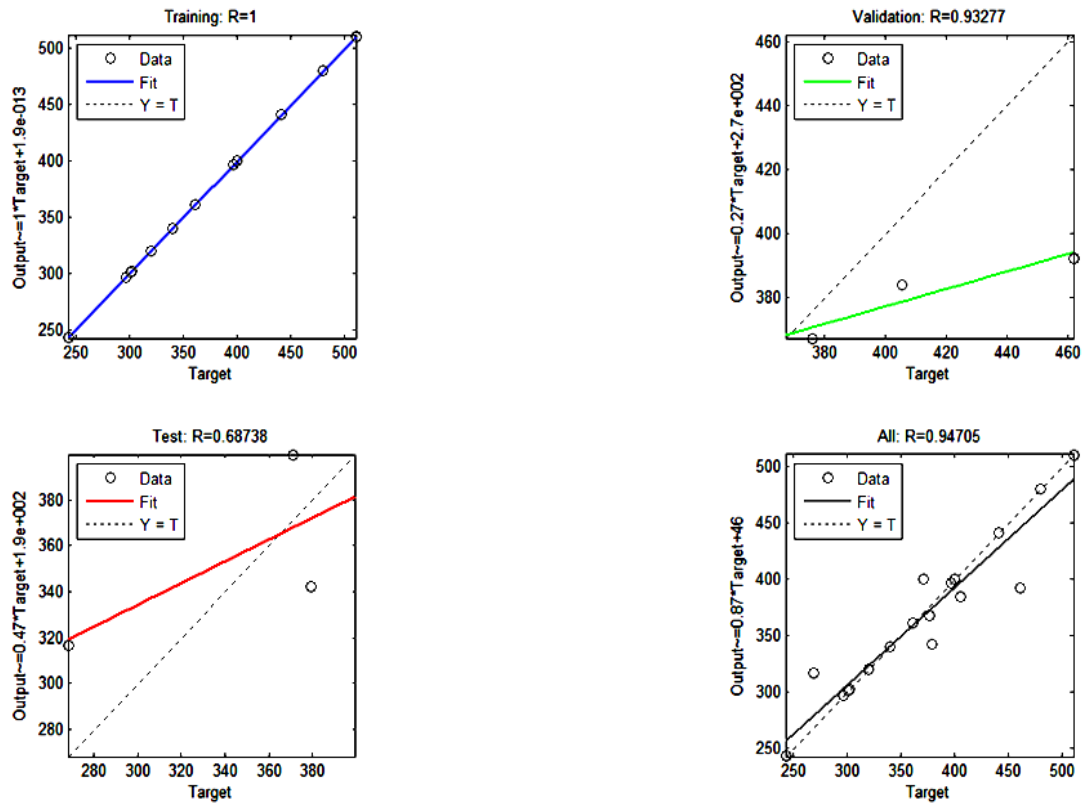


Figure 7.8: Linear regression analysis between the experimental values and predicted values of loading rate for training, validation, testing and overall

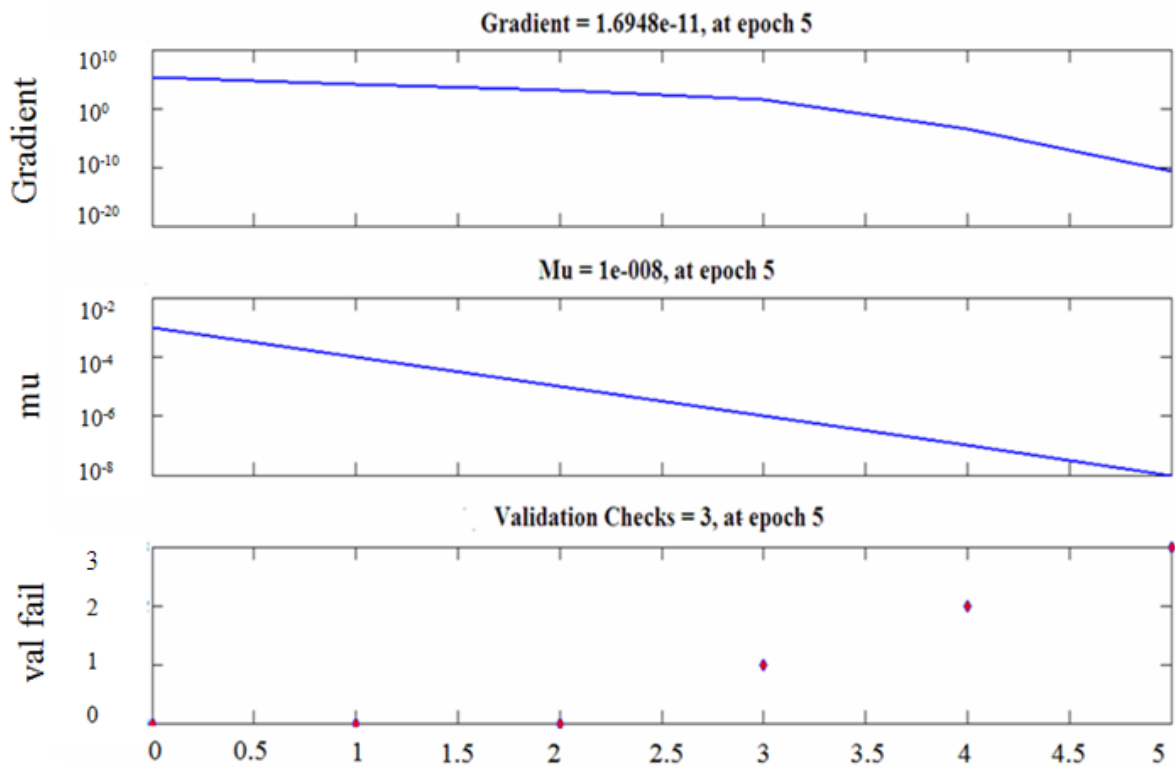


Figure 7.9: Learning behavior of the neural network model

To estimate the relationship between the experimental value and predicted value, paired-sample t-test and correlation test were used and the results are summarized in Table 7.6 and 7.7. It can be observed from Table 7.6 that experimental value and the predicted value are in close agreement at 99.8%. Also, from Table 7.7, the variation in value of experimental results and predicted value of mean loading rate was 1.3311,  $t(17) = 1.121$ ,  $p=0.278>0.05$ . It predicts that the experimental results and model predicted results are not significantly different at 95% confidence range.

Table 7.6: Correlation between the experimental value and ANN model value

| Pair Sample(1)     | No. of experiments (N) | Mean    | Standard deviation | Standard error mean | Correlation | Significance |
|--------------------|------------------------|---------|--------------------|---------------------|-------------|--------------|
| Experimental value | 18                     | 369.494 | 74.174             | 17.483              | 0.998       | 0.000        |
| Predicted value    | 18                     | 368.163 | 72.144             | 17.004              |             |              |

Table 7.7: Paired sample t- test of pair (Experimental value and ANN model value)

| Pair<br>Sample(1)                                | Paired differences |                       |                        |                                                 |         | t-test | Significance |
|--------------------------------------------------|--------------------|-----------------------|------------------------|-------------------------------------------------|---------|--------|--------------|
|                                                  | Mean               | Standard<br>deviation | Standard<br>error mean | 95% confidence<br>interval of the<br>difference |         |        |              |
|                                                  |                    |                       |                        | Lower                                           | Upper   |        |              |
| Experimental<br>and<br>ANN<br>predicted<br>value | 1.3311             | 5.03644               | 1.18710                | -1.17345                                        | 3.83567 | 1.121  | 0.278        |

From the results, it can be concluded that the instantaneous loading rate increases due to the combined effect of higher load, high lifting frequency and vertical distance and may lead to exertion as well as chronic injury. The ANN model accurately predicts the loading rate and can be used as a reliable tool for study of loading rate in case of complex problems that involve both qualitative and quantitative factors.

## CHAPTER 8

### OPTIMIZATION FOR EXPERIMENTAL SETTINGS FOR SAFE LIFTING

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This chapter explains an experimental study carried out to evaluate the effect of the lifting parameters (namely lifting frequency, load, vertical distance, horizontal distance from the object, coupling (grip), asymmetric angle and travel distance) on oxygen uptake, heart rate, perceived exertion and ground reaction forces of workers using the Taguchi  $L_{27}$  experimental design. All responses i.e. oxygen uptake, heart rate, perceived exertion and loading rate were measured during each trial separately and optimized simultaneously using Analytical Hierarchy Process (AHP) for different lifting frequencies and optimal level settings for a manual lifting task were generated.

#### 8.1 EXPERIMENTAL DESIGN

To measure the physiological stress and vertical ground reaction forces of the workmen, pulmonary oxygen uptake, heart rate, perceived exertion and loading rate were used as output responses during the experimental study. On the basis of a pilot experiment, the control factors and their selected levels were chosen by varying one factor at a time. The details are given in Table 8.1. The lifting parameters (frequency of lift, load, vertical distance, horizontal distance, grip (coupling), asymmetric angle and travel distance) were identified as control factors. The study was carried out in the Ergonomics Laboratory of the University. Twelve young male workers who had no previous history of illness or other chronic health problems and had experience in manual material handling, participated in this study. The demographic details (age, height, resting heart rate, resting oxygen uptake, metabolic rate, maximum aerobic capacity) of workers were measured. As all workers had similar resting metabolic rate, the same was not normalized after they completed the task as per various trial conditions of the experiment. A three level orthogonal array ( $L_{27}$ ) of Taguchi experimental design was used for conducting the experimental trials. Taguchi Linear Graphs and Triangular Tables (Ross, [142]) with statistical software MINITAB 16 were used for the assignment of factors. The experimental time period for one trial was set as 20 minutes. Sufficient break was given between two trials to allow operators to fully recover from the fatigue. The pulmonary oxygen uptake (ml/kg-min), heart rate (beats/min), loading rate (Newton/sec) and perceived exertion (Borg scale) were considered as the response parameters.

Table 8.1: Factors studied with their levels

| Factors (unit)                      | Levels      |              |            |
|-------------------------------------|-------------|--------------|------------|
|                                     | Level – 1   | Level – 2    | Level – 3  |
| Lifting frequency, A(lifts/ 20 min) | 110         | 140          | 180        |
| Load, B (kg)                        | 13          | 18           | 23         |
| Vertical height, C (cm)             | 55          | 110          | 150        |
| Horizontal distance, D(cm)          | 15          | 30           | 55         |
| Coupling Grip, E                    | With Gloves | With Cushion | W/o Gloves |
| Assy. Angle, F (in $^{\circ}$ )     | 0           | 40           | 60         |
| Travel Distance, G (cm)             | 25          | 45           | 60         |



Figure 8.1: Experimental Set up with Kistler force platforms and COSMED pulmonary function equipment

## 8.2 MEASUREMENT OF RESPONSES

The COSMED pulmonary function equipment was used to measure two responses i.e. heart rate (beats/min) and oxygen uptake (ml/kg-min) at normal environment temperature with the help of a face oxygen mask and a heart rate probe. It also plots two curves for each of the two responses against time span. Two force platforms (Kistler 9286AA, 200 Hz) were used to measure the vertical ground reaction forces (VGRF,  $F_z$ ) produced during lifting and to complete the carrying task. Experimental set up is shown in Figure 8.1. Perceived exertion was measured by combining all sensations and feelings of physical stress, effort, and fatigue reflected by worker at the time of the experimentation (Borg [17]). A stop watch and a measuring tape were used to measure the time of experiment and distances involved in the experimental setup layout respectively. The mean of oxygen uptake, heart rate and perceived exertion were measured at the end of each trial. Rating of Perceived Exertion (RPE) scale (6 to 20, Borg [17]; Champaign [25]) was used for workers who felt low exertion (6-12), moderate exertion (13-14) and high exertion (15-20) on the basis of information provided by the workers during trials.

The Vertical Ground Reaction Force ( $F_z$ ) was measured for each worker after each trial. The calculations were made from a plot  $F_z$  with time (see Figure 8.2 (a)). The variation of  $F_z$  with time has been shown in a 60 sec graphical output (complete plot is not feasible to show here). Nine lifts (one lift time period approximate 6.5 sec) can be observed in 60 sec time span in this plot as shown in figure 8.2 (a).

To further elaborate the lifting task, one lift is shown in Figure 8.2 (b). In this plot, four time spans are identified in one lift and the VGRF or  $F_z$  can be measured for each span. Position A is the initial stationary and standing position where  $F_z$  is the same as body weight of the worker. Position B is at the initiation of lift when the worker bends to lift and  $F_z$  is lower than body weight.  $F_z$  decreases even more with increased frequency and vertical distance primarily because of the jerking action required to initiate the lift. Position C represents the lifting phase and  $F_z$  is larger in magnitude in relative comparison to body weight. Position D is the final stationary and standing position where  $F_z$  is equal to body weight.

Loading rate was calculated from vertical ground reaction force. The peak rate of vertical ground reaction force (loading rate) is an indication of the risk of chronic injury due to sports and dynamic lifting activities (Miller and Nigg [119, 128]). The instantaneous loading rate is obtained by measuring the gradient of a tangent that is drawn at the point on the  $F_z$ -time curve where the rate of change is considered to be the greatest (Figure 8.2(b)).

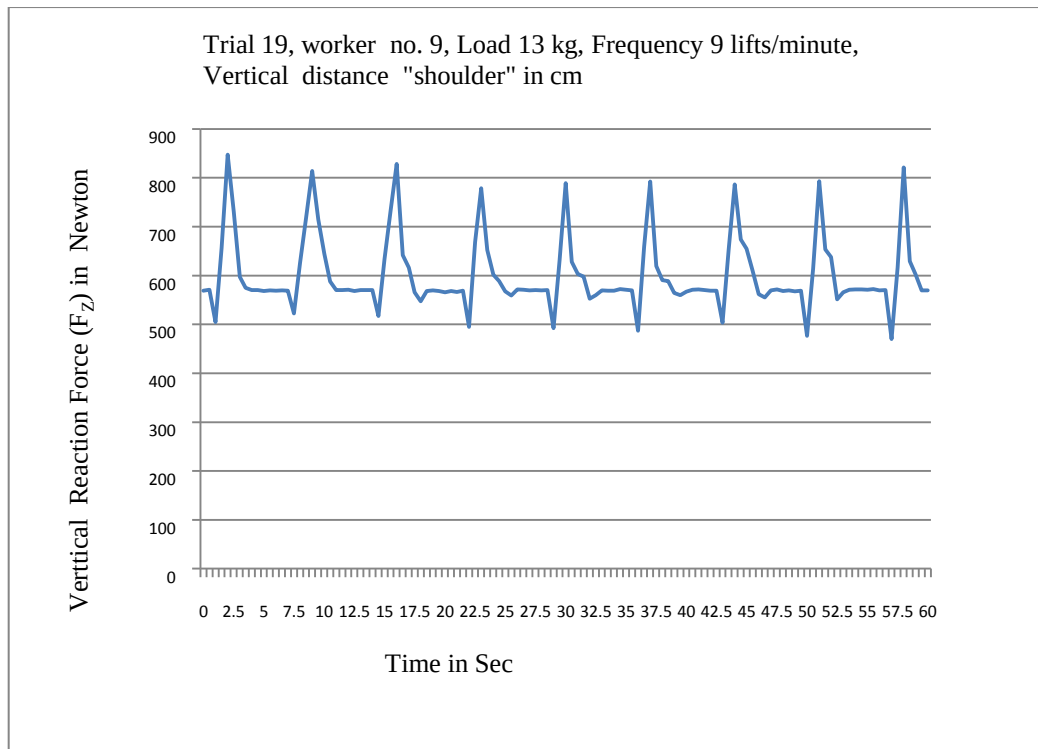


Figure 8.2 (a): Vertical reaction force-time graph for workers involved in lifting task (Trial no 19, worker no. 9, weight 13 kg, frequency 9 lifts/min, vertical distance shoulder height in cm for 9 lifts in 60 seconds)

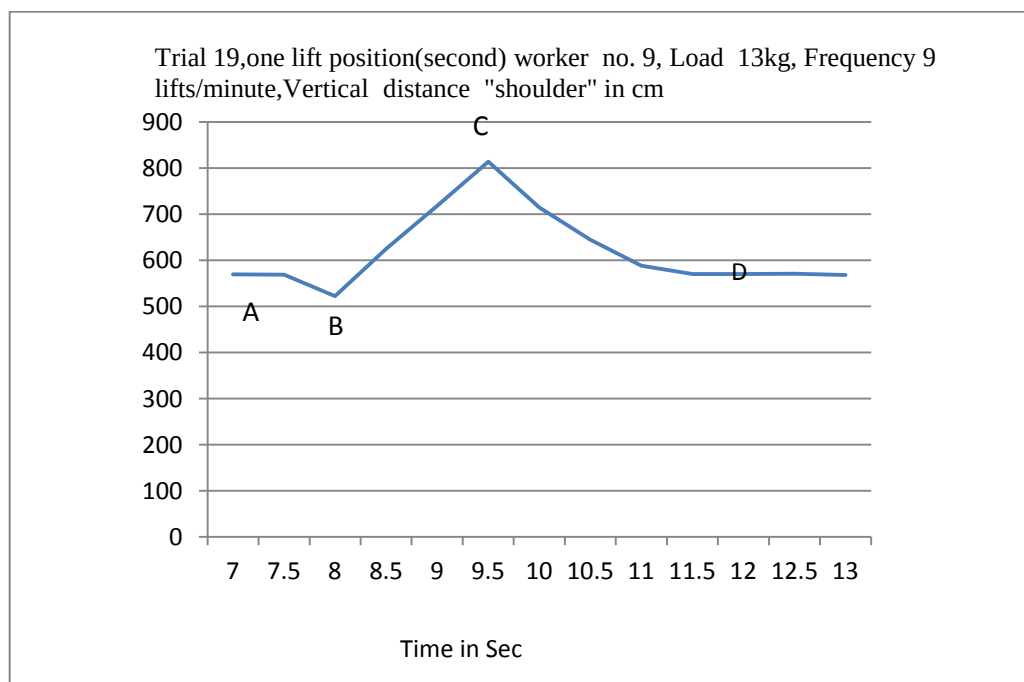


Figure 8.2 (b): Vertical reaction force-time graph for workers involved in lifting task (Trial no 19, worker no. 9, weight 13 kg, frequency 9 lifts/min, vertical distance shoulder height in cm for one lift (2<sup>nd</sup>, in this case) in 6.5sec) Vertical reaction force ( $F_z$ ) in Newton)

Table 8.2: Design of Experiment (L<sub>27</sub>) with output responses

| Trial.<br>No.<br>n=<br>(1-27) | Control Factors           |              |             |             |       |                       |             | Output Responses                    |                                  |                            |                       |
|-------------------------------|---------------------------|--------------|-------------|-------------|-------|-----------------------|-------------|-------------------------------------|----------------------------------|----------------------------|-----------------------|
|                               | Frequency<br>(lift/20min) | Load<br>(kg) | V.D<br>(cm) | H.D<br>(cm) | Grip  | Assy.<br>Angle<br>(°) | T.D<br>(cm) | Means at normal temperature         |                                  |                            |                       |
|                               |                           |              |             |             |       |                       |             | Oxygen<br>uptake<br>(ml/kg/<br>min) | Heart<br>rate<br>(beats/<br>min) | Loading<br>rate<br>(N/sec) | Perceived<br>exertion |
| 1                             | Sample I,110              | 13           | 55          | 15          | WG    | 0                     | 25          | 9.68                                | 97.35                            | 238.1                      | 10                    |
| 2                             | Sample I,110              | 13           | 110         | 30          | WC    | 40                    | 45          | 10.29                               | 101.87                           | 266.9                      | 11                    |
| 3                             | Sample I,110              | 13           | 150         | 55          | W/o G | 60                    | 60          | 11.92                               | 103.17                           | 308.7                      | 12                    |
| 4                             | Sample I,110              | 18           | 55          | 55          | WC    | 0                     | 60          | 11.65                               | 102.78                           | 294.5                      | 12                    |
| 5                             | Sample I,110              | 18           | 110         | 15          | W/o G | 40                    | 25          | 12.49                               | 104.63                           | 333.4                      | 13                    |
| 6                             | Sample I,110              | 18           | 150         | 30          | WG    | 60                    | 45          | 12.84                               | 106.71                           | 369.3                      | 13                    |
| 7                             | Sample I,110              | 23           | 55          | 30          | W/o G | 0                     | 45          | 12.43                               | 105.58                           | 357.6                      | 13                    |
| 8                             | Sample I,110              | 23           | 110         | 55          | WG    | 40                    | 60          | 13.05                               | 107.83                           | 396.5                      | 14                    |
| 9                             | Sample I,110              | 23           | 150         | 15          | WC    | 60                    | 25          | 13.68                               | 110                              | 438.1                      | 14                    |
| 10                            | Sample II,140             | 13           | 55          | 30          | W/o G | 60                    | 60          | 10.27                               | 100.36                           | 267.9                      | 11                    |
| 11                            | Sample II,140             | 13           | 110         | 55          | WG    | 0                     | 25          | 10.71                               | 103.38                           | 298.2                      | 11                    |
| 12                            | Sample II,140             | 13           | 150         | 15          | WC    | 40                    | 45          | 12.21                               | 105.12                           | 339.8                      | 13                    |
| 13                            | Sample II,140             | 18           | 55          | 15          | WG    | 60                    | 45          | 11.79                               | 102.91                           | 313.5                      | 12                    |
| 14                            | Sample II,140             | 18           | 110         | 30          | WC    | 0                     | 60          | 12.62                               | 105.01                           | 358.4                      | 13                    |
| 15                            | Sample II,140             | 18           | 150         | 55          | W/o G | 40                    | 25          | 12.9                                | 107.87                           | 379.9                      | 13                    |
| 16                            | Sample II,140             | 23           | 55          | 55          | WC    | 60                    | 25          | 12.58                               | 106.39                           | 372.3                      | 13                    |
| 17                            | Sample II,140             | 23           | 110         | 15          | W/o G | 0                     | 45          | 13.25                               | 110.73                           | 446.4                      | 15                    |
| 18                            | Sample II,140             | 23           | 150         | 30          | WG    | 40                    | 60          | 13.93                               | 113.06                           | 507.3                      | 15                    |
| 19                            | Sample III,180            | 13           | 55          | 55          | WC    | 40                    | 45          | 10.83                               | 104.1                            | 297.6                      | 11                    |
| 20                            | Sample III,180            | 13           | 110         | 15          | W/o G | 60                    | 60          | 12.34                               | 105.65                           | 329.4                      | 13                    |
| 21                            | Sample III,180            | 13           | 150         | 30          | WG    | 0                     | 25          | 12.91                               | 108.05                           | 378.2                      | 13                    |
| 22                            | Sample III,180            | 18           | 55          | 30          | W/o G | 40                    | 25          | 11.97                               | 106.12                           | 361.8                      | 12                    |
| 23                            | Sample III,180            | 18           | 110         | 55          | WG    | 60                    | 45          | 12.75                               | 108.34                           | 398.6                      | 13                    |
| 24                            | Sample III,180            | 18           | 150         | 15          | WC    | 0                     | 60          | 14.07                               | 109.98                           | 451.7                      | 17                    |
| 25                            | Sample III,180            | 23           | 55          | 15          | WG    | 40                    | 60          | 12.69                               | 109.34                           | 403.9                      | 13                    |
| 26                            | Sample III,180            | 23           | 110         | 30          | WC    | 60                    | 25          | 13.98                               | 112.57                           | 471.3                      | 16                    |
| 27                            | Sample III,180            | 23           | 150         | 55          | W/o G | 0                     | 45          | 14.92                               | 118.34                           | 533.2                      | 18                    |

(Note: Abbreviations V.D: vertical Distance, H.D: Horizontal Distance, T.D: Travel distance WG: With Gloves; WC: With Cushion; w/o G: Without Gloves)

All responses were measured as per the previously described methods and are given in Table 8.2 under output response. Lifting frequency, load and vertical distance were identified as significant factors affecting the oxygen uptake, heart rate and loading rate using Analysis of Variance (see Table 8.3). The contribution of control factors in percentage (%) has been shown in ANOVA table.

Table 8.3: Analysis of variance for oxygen uptake, heart rate and loading rate

| Factors      | D<br>O<br>F | Sum of Squares  |        |        | Variance        |        |         | F-value         |        |        | Percentage Contribution |       |       |
|--------------|-------------|-----------------|--------|--------|-----------------|--------|---------|-----------------|--------|--------|-------------------------|-------|-------|
|              |             | VO <sub>2</sub> | Hr     | LR     | VO <sub>2</sub> | Hr     | LR      | VO <sub>2</sub> | Hr     | LR     | VO <sub>2</sub>         | Hr    | LR    |
| Freq (A)     | 2           | 4.24            | 103.68 | 21605  | 2.12            | 51.84  | 10802.4 | 21.36           | 63.64  | 105.90 | 7.68                    | 19.35 | 14.42 |
| Wt. (B)      | 2           | 21.17           | 236.94 | 80549  | 10.58           | 118.47 | 40274.7 | 106.67          | 145.43 | 394.84 | 49.12                   | 46.81 | 56.15 |
| V. D (C)     | 2           | 13.33           | 124.80 | 35471  | 6.66            | 62.40  | 17735.4 | 67.16           | 76.61  | 173.87 | 29.93                   | 23.7  | 24.24 |
| Pooled Error | 20          | 2.11            | 19.832 | 3644   | 0.10            | 0.99   | 182.2   |                 |        |        |                         |       |       |
| Total        | 26          | 40.86           | 485.26 | 141269 |                 |        |         |                 |        |        |                         |       |       |

(Note : Freq : Frequency, Wt : Weight, V. height=Vertical distance, DOF= Degrees of freedom, VO<sub>2</sub>= Oxygen uptake, Hr= Heart rate, LR=loading rate)

The oxygen uptake and heart rate significantly increases with the increase in lifting frequency, load and vertical distance as depicted by Figures 8.3 (a) & (b). There were no significant effects on responses with the change of grip, horizontal distance, asymmetric angle and travel distance.

The Borg scale number increases linearly as the rate of exertion increases. Based on the above discussion, high exertion was reported during trials 17, 18, 24, 26 and 27. Moderate exertion was reported during trials 5 to 7, 12, 14,15,20,21 and 23.

The oxygen uptake and heart rate plots with time were obtained for all trials. Two such output plots of high exertion and three of moderate exertion are shown in Figures 8.3 (a) & (b) and Figures 8.4 (a), (b) & (c).

### 8.3 ANALYTICAL HIERARCHICAL PROCESS

In order to get the best parameter setting for safe lifting, it is important that all the responses are optimized simultaneously. The Analytical Hierarchy Process (AHP) is a technique with the application of which it can be achieved. AHP has been designed for the situation in which ideas, feelings and emotions are quantified into numerical scale (Taha [166]. Saaty [146, 147,

148], Kanungo [124], Stohr [160]) explained AHP as one of the most successful techniques to solve decision making problems involving the decision goal, the alternatives for reaching it and the criteria for evaluating the alternatives.

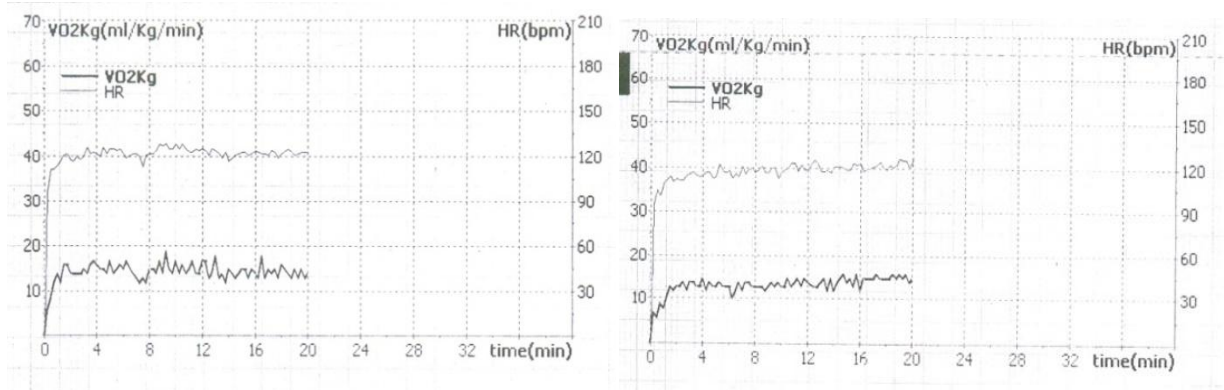
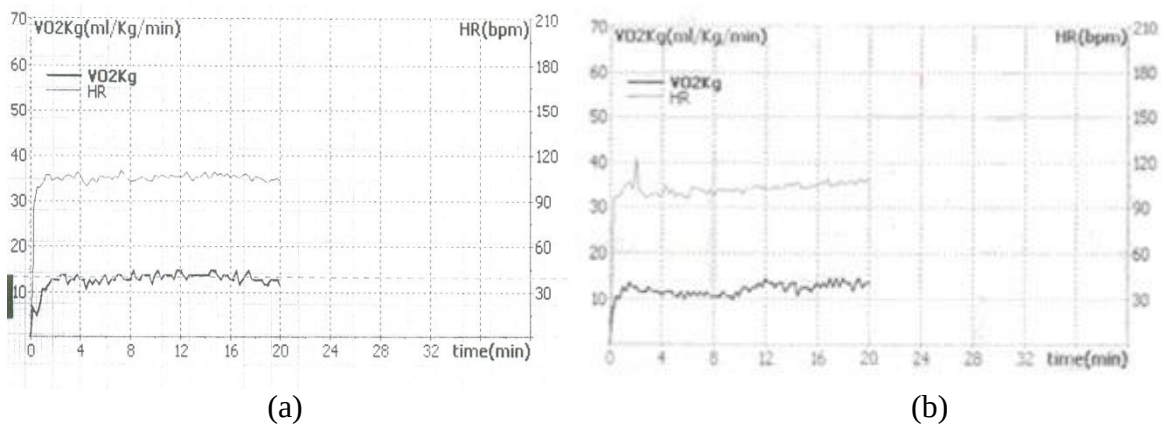
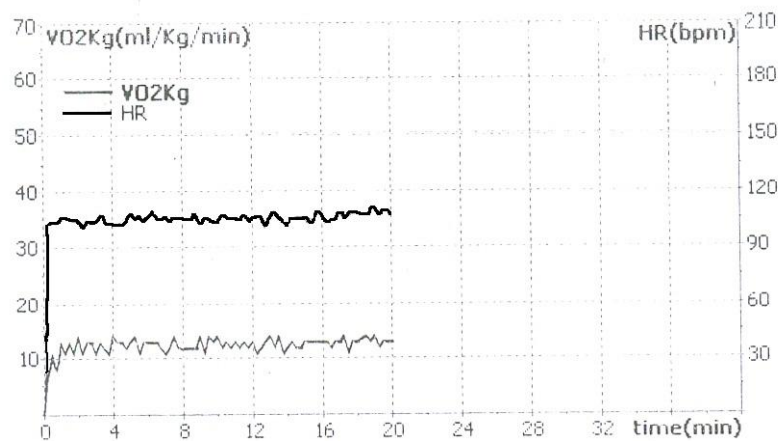


Figure 8.3: Oxygen uptake and heart rate for trials where high exertion was reported (a) 23<sup>rd</sup> trial, (b) 27<sup>th</sup> trial



(a)

(b)



(c)

Figure 8.4: Oxygen uptake and heart rate for trials where moderate exertion was reported (a) 6<sup>th</sup> trial, (b) 15<sup>th</sup> trial (c) 21<sup>th</sup> trial

It is based on the well-defined mathematical structure of consistent matrices and their associated eigenvector's ability to generate true or approximate weights. A number of pair-wise comparison matrices are formed according to their relative importance with respect to the parent element in the adjacent upper level to derive weights of the criteria and the local weights of the alternatives using simple mathematical theory of Eigen vector and priority. The alternative with the highest global weight is selected as the best alternative. The advantage of this tool is that it combines both qualitative and quantitative parameters.

The procedure to carry out the AHP consists of the following steps:

**1. Hierarchical Structuring of a decision problem and selection of criteria**

It comprises of a goal or focus at the topmost level, criteria /sub criteria, at the intermediate levels, while the lowest level contains the available alternatives.

**2. Construction of a pair wise comparison matrix for each level with respect to higher levels and determine the relative importance of different alternatives with respect to its immediately above sub criteria.** Rating of the relative “priority “of the criteria is done by assigning a weight between 1 (equal importance) and 9 (extreme importance) to the more important criterion, whereas, the reciprocal of this value is assigned to the other criterion in the pair. The comparison is made on 9-point “fundamental scale of Saaty” represented in Table 8.4.

**3. Application of eigenvector methods to calculate relative weight for the pair wise comparison of options on each criterion.**

**4. Checking the consistency associated with the comparison matrix using consistency ratio (CR) of consistency index (CI) with the appropriate value of the random index (RI) from Table 8.5.**

**5. Repeat the above steps for all levels in the hierarchy.**

**6. Evaluate the overall relative value by linear addition function.**

Table 8.4: The Saaty Rating scale

| Intensity of importance | Definition                |
|-------------------------|---------------------------|
| 1                       | Equal importance          |
| 3                       | Somewhat more important   |
| 5                       | Much more important       |
| 7                       | Very much more important  |
| 9                       | Absolutely more important |
| 2,4,6,8                 | Intermediate values       |

Table 8.5: Random consistency index

| k  | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----|------|------|------|------|------|------|------|------|------|------|------|------|------|
| RI | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 | 1.48 |

#### 8.4 IMPLEMENTATION OF AHP IN LIFTING OPERATION

The main aim of implementation of AHP is to select the best combination of lifting parameters for safe lifting. The criteria used were to keep closer to the target value of oxygen uptake (12.93 ml/kg/min), heart rate (110 beats per min), loading rate (380 N/sec) and perceived exertion (13). The safe limit for oxygen uptake was calculated using 33% of the average maximum aerobic capacity of all participants (Bridger [18]). The average maximum aerobic capacity of twelve workers was 38.8 ml/kg/min. The safe limit was calculated as 12.93 ml/kg/min (33% of the maximum aerobic capacity of the workers) oxygen uptake, 110 beats per minute heart rate (Astrand and Rhodahl, [4]), 380 Newton per sec loading rate (second phase of study) and 13 perceived exertion (Borg [17]).

The design of experiment layout as given in left columns of Table 8.2 had 27 trials with 9 trials each for different frequencies, sample I (110 per 20 min) (trials 1-9), sample II (140 per 20 min) (trials 10-18), sample III (180 per 20 min) (trials 19-27) leading to three optimum solutions, one each for each assigned frequency. Hierarchy for AHP solution is shown in Figure 8.5. With reference from the target value of responses, the decision to select the weight criteria (relative rating between two alternatives) was made on the basis of experimental results obtained for each response as given in Table 8.2 and a subjective criteria described in Table 8.4. Oxygen uptake is the best parameter for measurement of physical activity. Loading rate is also based upon oxygen uptake and heart rate. Oxygen uptake and loading rate are given equal importance. Heart rate depends upon the body's demand for oxygen therefore oxygen uptake is slightly more important in comparison to heart rate. Perceived exertion is measured by combining all sensations and feelings of physical stress, effort, and fatigue reflected by worker at the time of the experimentation so it depends on workers report. Weights are given according to rating scale based on relative importance of parameters. The same procedure to assign the weights was adopted for all the response parameters. A pair wise comparison (4x4 matrix) was established for oxygen uptake, heart rate, loading rate and perceived exertion as shown in Table 8.6. Subsequently the pair wise comparison matrices (9x9) of experimental

trials (alternatives  $T_1 \dots T_9$ ,  $T_{10} \dots T_{18}$ ,  $T_{19} \dots T_{27}$ ) were developed for oxygen uptake, heart rate and perceived exertion for different sets of frequency respectively (see Tables 8.7 to 8.18).

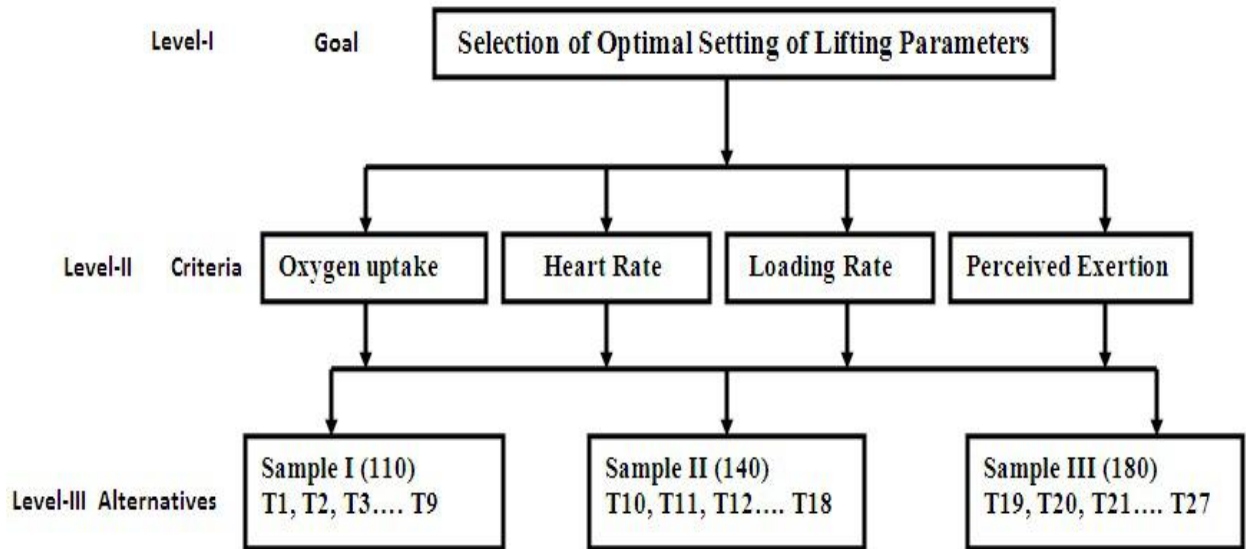


Figure 8.5: - Hierarchy tree of the studied problem of analytic hierarchy process

Table 8.6: Pair-wise comparison of criteria

|                             | Oxygen uptake | Heart rate                       | Loading rate | Perceived Exertion | Priority vector |
|-----------------------------|---------------|----------------------------------|--------------|--------------------|-----------------|
| Oxygen uptake               | 1             | 2                                | 1            | 5                  | 0.3684          |
| Heart rate                  | 1/2           | 1                                | 1/2          | 3                  | 0.1928          |
| Loading rate                | 1             | 2                                | 1            | 5                  | 0.3684          |
| Perceived Exertion          | 1/5           | 1/3                              | 1/5          | 1                  | 0.0704          |
| $\lambda_{\max} = 4.003562$ |               | CI= 0.00396, RI= 0.90, CR=0.0044 |              |                    |                 |

Table 8.7: Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample I

|    | T1 | T2 | T3  | T4  | T5  | T6  | T7  | T8 | T9 | Priority vector |
|----|----|----|-----|-----|-----|-----|-----|----|----|-----------------|
| T1 | 1  | 1  | 1/2 | 1/2 | 1/3 | 1/3 | 1/3 | 2  | 2  | 0.0635          |
| T2 | 1  | 1  | 1/2 | 1/2 | 1/3 | 1/3 | 1/3 | 2  | 2  | 0.0635          |
| T3 | 2  | 2  | 1   | 1   | 1/2 | 1/2 | 1/2 | 3  | 3  | 0.1082          |
| T4 | 2  | 2  | 1   | 1   | 1/2 | 1/2 | 1/2 | 3  | 3  | 0.1082          |
| T5 | 3  | 3  | 2   | 2   | 1   | 1   | 1   | 5  | 5  | 0.1949          |

|                           |     |     |     |     |                                 |     |     |   |   |        |
|---------------------------|-----|-----|-----|-----|---------------------------------|-----|-----|---|---|--------|
| T6                        | 3   | 3   | 2   | 2   | 1                               | 1   | 1   | 5 | 5 | 0.1949 |
| T7                        | 3   | 3   | 2   | 2   | 1                               | 1   | 1   | 5 | 5 | 0.1949 |
| T8                        | 1/2 | 1/2 | 1/3 | 1/3 | 1/5                             | 1/5 | 1/5 | 1 | 1 | 0.0359 |
| T9                        | 1/2 | 1/2 | 1/3 | 1/3 | 1/5                             | 1/5 | 1/5 | 1 | 1 | 0.0359 |
| $\lambda_{\max} = 9.0281$ |     |     |     |     | CI= 0.0035, RI= 1.45, CR=0.0024 |     |     |   |   |        |

Table 8.8: Pair-wise comparison of heart rate w.r.t. their alternatives for sample I

|                           | T1 | T2  | T3  | T4  | T5                              | T6  | T7  | T8  | T9  | Priority vector |
|---------------------------|----|-----|-----|-----|---------------------------------|-----|-----|-----|-----|-----------------|
| T1                        | 1  | 1/2 | 1/3 | 1/2 | 1/4                             | 1/5 | 1/4 | 1/6 | 1/7 | 0.0252          |
| T2                        | 2  | 1   | 1/2 | 1   | 1/3                             | 1/4 | 1/3 | 1/5 | 1/6 | 0.0376          |
| T3                        | 3  | 2   | 1   | 2   | 1/2                             | 1/3 | 1/2 | 1/4 | 1/5 | 0.0586          |
| T4                        | 2  | 1   | 1/2 | 1   | 1/3                             | 1/4 | 1/3 | 1/5 | 1/6 | 0.0376          |
| T5                        | 4  | 3   | 2   | 3   | 1                               | 1/2 | 1   | 1/3 | 1/4 | 0.0924          |
| T6                        | 5  | 4   | 3   | 4   | 2                               | 1   | 2   | 1/2 | 1/3 | 0.1437          |
| T7                        | 4  | 3   | 2   | 3   | 1                               | 1/2 | 1   | 1/3 | 1/4 | 0.0924          |
| T8                        | 6  | 5   | 4   | 5   | 3                               | 2   | 3   | 1   | 1/2 | 0.2124          |
| T9                        | 7  | 6   | 5   | 6   | 4                               | 3   | 4   | 2   | 1   | 0.3001          |
| $\lambda_{\max} = 9.2250$ |    |     |     |     | CI= 0.0281, RI= 1.45, CR=0.0194 |     |     |     |     |                 |

Table 8.9: Pair-wise comparison of loading rate w.r.t. their alternatives for sample I

|                           | T1  | T2  | T3  | T4  | T5                              | T6  | T7  | T8  | T9 | Priority vector |
|---------------------------|-----|-----|-----|-----|---------------------------------|-----|-----|-----|----|-----------------|
| T1                        | 1   | 1   | 1/2 | 1/2 | 1/3                             | 1/4 | 1/4 | 2   | 3  | 0.0587          |
| T2                        | 1   | 1   | 1/2 | 1/2 | 1/3                             | 1/4 | 1/4 | 2   | 3  | 0.0587          |
| T3                        | 2   | 2   | 1   | 1   | 1/2                             | 1/3 | 1/3 | 3   | 4  | 0.0963          |
| T4                        | 2   | 2   | 1   | 1   | 1/2                             | 1/3 | 1/3 | 3   | 4  | 0.0963          |
| T5                        | 3   | 3   | 2   | 2   | 1                               | 1/2 | 1/2 | 4   | 5  | 0.1538          |
| T6                        | 4   | 4   | 3   | 3   | 2                               | 1   | 1   | 5   | 6  | 0.2364          |
| T7                        | 4   | 4   | 3   | 3   | 2                               | 1   | 1   | 5   | 6  | 0.2364          |
| T8                        | 1/2 | 1/2 | 1/3 | 1/3 | 1/4                             | 1/5 | 1/5 | 1   | 2  | 0.0375          |
| T9                        | 1/3 | 1/3 | 1/4 | 1/4 | 1/5                             | 1/6 | 1/6 | 1/2 | 1  | 0.0258          |
| $\lambda_{\max} = 9.1664$ |     |     |     |     | CI= 0.0208, RI= 1.45, CR=0.0143 |     |     |     |    |                 |

Table 8.10: Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample I

|                           | T1  | T2  | T3  | T4  | T5                              | T6  | T7  | T8  | T9 | Priority vector |
|---------------------------|-----|-----|-----|-----|---------------------------------|-----|-----|-----|----|-----------------|
| T1                        | 1   | 1   | 1/2 | 1/2 | 1/3                             | 1/3 | 1/3 | 2   | 3  | 0.0666          |
| T2                        | 1   | 1   | 1/2 | 1/2 | 1/3                             | 1/3 | 1/3 | 2   | 3  | 0.0666          |
| T3                        | 2   | 2   | 1   | 1   | 1/2                             | 1/2 | 1/2 | 3   | 4  | 0.1120          |
| T4                        | 2   | 2   | 1   | 1   | 1/2                             | 1/2 | 1/2 | 3   | 4  | 0.1120          |
| T5                        | 3   | 3   | 2   | 2   | 1                               | 1   | 1   | 4   | 5  | 0.1907          |
| T6                        | 3   | 3   | 2   | 2   | 1                               | 1   | 1   | 4   | 5  | 0.1907          |
| T7                        | 3   | 3   | 2   | 2   | 1                               | 1   | 1   | 4   | 5  | 0.1907          |
| T8                        | 1/2 | 1/2 | 1/3 | 1/3 | 1/4                             | 1/4 | 1/4 | 1   | 2  | 0.0419          |
| T9                        | 1/3 | 1/3 | 1/4 | 1/4 | 1/5                             | 1/5 | 1/5 | 1/2 | 1  | 0.0286          |
| $\lambda_{\max} = 9.1026$ |     |     |     |     | CI= 0.0128, RI= 1.45, CR=0.0088 |     |     |     |    |                 |

Table 8.11: Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample II

|                           | T10 | T11 | T12 | T13 | T14                              | T15 | T16 | T17 | T18 | Priority vector |
|---------------------------|-----|-----|-----|-----|----------------------------------|-----|-----|-----|-----|-----------------|
| T10                       | 1   | 1   | 1/3 | 1/2 | 1/3                              | 1/4 | 1/3 | 2   | 3   | 0.0593          |
| T11                       | 1   | 1   | 1/3 | 1/2 | 1/3                              | 1/4 | 1/3 | 2   | 3   | 0.0593          |
| T12                       | 3   | 3   | 1   | 2   | 1                                | 1/2 | 1   | 4   | 5   | 0.1572          |
| T13                       | 2   | 2   | 1/2 | 1   | 1/2                              | 1/3 | 1/2 | 3   | 4   | 0.0953          |
| T14                       | 3   | 3   | 1   | 2   | 1                                | 1/2 | 1   | 4   | 5   | 0.1572          |
| T15                       | 4   | 4   | 2   | 3   | 2                                | 1   | 2   | 5   | 6   | 0.2496          |
| T16                       | 3   | 3   | 1   | 2   | 1                                | 1/2 | 1   | 4   | 5   | 0.1572          |
| T17                       | 1/2 | 1/2 | 1/4 | 1/3 | 1/4                              | 1/5 | 1/4 | 1   | 2   | 0.0381          |
| T18                       | 1/3 | 1/3 | 1/5 | 1/4 | 1/5                              | 1/6 | 1/5 | 1/2 | 1   | 0.0263          |
| $\lambda_{\max} = 9.1452$ |     |     |     |     | CI= 0.0181, RI= 1.45, CR= 0.0125 |     |     |     |     |                 |

Table 8.12: Pair-wise comparison of heart rate w.r.t. their alternatives for sample II

|     | T10 | T11 | T12 | T13 | T14 | T15 | T16 | T17 | T18 | Priority vector |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------------|
| T10 | 1   | 1/2 | 1/3 | 1/2 | 1/3 | 1/4 | 1/3 | 2   | 3   | 0.0548          |
| T11 | 2   | 1   | 1/2 | 1   | 1/2 | 1/3 | 1/2 | 3   | 5   | 0.0904          |
| T12 | 3   | 2   | 1   | 2   | 1   | 1/2 | 1   | 4   | 6   | 0.1532          |
| T13 | 2   | 1   | 1/2 | 1   | 1/2 | 1/3 | 1/2 | 3   | 5   | 0.0904          |

|                           |               |               |               |               |                                  |               |               |               |   |        |
|---------------------------|---------------|---------------|---------------|---------------|----------------------------------|---------------|---------------|---------------|---|--------|
| T14                       | 3             | 2             | 1             | 2             | 1                                | $\frac{1}{2}$ | 1             | 4             | 6 | 0.1532 |
| T15                       | 4             | 3             | 2             | 3             | 2                                | 1             | 2             | 5             | 7 | 0.2457 |
| T16                       | 3             | 2             | 1             | 2             | 1                                | $\frac{1}{2}$ | 1             | 4             | 6 | 0.1532 |
| T17                       | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{4}$ | $\frac{1}{3}$ | $\frac{1}{4}$                    | $\frac{1}{5}$ | $\frac{1}{4}$ | 1             | 2 | 0.0364 |
| T18                       | $\frac{1}{3}$ | $\frac{1}{5}$ | $\frac{1}{6}$ | $\frac{1}{5}$ | $\frac{1}{6}$                    | $\frac{1}{7}$ | $\frac{1}{6}$ | $\frac{1}{2}$ | 1 | 0.0224 |
| $\lambda_{\max} = 9.1241$ |               |               |               |               | CI= 0.0155, RI= 1.45, CR= 0.0107 |               |               |               |   |        |

Table 8.13: Pair-wise comparison of loading rate w.r.t. their alternatives for sample II

|                           | T10           | T11           | T12           | T13           | T14                              | T15           | T16           | T17           | T18 | Priority vector |
|---------------------------|---------------|---------------|---------------|---------------|----------------------------------|---------------|---------------|---------------|-----|-----------------|
| T10                       | 1             | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{2}$ | $\frac{1}{3}$                    | $\frac{1}{4}$ | $\frac{1}{4}$ | 2             | 3   | 0.0519          |
| T11                       | 2             | 1             | $\frac{1}{2}$ | 1             | $\frac{1}{2}$                    | $\frac{1}{3}$ | $\frac{1}{3}$ | 3             | 5   | 0.0845          |
| T12                       | 3             | 2             | 1             | 2             | 1                                | $\frac{1}{2}$ | $\frac{1}{2}$ | 4             | 6   | 0.1388          |
| T13                       | 2             | 1             | $\frac{1}{2}$ | 1             | $\frac{1}{2}$                    | $\frac{1}{3}$ | $\frac{1}{3}$ | 3             | 5   | 0.0845          |
| T14                       | 3             | 2             | 1             | 2             | 1                                | $\frac{1}{2}$ | $\frac{1}{2}$ | 4             | 6   | 0.1387          |
| T15                       | 4             | 3             | 2             | 3             | 2                                | 1             | 1             | 5             | 7   | 0.2225          |
| T16                       | 4             | 3             | 2             | 3             | 2                                | 1             | 1             | 5             | 7   | 0.2225          |
| T17                       | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{4}$ | $\frac{1}{3}$ | $\frac{1}{4}$                    | $\frac{1}{5}$ | $\frac{1}{5}$ | 1             | 2   | 0.0347          |
| T18                       | $\frac{1}{3}$ | $\frac{1}{5}$ | $\frac{1}{6}$ | $\frac{1}{5}$ | $\frac{1}{6}$                    | $\frac{1}{7}$ | $\frac{1}{7}$ | $\frac{1}{2}$ | 1   | 0.0215          |
| $\lambda_{\max} = 9.1519$ |               |               |               |               | CI= 0.0189, RI= 1.45, CR= 0.0131 |               |               |               |     |                 |

Table 8.14: Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample II

|                           | T10           | T11           | T12           | T13           | T14                              | T15           | T16           | T17 | T18 | Priority vector |
|---------------------------|---------------|---------------|---------------|---------------|----------------------------------|---------------|---------------|-----|-----|-----------------|
| T10                       | 1             | 1             | $\frac{1}{3}$ | $\frac{1}{2}$ | $\frac{1}{3}$                    | $\frac{1}{3}$ | $\frac{1}{3}$ | 3   | 3   | 0.0649          |
| T11                       | 1             | 1             | $\frac{1}{3}$ | $\frac{1}{2}$ | $\frac{1}{3}$                    | $\frac{1}{3}$ | $\frac{1}{3}$ | 3   | 3   | 0.0649          |
| T12                       | 3             | 3             | 1             | 2             | 1                                | 1             | 1             | 5   | 5   | 0.1766          |
| T13                       | 2             | 2             | $\frac{1}{2}$ | 1             | $\frac{1}{2}$                    | $\frac{1}{2}$ | $\frac{1}{2}$ | 4   | 4   | 0.1045          |
| T14                       | 3             | 3             | 1             | 2             | 1                                | 1             | 1             | 5   | 5   | 0.1766          |
| T15                       | 3             | 3             | 1             | 2             | 1                                | 1             | 1             | 5   | 5   | 0.1766          |
| T16                       | 3             | 3             | 1             | 2             | 1                                | 1             | 1             | 5   | 5   | 0.1766          |
| T17                       | $\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{1}{5}$ | $\frac{1}{4}$ | $\frac{1}{5}$                    | $\frac{1}{5}$ | $\frac{1}{5}$ | 1   | 1   | 0.0294          |
| T18                       | $\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{1}{5}$ | $\frac{1}{4}$ | $\frac{1}{5}$                    | $\frac{1}{5}$ | $\frac{1}{5}$ | 1   | 1   | 0.0294          |
| $\lambda_{\max} = 9.1068$ |               |               |               |               | CI= 0.0133, RI= 1.45, CR= 0.0092 |               |               |     |     |                 |

Table 8.15: Pair-wise comparison of oxygen uptake w.r.t. their alternatives for sample III

|                           | T19 | T20 | T21 | T22 | T23                              | T24 | T25 | T26 | T27 | Priority vector |
|---------------------------|-----|-----|-----|-----|----------------------------------|-----|-----|-----|-----|-----------------|
| T19                       | 1   | 1/2 | 1/3 | 1   | 1/2                              | 2   | 1/2 | 2   | 3   | 0.0853          |
| T20                       | 2   | 1   | 1/2 | 2   | 1                                | 3   | 1   | 3   | 5   | 0.1520          |
| T21                       | 3   | 2   | 1   | 3   | 2                                | 4   | 2   | 4   | 5   | 0.2413          |
| T22                       | 1   | 1/2 | 1/3 | 1   | 1/2                              | 2   | 1/2 | 2   | 3   | 0.0853          |
| T23                       | 2   | 1   | 1/2 | 2   | 1                                | 3   | 1   | 3   | 5   | 0.1520          |
| T24                       | 1/2 | 1/3 | 1/4 | 1/2 | 1/3                              | 1   | 1/3 | 1   | 2   | 0.0507          |
| T25                       | 2   | 1   | 1/2 | 2   | 1                                | 3   | 1   | 3   | 5   | 0.1520          |
| T26                       | 1/2 | 1/3 | 1/4 | 1/2 | 1/3                              | 1   | 1/3 | 1   | 2   | 0.0507          |
| T27                       | 1/3 | 1/5 | 1/5 | 1/3 | 1/5                              | 1/2 | 1/5 | 1/2 | 1   | 0.0302          |
| $\lambda_{\max} = 9.0799$ |     |     |     |     | CI= 0.0099, RI= 1.45, CR= 0.0068 |     |     |     |     |                 |

Table 8.16: Pair-wise comparison of heart rate w.r.t. their alternatives for sample III

|                           | T19 | T20 | T21 | T22 | T23                              | T24 | T25 | T26 | T27 | Priority vector |
|---------------------------|-----|-----|-----|-----|----------------------------------|-----|-----|-----|-----|-----------------|
| T19                       | 1   | 1/2 | 1/3 | 1/2 | 1/3                              | 1/5 | 1/5 | 2   | 3   | 0.0480          |
| T20                       | 2   | 1   | 1/2 | 1   | 1/2                              | 1/4 | 1/4 | 3   | 4   | 0.0751          |
| T21                       | 3   | 2   | 1   | 2   | 1                                | 1/2 | 1/2 | 4   | 5   | 0.1321          |
| T22                       | 2   | 1   | 1/2 | 1   | 1/2                              | 1/4 | 1/4 | 3   | 4   | 0.0751          |
| T23                       | 3   | 2   | 1   | 2   | 1                                | 1/2 | 1/2 | 4   | 5   | 0.1321          |
| T24                       | 5   | 4   | 2   | 4   | 2                                | 1   | 1   | 6   | 7   | 0.2410          |
| T25                       | 5   | 4   | 2   | 4   | 2                                | 1   | 1   | 6   | 7   | 0.2410          |
| T26                       | 1/2 | 1/3 | 1/4 | 1/3 | 1/4                              | 1/6 | 1/6 | 1   | 2   | 0.0324          |
| T27                       | 1/3 | 1/4 | 1/5 | 1/4 | 1/5                              | 1/7 | 1/7 | 1/2 | 1   | 0.0229          |
| $\lambda_{\max} = 9.1618$ |     |     |     |     | CI= 0.0202, RI= 1.45, CR= 0.0139 |     |     |     |     |                 |

Table 8.17: Pair-wise comparison of loading rate w.r.t. their alternatives for sample III

|     | T19 | T20 | T21 | T22 | T23 | T24 | T25 | T26 | T27 | Priority vector |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------------|
| T19 | 1   | 1/2 | 1/4 | 1/3 | 2   | 3   | 2   | 3   | 4   | 0.0989          |
| T20 | 2   | 1   | 1/3 | 1/2 | 3   | 4   | 3   | 4   | 5   | 0.1490          |
| T21 | 4   | 3   | 1   | 2   | 5   | 6   | 5   | 6   | 7   | 0.3050          |
| T22 | 3   | 2   | 1/2 | 1   | 4   | 5   | 4   | 5   | 6   | 0.2175          |
| T23 | 1/2 | 1/3 | 1/5 | 1/4 | 1   | 2   | 1   | 2   | 3   | 0.0627          |
| T24 | 1/3 | 1/4 | 1/6 | 1/5 | 1/2 | 1   | 1/2 | 1   | 2   | 0.0390          |

|                           |     |     |     |     |                                  |     |     |     |   |        |
|---------------------------|-----|-----|-----|-----|----------------------------------|-----|-----|-----|---|--------|
| T25                       | 1/2 | 1/3 | 1/5 | 1/4 | 1                                | 2   | 1   | 2   | 3 | 0.0627 |
| T26                       | 1/3 | 1/4 | 1/6 | 1/5 | 1/2                              | 1   | 1/2 | 1   | 2 | 0.0390 |
| T27                       | 1/4 | 1/5 | 1/7 | 1/6 | 1/3                              | 1/2 | 1/3 | 1/2 | 1 | 0.0257 |
| $\lambda_{\max} = 9.2187$ |     |     |     |     | CI= 0.0273, RI= 1.45, CR= 0.0188 |     |     |     |   |        |

Table 8.18: Pair-wise comparison of perceived exertion w.r.t. their alternatives for sample III

|                           | T19 | T20 | T21 | T22 | T23                              | T24 | T25 | T26 | T27 | Priority vector |
|---------------------------|-----|-----|-----|-----|----------------------------------|-----|-----|-----|-----|-----------------|
| T19                       | 1   | 1/3 | 1/3 | 1/2 | 1/3                              | 3   | 1/3 | 2   | 4   | 0.0700          |
| T20                       | 3   | 1   | 1   | 2   | 1                                | 5   | 1   | 4   | 6   | 0.1798          |
| T21                       | 3   | 1   | 1   | 2   | 1                                | 5   | 1   | 4   | 6   | 0.1798          |
| T22                       | 2   | 1/2 | 1/2 | 1   | 1/2                              | 4   | 1/2 | 3   | 5   | 0.1083          |
| T23                       | 3   | 1   | 1   | 2   | 1                                | 5   | 1   | 4   | 6   | 0.1798          |
| T24                       | 1/3 | 1/5 | 1/5 | 1/4 | 1/5                              | 1   | 1/5 | 1/2 | 3   | 0.0336          |
| T25                       | 3   | 1   | 1   | 2   | 1                                | 5   | 1   | 4   | 6   | 0.1798          |
| T26                       | 1/2 | 1/4 | 1/4 | 1/3 | 1/4                              | 2   | 1/4 | 1   | 3   | 0.0467          |
| T27                       | 1/4 | 1/6 | 1/6 | 1/5 | 1/6                              | 1/3 | 1/6 | 1/3 | 1   | 0.0219          |
| $\lambda_{\max} = 9.2057$ |     |     |     |     | CI= 0.0257, RI= 1.45, CR= 0.0177 |     |     |     |     |                 |

One sample calculation for sample I (110) ( $T_1 \dots T_9$ ) for oxygen uptake is as under: (see Table 8.19)

Step 1: The entries in each row of the matrix were multiplied together and nth root of that product was taken.

Step 2: The nth roots were summed and the sum was used to normalize the eigenvector elements to add to 1.00. The 9<sup>th</sup> root for the sixth row was 2.12936 and that was divided by 10.9239 to give 0.1949 as the element in the priority vector.

Step 3: Priority vectors were multiplied with corresponding judgments to obtain the new vector 1.7575 (sixth row). Calculations for remaining alternatives were carried out.

Step 4: New vector was divided by corresponding priority vector to get the value of max eigen value ( $\lambda_{\max} = 9.016273$ ). Average max eigen value ( $\lambda_{\max} = 9.028146$ ) of the all alternatives is shown in Table 8.19.

Step 5: The Consistency Index for a matrix was calculated from the formula,  $(\lambda_{\max} - n) / (n - 1)$ . Since  $n=9$  for this matrix, the CI came out to be 0.00351825.

Step 6: The Consistency Ratio was calculated from the formula, CI/RI (Table 8.5, for  $n=9$ , RI=1.45). The value obtained was 0.002426.

Step 7: The consistency was checked as per defined rule  $CR < 0.1$ , the above calculated result for sample I (110) oxygen uptake shows consistency.

Table 8.19: Calculation of pair-wise comparison of Sample I (110,  $T_1 \dots T_9$ ) Oxygen uptake

|    | T1  | T2  | T3  | T4  | T5  | T6  | T7  | T8 | T9 | Multipl<br>ication | nth<br>root | Priority<br>vector | New<br>vector<br>(multipli<br>cation) | $\lambda_{\max}$ |
|----|-----|-----|-----|-----|-----|-----|-----|----|----|--------------------|-------------|--------------------|---------------------------------------|------------------|
| T1 | 1   | 1   | 1/2 | 1/2 | 1/3 | 1/3 | 1/3 | 2  | 2  | 0.037              | 0.693       | 0.064              | 0.574                                 | 9.039            |
| T2 | 1   | 1   | 1/2 | 1/2 | 1/3 | 1/3 | 1/3 | 2  | 2  | 0.037              | 0.693       | 0.064              | 0.574                                 | 9.039            |
| T3 | 2   | 2   | 1   | 1   | 1/2 | 1/2 | 1/2 | 3  | 3  | 4.500              | 1.182       | 0.108              | 0.978                                 | 9.041            |
| T4 | 2   | 2   | 1   | 1   | 1/2 | 1/2 | 1/2 | 3  | 3  | 4.500              | 1.182       | 0.108              | 0.978                                 | 9.041            |
| T5 | 3   | 3   | 2   | 2   | 1   | 1   | 1   | 5  | 5  | 900.0              | 2.129       | 0.195              | 1.758                                 | 9.016            |
| T6 | 3   | 3   | 2   | 2   | 1   | 1   | 1   | 5  | 5  | 900.0              | 2.129       | 0.195              | 1.758                                 | 9.016            |
| T7 | 3   | 3   | 2   | 2   | 1   | 1   | 1   | 5  | 5  | 900.0              | 2.129       | 0.195              | 1.758                                 | 9.016            |
| T8 | 1/2 | 1/2 | 1/3 | 1/3 | 1/5 | 1/5 | 1/5 | 1  | 1  | 0.000              | 0.393       | 0.036              | 0.324                                 | 9.023            |
| T9 | 1/2 | 1/2 | 1/3 | 1/3 | 1/5 | 1/5 | 1/5 | 1  | 1  | 0.000              | 0.393       | 0.036              | 0.324                                 | 9.023            |
|    |     |     |     |     |     |     |     |    |    |                    | 10.924      | 1.000              |                                       | 9.028            |

Similarly, the pair wise comparison matrix, priority vectors and validation of constructed matrix were evaluated for each response parameter.

The overall priority weight was calculated by multiplying the alternative available priority vectors for each sample with the criteria weight and as given in Tables 8.20 to 8.23.

Table 8.20: Overall weight matrix of sample I for priority

| Trials | Oxygen<br>uptake<br>(0.3684) | Heart rate<br>(0.1928) | Loading rate<br>(0.3684) | Perceived<br>exertion<br>(0.0704) | Overall<br>priority<br>vector | Ideal<br>weight<br>vector |
|--------|------------------------------|------------------------|--------------------------|-----------------------------------|-------------------------------|---------------------------|
| T1     | 0.0635                       | 0.0251                 | 0.0587                   | 0.0665                            | 0.0545                        | 0.2727                    |
| T2     | 0.0635                       | 0.0376                 | 0.0587                   | 0.0665                            | 0.0569                        | 0.2847                    |
| T3     | 0.1082                       | 0.0586                 | 0.0963                   | 0.1120                            | 0.0945                        | 0.4725                    |
| T4     | 0.1082                       | 0.0376                 | 0.0963                   | 0.1120                            | 0.0904                        | 0.4523                    |
| T5     | 0.1949                       | 0.0923                 | 0.1538                   | 0.1907                            | 0.1596                        | 0.7984                    |
| T6     | 0.1949                       | 0.1436                 | 0.2364                   | 0.1907                            | 0.2000                        | 1.000*                    |
| T7     | 0.1949                       | 0.0923                 | 0.2364                   | 0.1907                            | 0.1901                        | 0.9505                    |
| T8     | 0.0359                       | 0.2124                 | 0.0375                   | 0.0419                            | 0.0709                        | 0.3547                    |
| T9     | 0.0359                       | 0.3001                 | 0.0258                   | 0.0286                            | 0.0826                        | 0.4129                    |

\*1<sup>st</sup> rank

Table 8.21: Overall weight matrix of sample II for priority.

| Trials | Oxygen uptake<br>(0.3684) | Heart rate<br>(0.1928) | Loading rate<br>(0.3684) | Perceived exertion<br>(0.0704) | Overall priority vector | Ideal weight vector |
|--------|---------------------------|------------------------|--------------------------|--------------------------------|-------------------------|---------------------|
| T10    | 0.0593                    | 0.0548                 | 0.0519                   | 0.0649                         | 0.0561                  | 0.2401              |
| T11    | 0.0593                    | 0.0904                 | 0.0845                   | 0.0649                         | 0.0750                  | 0.3209              |
| T12    | 0.1572                    | 0.1532                 | 0.1387                   | 0.1766                         | 0.1510                  | 0.6461              |
| T13    | 0.0953                    | 0.0904                 | 0.0845                   | 0.1045                         | 0.0910                  | 0.3896              |
| T14    | 0.1572                    | 0.1532                 | 0.1387                   | 0.1766                         | 0.1510                  | 0.6461              |
| T15    | 0.2496                    | 0.2457                 | 0.2225                   | 0.1766                         | 0.2337                  | 0.999*              |
| T16    | 0.1572                    | 0.1532                 | 0.2225                   | 0.1766                         | 0.1819                  | 0.7781              |
| T17    | 0.0381                    | 0.0364                 | 0.0347                   | 0.0294                         | 0.0359                  | 0.1537              |
| T18    | 0.0263                    | 0.0224                 | 0.0215                   | 0.0294                         | 0.0240                  | 0.1027              |

\*1<sup>st</sup> rank

Table 8.22: Overall weight matrix of sample III for priority

| Trials | Oxygen uptake<br>(0.3684) | Heart rate<br>(0.1928) | Loading rate<br>(0.3684) | Perceived exertion<br>(0.0704) | Overall priority vector | Ideal weight vector |
|--------|---------------------------|------------------------|--------------------------|--------------------------------|-------------------------|---------------------|
| T19    | 0.0853                    | 0.0480                 | 0.0989                   | 0.0700                         | 0.0820                  | 0.3428              |
| T20    | 0.1520                    | 0.0751                 | 0.1490                   | 0.1798                         | 0.1380                  | 0.5766              |
| T21    | 0.2413                    | 0.1321                 | 0.3050                   | 0.1798                         | 0.2394                  | 1.000*              |
| T22    | 0.0853                    | 0.0751                 | 0.2175                   | 0.1083                         | 0.1337                  | 0.5584              |
| T23    | 0.1520                    | 0.1321                 | 0.0627                   | 0.1798                         | 0.1172                  | 0.4897              |
| T24    | 0.0507                    | 0.2410                 | 0.0390                   | 0.0336                         | 0.0819                  | 0.3421              |
| T25    | 0.1520                    | 0.2410                 | 0.0627                   | 0.1798                         | 0.1382                  | 0.5774              |
| T26    | 0.0507                    | 0.0324                 | 0.0390                   | 0.0467                         | 0.0426                  | 0.1779              |
| T27    | 0.0302                    | 0.0229                 | 0.0257                   | 0.0219                         | 0.0266                  | 0.1111              |

\*1<sup>st</sup> rank

To maintain the consistency during pair wise comparison of alternatives, the assigned value has not been taken greater than 9, which is the maximum limit of the fundamental scale.

The overall priority weight for each alternative was obtained as demonstrated below:

Overall priority weight of T6 (Sample I, 110)

$$= 0.3684(0.1949) + 0.1928 (0.1436) + 0.3684 (0.2364) + 0.0704 (0.1907) = 0.2$$

Similarly, the overall priority weight was calculated for each trial conducted with three samples.

The ideal weight vector was calculated by dividing the priority weight vector with the largest priority weight element in the matrix. From above calculations, maximum overall priority weight (the ideal weight vector 1) for sample I (110) (see Table 8.20) corresponds to trial number 6 in the original  $L_{27}$  array (see Table 8.2). This was performed with a lifting frequency of 110 per 20 minutes, 18 kg load, shoulder vertical distance, grip with gloves, 30 cm horizontal distance,  $40^0$  asymmetric angle and 60 cm travel distance.

Similarly, the maximum overall weight for sample II (140) as obtained in Table 8.21 corresponds to trial number 15 of the original  $L_{27}$  array. The values of parameters used for this trial were as follow: 140 per 20 minutes lifting frequency, 18 kg load, shoulder vertical distance, grip without gloves, 55 cm horizontal distance,  $0^0$  asymmetric angle, 45 cm travel distance. Similarly trial number 15 of the original  $L_{27}$  array of sample III (180) (see Table 8.22) had a maximum priority weight. This trial was established with a lifting frequency of 180 per 20 minutes, 13 kg load, shoulder vertical distance, grip with gloves, 30 cm horizontal distance,  $0^0$  asymmetric angle and 25 cm travel distance. The solution that globally optimizes oxygen uptake, heart rate, loading rate and perceived exertion for three different sets of frequencies are given in Table 8.23 with their most suitable levels. Correlation plots of three optimal process settings are shown in Figure 8.6 for safe lifting. It can also be observed from Figure 8.6 that the lifting frequency decreases with increase in the weight at constant vertical distance (shoulder height).

Table 8.23: Optimal lifting parameter setting for safe lifting for different sets of frequencies

| Frequency sets                           | Optimal parameters setting for safe lifting                                                                                                                                                     |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sample I(110)<br>$T_1 \dots T_9$         | Trial 06 $\equiv$ 110 per 20 min lifting frequency, 18 kg weight, shoulder vertical distance, grip with gloves, 30 cm horizontal distance, $40^0$ asymmetric angle and 60 cm travel distance.   |
| Sample II(140)<br>$T_{10} \dots T_{18}$  | Trial 15 $\equiv$ 140 per 20 min lifting frequency, 18 kg weight, shoulder vertical distance, grip without gloves, 55 cm horizontal distance, $0^0$ asymmetric angle and 45 cm travel distance. |
| Sample III(180)<br>$T_{19} \dots T_{27}$ | Trial 21 $\equiv$ 180 per 20 min lifting frequency, 13 kg weight, shoulder vertical distance, grip with gloves, 30 cm horizontal distance, $0^0$ asymmetric angle and 25 cm travel distance     |

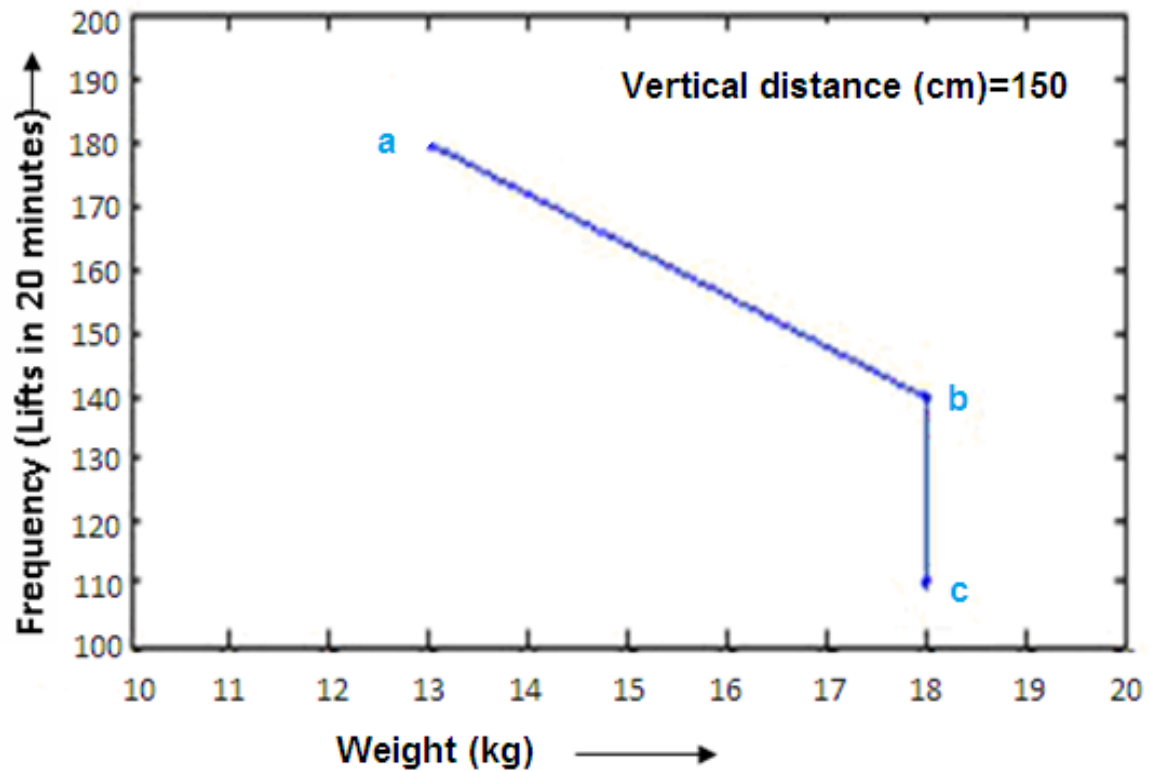


Figure 8.6: Correlation in optimal setting parameters for safe lifting using AHP  
 (Note: a-13W, 180fr, 150V.H, b-18W, 140fr, 150V.H, c-18W, 110fr, 150V.H, where W, fr, V.H represents Weight, Frequency and Vertical Distance respectively)

The overall optimal process settings for Trials 6, 15, 21 reveal that higher load, lower lifting frequency and vice versa for same vertical height (shoulder) are the best combination for safe lifting. It is believed that such an approach will enhance the reliability of the results thus obtained.

## CHAPTER 9

### RESULTS, DISCUSSION AND CONCLUSIONS

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This chapter presents results of the work undertaken in this study, the discussions of the results and conclusions drawn from the work. Scope for future work has also been covered in the chapter. The effect of load weight, frequency of lift, coupling (grip), posture (asymmetry), vertical distance from ground level, horizontal distance from lifting object, travel distance (carrying distance) and their interactions on the oxygen uptake, heart rate and perceived exertion under different environmental conditions and ground reaction force of workers involved in lifting task were studied. The analysis was carried out using ANOVA and factorial design analysis. For an in depth understanding of the significance of lifting parameters, plots for mean responses during each trial and level effect for each factor, radar charts and design matrix for identifying the safe lifting task were developed.

Multi response optimization and regression analysis for oxygen uptake and heart rate were carried out. Predicted heart rate and oxygen uptake equations were developed. Different optimization methods were used for suitable trials and statistical tools were applied for verification of results. A summary of the results of the experimental work discussed in details in the previous chapters and conclusions of the study are given in the following sections.

#### 9.1 EFFECT OF ENVIRONMENTAL CONDITIONS DURING MANUAL LIFTING

- Three control factors namely (i) load weight (percentage contribution (pc) 32 % for  $VO_2$  and 41 % for HR) (ii) lifting frequency (pc 11 % for  $VO_2$  and 9 % for HR) and (iii) vertical distance (pc 27 % for  $VO_2$  and 29 % for HR) were identified as significant factors after ANOVA for oxygen uptake, heart rate. Load weight was found to be most significant factor for oxygen uptake and heart rate and the coupling (grip) were found to be least significant (pc less than 1 percent for both responses).
- Lifting frequency more than 7 lifts per minute, weight above 18 kg and vertical distance above the waist level (110 centimeter) increased the physiological workload on the subjects involved in the task. The tasks become even more stressful when the vertical distance of the lift is above the shoulder level.
- The ambient temperature showed the largest affect (pc 29 % for  $VO_2$  and 50 % for HR) on the two response parameters. Ambient temperature contributed to significant changes in the oxygen uptake and heart rate when plotted for each factor separately (see

chapter 4, Figures 4.2, 4.3 and 4.4). Oxygen uptake, heart rate and perceived exertion significantly increased during winter under similar experimental conditions (see trials 19 to 27 in Table 9.1). This signifies an increased exertion to the workers engaged in lifting tasks during winter as compared to summer. The percentage change in oxygen uptake, heart rate and perceived exertion in summer and winter were calculated and are given in Table 9.1.

Table 9.1: Percentage change in oxygen uptake, heart rate and perceived exertion in summer and winter

| Trial No. | Mean oxygen uptake (ml/kg-min) |        | Mean heart rate (beats/min) |        | Perceived Exertion (Borg RPE Scale) |        | Percentage change |            |                    |
|-----------|--------------------------------|--------|-----------------------------|--------|-------------------------------------|--------|-------------------|------------|--------------------|
|           | Summer                         | Winter | Summer                      | Winter | Summer                              | Winter | Oxygen uptake     | Heart rate | Perceived exertion |
| 1         | 9.23                           | 10.42  | 96.73                       | 104.96 | 10                                  | 11     | 12.89             | 8.50       | 8.33               |
| 2         | 10.11                          | 11.88  | 98.66                       | 107.82 | 11                                  | 13     | 17.51             | 9.28       | 15.38              |
| 3         | 11.36                          | 12.87  | 100.19                      | 114.81 | 13                                  | 16     | 13.29             | 14.59      | 18.75              |
| 4         | 10.25                          | 11.84  | 90.13                       | 106.83 | 11                                  | 13     | 15.51             | 18.53      | 15.38              |
| 5         | 10.18                          | 11.90  | 99.15                       | 106.36 | 11                                  | 13     | 16.90             | 7.27       | 15.38              |
| 6         | 11.95                          | 15.16  | 103.51                      | 122.72 | 13                                  | 18     | 26.86             | 18.56      | 27.78              |
| 7         | 10.87                          | 13.34  | 96.83                       | 110.48 | 11                                  | 17     | 22.72             | 14.10      | 35.29              |
| 8         | 12.41                          | 14.02  | 102.34                      | 115.40 | 14                                  | 17     | 12.97             | 12.76      | 17.65              |
| 9         | 12.69                          | 14.97  | 103.81                      | 112.74 | 14                                  | 18     | 17.97             | 8.60       | 22.22              |
| 10        | 12.08                          | 13.08  | 100.42                      | 111.82 | 14                                  | 16     | 8.28              | 11.35      | 12.50              |
| 11        | 10.23                          | 12.99  | 103.03                      | 112.59 | 12                                  | 16     | 26.98             | 9.28       | 25.00              |
| 12        | 12.79                          | 16.06  | 103.55                      | 122.16 | 14                                  | 19     | 25.57             | 17.97      | 26.32              |
| 13        | 11.95                          | 12.68  | 99.09                       | 105.47 | 13                                  | 13     | 6.11              | 6.44       | 0.00               |
| 14        | 12.20                          | 14.65  | 106.87                      | 121.51 | 15                                  | 18     | 20.08             | 13.70      | 16.67              |
| 15        | 12.39                          | 14.11  | 105.37                      | 116.38 | 15                                  | 17     | 13.88             | 10.45      | 11.76              |
| 16        | 11.48                          | 14.84  | 98.17                       | 114.80 | 12                                  | 16     | 29.27             | 16.94      | 25.00              |
| 17        | 12.11                          | 14.79  | 97.85                       | 119.91 | 14                                  | 17     | 22.13             | 22.54      | 17.65              |
| 18        | 14.91                          | 16.01  | 105.47                      | 121.67 | 18                                  | 19     | 7.38              | 15.36      | 5.26               |
| 19        | 12.66                          | 13.98  | 98.61                       | 105.72 | 13                                  | 14     | 10.43             | 7.21       | 7.14               |
| 20        | 13.03                          | 15.16  | 106.24                      | 118.27 | 17                                  | 18     | 16.35             | 11.32      | 5.56               |
| 21        | 13.61                          | 15.13  | 108.67                      | 118.23 | 17                                  | 18     | 11.17             | 8.80       | 5.56               |
| 22        | 13.87                          | 14.19  | 107.34                      | 117.22 | 17                                  | 17     | 2.31              | 9.20       | 0.00               |
| 23        | 14.10                          | 14.99  | 110.96                      | 122.85 | 18                                  | 18     | 6.31              | 10.72      | 0.00               |
| 24        | 13.64                          | 15.76  | 113.63                      | 126.98 | 17                                  | 19     | 15.54             | 11.75      | 10.53              |
| 25        | 12.46                          | 14.00  | 108.44                      | 123.88 | 15                                  | 18     | 12.36             | 14.24      | 16.67              |

|    |       |       |        |        |    |    |       |       |       |
|----|-------|-------|--------|--------|----|----|-------|-------|-------|
| 26 | 12.95 | 14.48 | 110.45 | 129.39 | 17 | 19 | 11.81 | 17.15 | 10.53 |
| 27 | 14.60 | 17.09 | 113.98 | 128.10 | 19 | 20 | 17.05 | 12.39 | 5.00  |

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- The labour productivity will be very low with low level settings of weight, lifting frequency and vertical distance. The optimum setting would be for oxygen uptake and heart rate at a level which would cause low to moderate exertion. The settings for the three significant factors have to be selected for this level of moderate exertion. The optimal settings for oxygen uptake and heart rate have been calculated to be 12.93 ml/kg-min and 110 beats/minute respectively.
- Decision matrix was developed for identifying safe lifting tasks. Yes and No options were given for suitable trials for summer and winter. The mean value of responses was compared with safe limits to identify the safe combinations of the three factors. The combinations can be used to design the lifting task parameters. The safe combinations are given below (from Table 9.2):

#### **For oxygen uptake**

Summer (A<sub>1</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>3</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>3</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>3</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>3</sub>, A<sub>2</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>2</sub>E<sub>2</sub>, A<sub>2</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>3</sub>E<sub>2</sub>, A<sub>3</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>3</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>3</sub>B<sub>2</sub>E<sub>1</sub>)

Winter (A<sub>1</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>1</sub>)

#### **For heart rate**

Summer (A<sub>1</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>3</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>3</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>3</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>3</sub>, A<sub>2</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>2</sub>E<sub>2</sub>, A<sub>2</sub>B<sub>2</sub>E<sub>3</sub>, A<sub>2</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>3</sub>E<sub>2</sub>, A<sub>2</sub>B<sub>3</sub>E<sub>3</sub>, A<sub>3</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>3</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>3</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>3</sub>B<sub>3</sub>E<sub>1</sub>)

Winter (A<sub>1</sub>B<sub>1</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>1</sub>E<sub>2</sub>, A<sub>1</sub>B<sub>2</sub>E<sub>1</sub>, A<sub>1</sub>B<sub>3</sub>E<sub>1</sub>, A<sub>2</sub>B<sub>1</sub>E<sub>1</sub>)

(For example, A<sub>1</sub> B<sub>2</sub> E<sub>3</sub> to be read as: factor A (load) set at level 1 (13 kg), factor B (lift frequency) set at level 2 (7lift/min) and factor E (vertical distance) set at level 3 (shoulder height) and so on.)

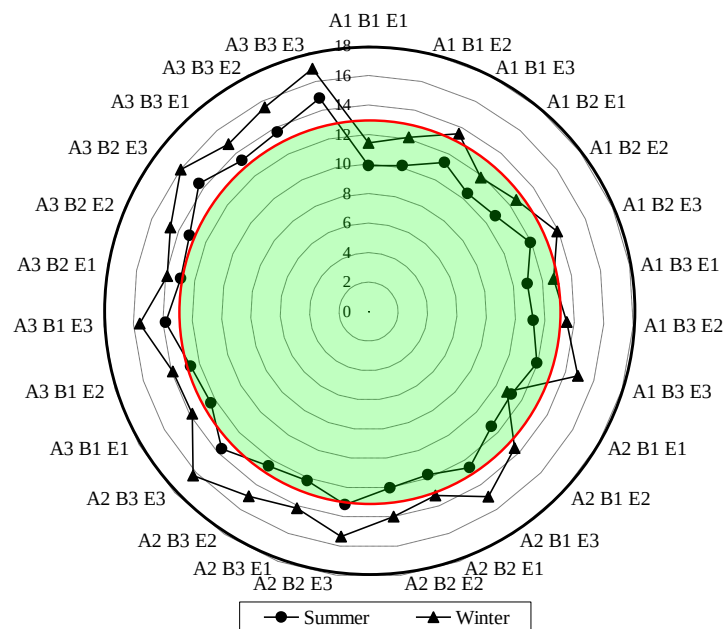
- The safe limits identified after the experimental study for both summer and winter are presented in Table 9.2. Figure 9.1 shows a radar plot of all experimental trial conditions for both summer and winter for oxygen uptake. All points beyond the safe limit of 12.93 ml/kg-min for oxygen uptake indicate unsafe lifting conditions which need to be avoided. Similarly, Figure 9.2 shows the safe limits using heart rate for both summer and winter.

Table 9.2: Decision with safe limit for identifying safe lifting task in summer and winter

| Trial No. | Different level setting of significant parameters (Load weight A, Frequency of lift B, Vertical distance E) | Optimum oxygen uptake (ml/kg-min) |        | Optimum heart rate (beats/min) |        | Decision with Safe limit $\leq 12.93$ ml/kg-min (Summer/Winter) | Decision with Safe limit $\leq 110$ beats/min (Summer/Winter) |
|-----------|-------------------------------------------------------------------------------------------------------------|-----------------------------------|--------|--------------------------------|--------|-----------------------------------------------------------------|---------------------------------------------------------------|
|           |                                                                                                             | Summer                            | Winter | Summer                         | Winter |                                                                 |                                                               |
| 1         | A <sub>1</sub> B <sub>1</sub> E <sub>1</sub>                                                                | 9.89                              | 11.41  | 93.74                          | 103.02 | Y / Y                                                           | Y / Y                                                         |
| 2         | A <sub>1</sub> B <sub>1</sub> E <sub>2</sub>                                                                | 10.16                             | 12.13  | 98.16                          | 108.94 | Y / Y                                                           | Y / Y                                                         |
| 3         | A <sub>1</sub> B <sub>1</sub> E <sub>3</sub>                                                                | 11.34                             | 13.5   | 100.67                         | 112.24 | Y / N                                                           | Y / N                                                         |
| 4         | A <sub>1</sub> B <sub>2</sub> E <sub>1</sub>                                                                | 10.44                             | 11.82  | 95.96                          | 106.30 | Y / Y                                                           | Y / Y                                                         |
| 5         | A <sub>1</sub> B <sub>2</sub> E <sub>2</sub>                                                                | 10.76                             | 12.54  | 100.38                         | 112.31 | Y / Y                                                           | Y / N                                                         |
| 6         | A <sub>1</sub> B <sub>2</sub> E <sub>3</sub>                                                                | 11.94                             | 13.91  | 102.89                         | 115.61 | Y / N                                                           | Y / N                                                         |
| 7         | A <sub>1</sub> B <sub>3</sub> E <sub>1</sub>                                                                | 10.93                             | 12.74  | 96.1                           | 109.73 | Y / Y                                                           | Y / Y                                                         |
| 8         | A <sub>1</sub> B <sub>3</sub> E <sub>2</sub>                                                                | 11.2                              | 13.46  | 100.52                         | 115.65 | Y / N                                                           | Y / N                                                         |
| 9         | A <sub>1</sub> B <sub>3</sub> E <sub>3</sub>                                                                | 11.94                             | 14.83  | 103.03                         | 118.95 | Y / N                                                           | Y / N                                                         |
| 10        | A <sub>2</sub> B <sub>1</sub> E <sub>1</sub>                                                                | 11.16                             | 10.84  | 96.9                           | 107.87 | Y / Y                                                           | Y / Y                                                         |
| 11        | A <sub>2</sub> B <sub>1</sub> E <sub>2</sub>                                                                | 11.4                              | 13.56  | 101.32                         | 113.79 | Y / N                                                           | Y / N                                                         |
| 12        | A <sub>2</sub> B <sub>1</sub> E <sub>3</sub>                                                                | 12.58                             | 14.93  | 103.83                         | 117.09 | Y / N                                                           | Y / N                                                         |
| 13        | A <sub>2</sub> B <sub>2</sub> E <sub>1</sub>                                                                | 11.73                             | 13.25  | 99.12                          | 111.24 | Y / N                                                           | Y / N                                                         |
| 14        | A <sub>2</sub> B <sub>2</sub> E <sub>2</sub>                                                                | 12                                | 13.97  | 103.54                         | 117.16 | Y / N                                                           | Y / N                                                         |
| 15        | A <sub>2</sub> B <sub>2</sub> E <sub>3</sub>                                                                | 13.18                             | 15.34  | 106.05                         | 120.46 | N / N                                                           | Y / N                                                         |
| 16        | A <sub>2</sub> B <sub>3</sub> E <sub>1</sub>                                                                | 12.17                             | 14.17  | 99.26                          | 114.58 | Y / N                                                           | Y / N                                                         |
| 17        | A <sub>2</sub> B <sub>3</sub> E <sub>2</sub>                                                                | 12.44                             | 14.89  | 103.68                         | 120.5  | Y / N                                                           | Y / N                                                         |
| 18        | A <sub>2</sub> B <sub>3</sub> E <sub>3</sub>                                                                | 13.62                             | 16.26  | 106.19                         | 123.8  | N / N                                                           | Y / N                                                         |
| 19        | A <sub>3</sub> B <sub>1</sub> E <sub>1</sub>                                                                | 12.33                             | 13.82  | 103.4                          | 112.68 | Y / N                                                           | Y / N                                                         |
| 20        | A <sub>3</sub> B <sub>1</sub> E <sub>2</sub>                                                                | 12.6                              | 13.88  | 107.82                         | 118.6  | Y / N                                                           | Y / N                                                         |
| 21        | A <sub>3</sub> B <sub>1</sub> E <sub>3</sub>                                                                | 13.78                             | 15.55  | 110.33                         | 121.9  | N / N                                                           | N / N                                                         |
| 22        | A <sub>3</sub> B <sub>2</sub> E <sub>1</sub>                                                                | 12.93                             | 13.87  | 105.62                         | 116.05 | Y / N                                                           | Y / N                                                         |
| 23        | A <sub>3</sub> B <sub>2</sub> E <sub>2</sub>                                                                | 13.2                              | 14.59  | 110.04                         | 121.97 | N / N                                                           | N / N                                                         |
| 24        | A <sub>3</sub> B <sub>2</sub> E <sub>3</sub>                                                                | 14.38                             | 15.96  | 112.55                         | 125.27 | N / N                                                           | N / N                                                         |
| 25        | A <sub>3</sub> B <sub>3</sub> E <sub>1</sub>                                                                | 13.37                             | 14.79  | 105.76                         | 119.39 | N / N                                                           | Y / N                                                         |
| 26        | A <sub>3</sub> B <sub>3</sub> E <sub>2</sub>                                                                | 13.64                             | 15.51  | 110.18                         | 125.31 | N / N                                                           | N / N                                                         |
| 27        | A <sub>3</sub> B <sub>3</sub> E <sub>3</sub>                                                                | 14.82                             | 16.88  | 112.69                         | 128.61 | N / N                                                           | N / N                                                         |

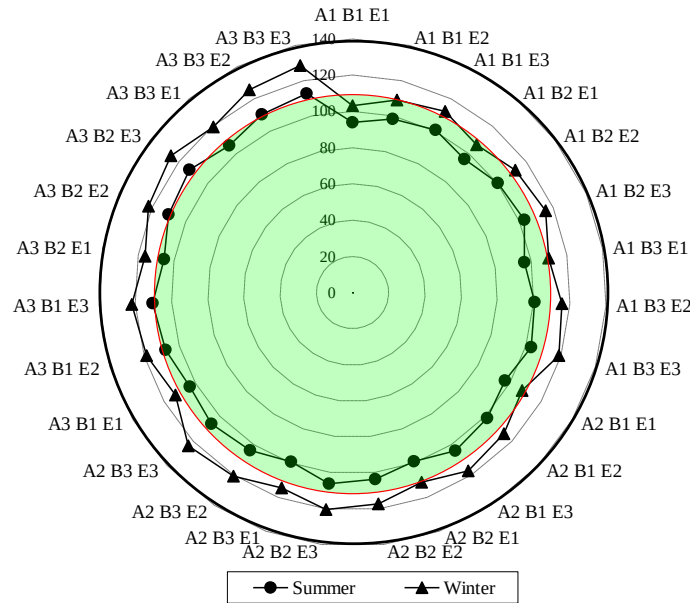
(Note: A<sub>i</sub> B<sub>i</sub> E<sub>i</sub> = Factors A, B, E set at i<sup>th</sup> level, Y=Safe lifting task, N=Unsafe lifting task)

- Figures 9.1 and 9.2 show the graphical representation in the form of radar charts of the optimum mean oxygen uptake and heart rate for 27 different combinations of the three significant factors namely (i) Factor A, load; (ii) Factor B, lift frequency; and (iii) Factor E, vertical distance described in Table 9.2. Each point on the circumference depicts one combination. For example, A2 B3 E1 to be read as: factor A (load) set at level 2 (18 kg), factor B (lift frequency) set at level 3 (9 lifts/min) and factor E (vertical distance) set at level 1 (knee height) and so on. All the points beyond the safe limit of oxygen uptake @ 12.93 ml/kg-min and heart rate @ 110 beats/min would cause high exertion/musculoskeletal injury to the workers and should be treated as potentially hazardous combinations (unsafe) in the long run. All points that are beyond the safe green region on the radar chart in Figures 9.1 and 9.2 depict the unsafe combinations of load, frequency and vertical distance.
- The effect of cold conditions on the two responses can also be visualized in these plots. Using the same safe limits for oxygen uptake and heart rate, fewer combinations exhibited safe work conditions and, thus, the load, lifting frequency and vertical distance would have to be significantly lowered in relative comparison to the results for summer.



(Note: A2 B3 E1= Factor A (load) set at level 2 (18 kg), factor B (lift frequency) set at level 3 (9lift/min) and factor E (vertical distance) set at level 1 (knee height) and so on)

Figure 9.1: Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task in summer and winter



(Note: A2 B3 E1= Factor A (load) set at level 2 (18 kg), factor B (lift frequency) set at level 3 (9lift/min) and factor E (vertical distance) set at level 1 (knee height) and so on)

Figure 9.2: Optimum heart rate for different level setting of significant factors for identifying safe lifting task in summer and winter

### Multiple Response Optimization

- Optimizing each response separately could lead to erroneous results. So a multiple-response optimization technique was used for identification of optimal conditions. Since S/N ratio is higher, the response is better. Load weight, vertical distance and lift frequency should be set at lower level i.e. 13 kg, 55 cm and 110 lifts/ 20min respectively for reducing the variation in oxygen uptake and heart rate.
- The load weight (pc 32.74% for winter, 54.82% for summer), vertical distance (pc 30.67% for winter, 44.66% for summer) and lifting frequency (pc 14.25% for winter, 11.33% for summer) were found to be most significant factors affecting the MRSN ratio. The coupling (grip), asymmetric angle, travel distance and horizontal distance had no significant effect on MRSN.
- MRSN (11.73 in winter) was more than the MRSN (10.68 in summer) in last 9 trials (conducted for 23 kg load weight) of experimental layout indicating that exertion leads to higher MRSN.
- The empirical model for MRSN (winter and summer) was developed and can be used to predict the response values during experimental trials involving similar work

conditions. The regression equation of MRSN was evaluated for winter and summer separately and is given below:

*For winter*

$$MRSN = 9.09 - 1.04 W - 0.714 F - 1.02 V.D$$

*For summer*

$$MRSN = 7.39 - 1.23 W - 0.414 F - 0.809 V.D$$

where W is load weight in kg, F frequency in lifts per minute and V.D vertical distance in centimeter. The above equations are in generalized form for winter and summer and can be used to predict the MRSN in different environmental conditions. The coefficients of the equation indicate that with the increase in task intensity or workload the oxygen uptake and heart rate would increase and can be significantly lowered by allowing adequate rest periods.

### **Predicted Heart Rate (PHR)**

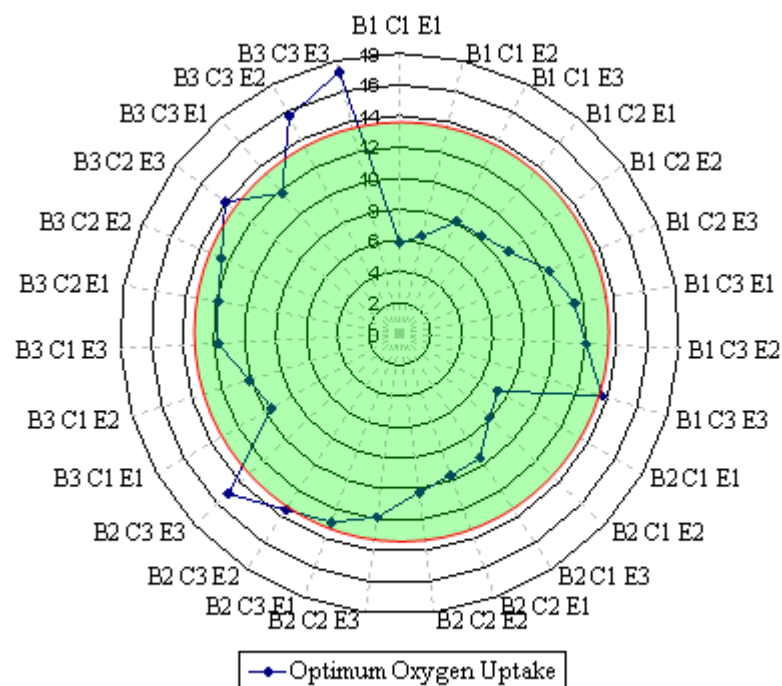
- The multiplicative equation to calculate Predicted Heart Rate (PHR) under different environmental conditions was developed by using the significant factors. The equation uses the maximum working heart rate along with the correction coefficients obtained statistically for load, lifting frequency, vertical distance and ambient temperature. It was found that the theoretical and the actual values are highly correlated.
- A safe task and a potentially unsafe task can be identified from the PHR index which is less than 1 for safe task and greater than 1 for unsafe task. An assessment chart designed to evaluate the task has been proposed for industry application (see Figure 4.19 in chapter 4).

## **9.2 PREDICTED OXYGEN UPTAKE**

- Using the three most significant factors (load, lifting frequency and vertical distance) a Predicted Oxygen Uptake (POU) equation was developed without considering the effect of environmental conditions. The equation uses the maximum aerobic capacity along with the correction coefficients for the three contributing factors. The correction coefficients were calculated and validated by statistical tools. The POU index can be used for identification of safe and unsafe lifting tasks.
- Optimum mean oxygen uptake for 27 different combinations of the three significant factors namely (i) Factor B, load; (ii) Factor C, lift frequency; and (iii) Factor E, vertical distance have been plotted on a radar chart. Each point on the circumference depicts one combination. All the points beyond the safe limit of oxygen uptake @

13.64 ml/kg-min are potentially hazardous and are likely to cause high exertion/musculoskeletal injury to the workers. All points that are beyond the safe green region on the radar chart in Figures 9.3 depict the unsafe combinations of load, frequency and vertical distance.

- The safe combinations of significant factors described in the study can be used to design the lifting task parameters. A chart (shown in Figure 5.7 in chapter 5) incorporating aerobic capacity, POU equation, Index and correction coefficients to assess the task, has been designed for industry application.



(Note: B1 C2 E3= Factor B (load) set at level 1 (13 kg), factor B (lift frequency) set at level 2 (5 lift/min) and factor E (vertical distance) set at level 3 (shoulder height) and so on)

Figure 9.3: Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task without the effect of ambient temperature

### 9.3 SAFE LIMITS OF MANUAL LIFTING TASK PARAMETERS USING BIOMECHANICS PRINCIPLE

- Three factors namely, (i) weight (pc 61.6%) (ii) vertical distance (pc 23%) and (iii) frequency (12.3%) were found to significantly affect the vertical ground reaction forces

of workers in different dynamic human lifting activities. All other factors were found to be insignificant.

- The vertical reaction forces are more when worker lifts the weight from floor to shoulder height with high frequency. The correlation plots (see Figures 9.4, 9.5 and 9.6) clearly show that the loading rate increases almost linearly with increase in load weight to be lifted, with increased frequency of lifting and also, with increased vertical distance. Even when the weight to be lifted is not increased, the loading rate increases with higher lifting frequency. The loading rate shows no considerable change when the vertical distance is increased from 55 cm (knee level) to 110 cm (waist height). However, there is a definite increase in loading rate when the vertical distance increases from 110 cm (waist height) to 150 cm (shoulder height). The increased loading rate signifies an increased exertion to the workers engaged in dynamic lifting tasks. So significant extra loading rate is required to change the lower level of load, frequency and vertical distance to higher one that may lead to chronic injury.

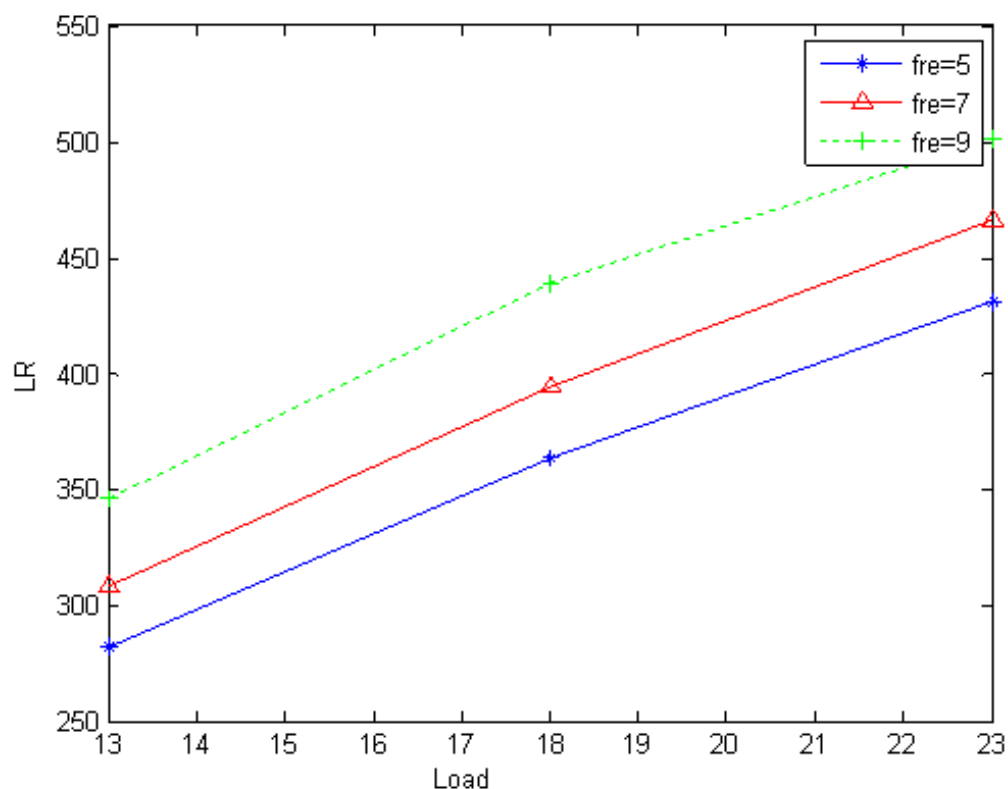


Figure 9.4: Loading rate plot with load and frequency keeping vertical distance constant  
(Note: LR= Loading rate in Newton/sec, fre= frequency in beats/minute, Load=load in kg)

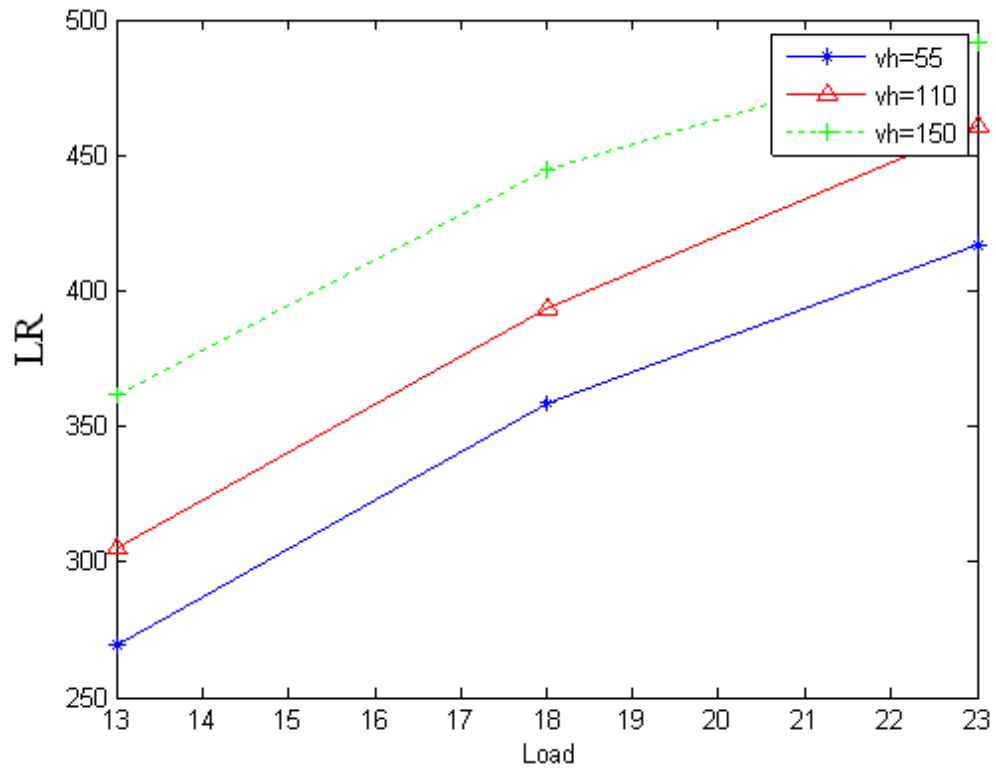


Figure 9.5: Loading rate plot with load and vertical distance keeping frequency constant

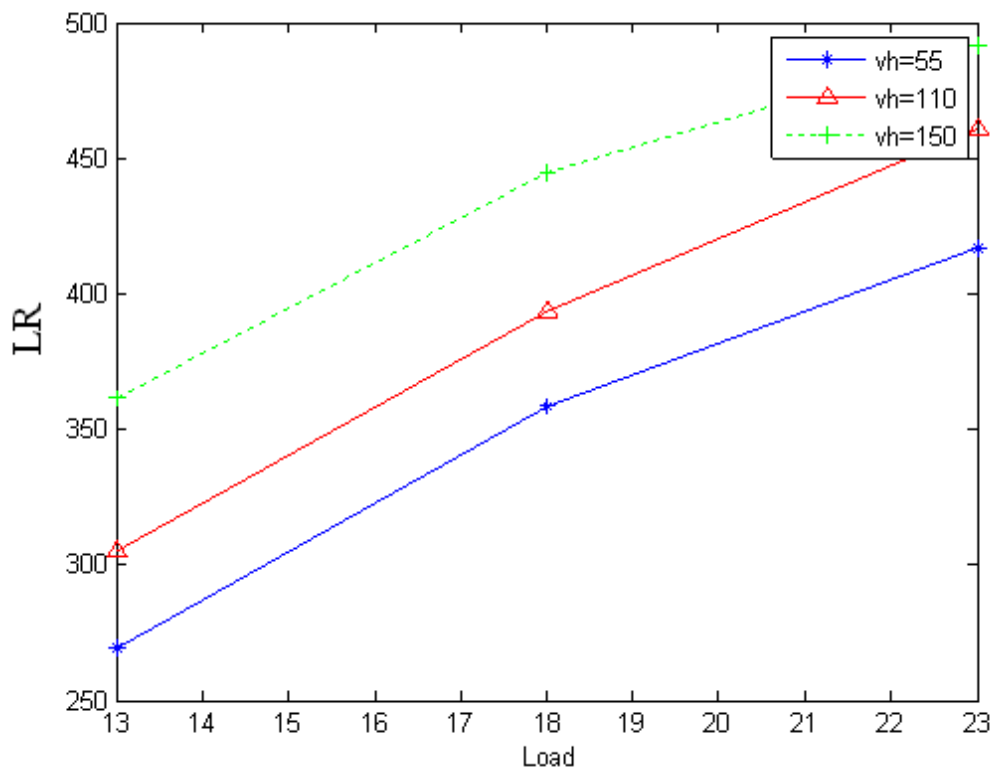


Figure 9.6: Loading rate plot with frequency and vertical distance keeping load constant  
(Note: LR= loading rate in Newton/sec, fre= frequency in beats/min, vh=vertical distance in cm)

- The results representing the resultant change in loading rate with the change in task parameters are given in Table 9.3. (For example when the weight was increased from 13 to 23kg by keeping the lifting frequency and vertical distance constant, the mean loading rate increased by 33.8 percent and so on).

Table 9.3: Percentage change in loading rate with changing levels of significant factors

| F & V.D fixed | Weight Increase (Kg) | Percent change in loading rate | W & V. D fixed | Frequency Increase lifts per minute | Percent change in loading rate | W & F fixed | Vertical Distance Increase | Percent change in loading rate |
|---------------|----------------------|--------------------------------|----------------|-------------------------------------|--------------------------------|-------------|----------------------------|--------------------------------|
| 5, 55         | 13 to 23             | 42.28                          | 13,55          | 5 to 9                              | 23.99                          | 13,5        | 55 to 150                  | 30.71                          |
| 9, 150        | 13 to 23             | 33.8                           | 23,150         | 5 to 9                              | 21.15                          | 23,9        | 55 to 150                  | 27.9                           |

(Note F is frequency in lifts per minute, W load weight in kg, V.D vertical distance in centimeter)

- As weight, lifting frequency and vertical distance significantly affected the loading rate, the best fit equation for three responses loading rate, oxygen uptake and heart rate was obtained. Each of three responses is mutually predictable. Loading rate can be calculated, if oxygen uptake and heart rate are known.

$$Z = -157.22 - 29.39 \times X + 2.55 \times X^2 + 4.46 \times Y$$

Where Z, X and Y are loading rate (LR) in Newton/sec, oxygen uptake (VO<sub>2</sub>) in ml/kg/min and heart rate (HR) in beats per minute respectively. Coefficients 157.22, 29.39, 2.55 and 4.46 are constants.

- The safe limits identified after the experimental study are presented in Table 9.4.

Table 9.4: Decision with safe limit for identifying safe lifting task

| Trial No. | Wt (kg) A | Freq (lifts/min) B | V.D (cm) E | Optimum mean             |                         |                      | Decision with Safe limit      |                                |                           |
|-----------|-----------|--------------------|------------|--------------------------|-------------------------|----------------------|-------------------------------|--------------------------------|---------------------------|
|           |           |                    |            | loading rate Newton /sec | oxygen uptake ml/kg-min | heart rate beats/min | Loading rate ≤380 Newton /sec | Oxygen uptake ≤12.93 ml/kg-min | Heart rate ≤110 beats/min |
| 1         | 13        | 5                  | E1         | 234.44                   | 10.65                   | 98.38                | Y                             | Y                              | Y                         |
| 2         | 13        | 5                  | E2         | 272.95                   | 11.145                  | 103.55               | Y                             | Y                              | Y                         |
| 3         | 13        | 5                  | E3         | 329.11                   | 12.42                   | 106.455              | Y                             | Y                              | Y                         |
| 4         | 13        | 7                  | E1         | 265.11                   | 11.13                   | 101.13               | Y                             | Y                              | Y                         |
| 5         | 13        | 7                  | E2         | 303.62                   | 11.65                   | 106.345              | Y                             | Y                              | Y                         |

|    |    |   |    |        |        |         |   |   |   |
|----|----|---|----|--------|--------|---------|---|---|---|
| 6  | 13 | 7 | E3 | 359.78 | 12.925 | 109.25  | Y | Y | Y |
| 7  | 13 | 9 | E1 | 304.27 | 11.835 | 102.915 | Y | Y | Y |
| 8  | 13 | 9 | E2 | 342.78 | 12.33  | 108.085 | Y | Y | Y |
| 9  | 13 | 9 | E3 | 398.94 | 13.385 | 110.99  | N | N | N |
| 10 | 18 | 5 | E1 | 321.51 | 11     | 102.385 | Y | Y | Y |
| 11 | 18 | 5 | E2 | 360.02 | 12.48  | 107.555 | Y | Y | Y |
| 12 | 18 | 5 | E3 | 416.18 | 13.755 | 110.46  | N | N | N |
| 13 | 18 | 7 | E1 | 352.18 | 12.49  | 105.18  | Y | Y | Y |
| 14 | 18 | 7 | E2 | 390.69 | 12.985 | 110.35  | N | N | N |
| 15 | 18 | 7 | E3 | 446.85 | 14.26  | 113.255 | N | N | N |
| 16 | 18 | 9 | E1 | 391.34 | 13.17  | 106.92  | N | N | Y |
| 17 | 18 | 9 | E2 | 429.85 | 13.665 | 112.09  | N | N | N |
| 18 | 18 | 9 | E3 | 486.01 | 14.94  | 114.995 | N | N | N |
| 19 | 23 | 5 | E1 | 389.26 | 13.075 | 108.04  | N | N | Y |
| 20 | 23 | 5 | E2 | 427.77 | 13.24  | 113.21  | N | N | N |
| 21 | 23 | 5 | E3 | 483.93 | 14.665 | 116.115 | N | N | N |
| 22 | 23 | 7 | E1 | 419.93 | 13.4   | 110.835 | N | N | N |
| 23 | 23 | 7 | E2 | 458.44 | 13.895 | 116.005 | N | N | N |
| 24 | 23 | 7 | E3 | 514.6  | 15.17  | 118.91  | N | N | N |
| 25 | 23 | 9 | E1 | 459.09 | 14.08  | 112.575 | N | N | N |
| 26 | 23 | 9 | E2 | 497.6  | 14.575 | 117.745 | N | N | N |
| 27 | 23 | 9 | E3 | 553.76 | 15.85  | 120.65  | N | N | N |

(Note: Wt: Weight, Freq: Frequency, V.D: Vertical distance, E<sub>i</sub>: Factor E set at i<sup>th</sup> level,  
Y: Safe lifting task, N: Unsafe lifting task)

- Figures 9.7, 9.8 and 9.9 show the graphical representation as radar charts of the optimum mean loading rate, oxygen uptake and heart rate for 27 trial conditions described in Table 9.4. Each point on the circumference depicts one trial. All the trials beyond the safe limit of loading rate @ 380 Newton/sec, oxygen uptake @ 12.93 ml/kg-min and heart rate @ 110 beats/min are potentially hazardous and are likely to cause high exertion/musculoskeletal injury to the workers. All trials that are beyond the safe dark colored circumference on the radar chart depict the unsafe trials or combinations of load, frequency and vertical distance.

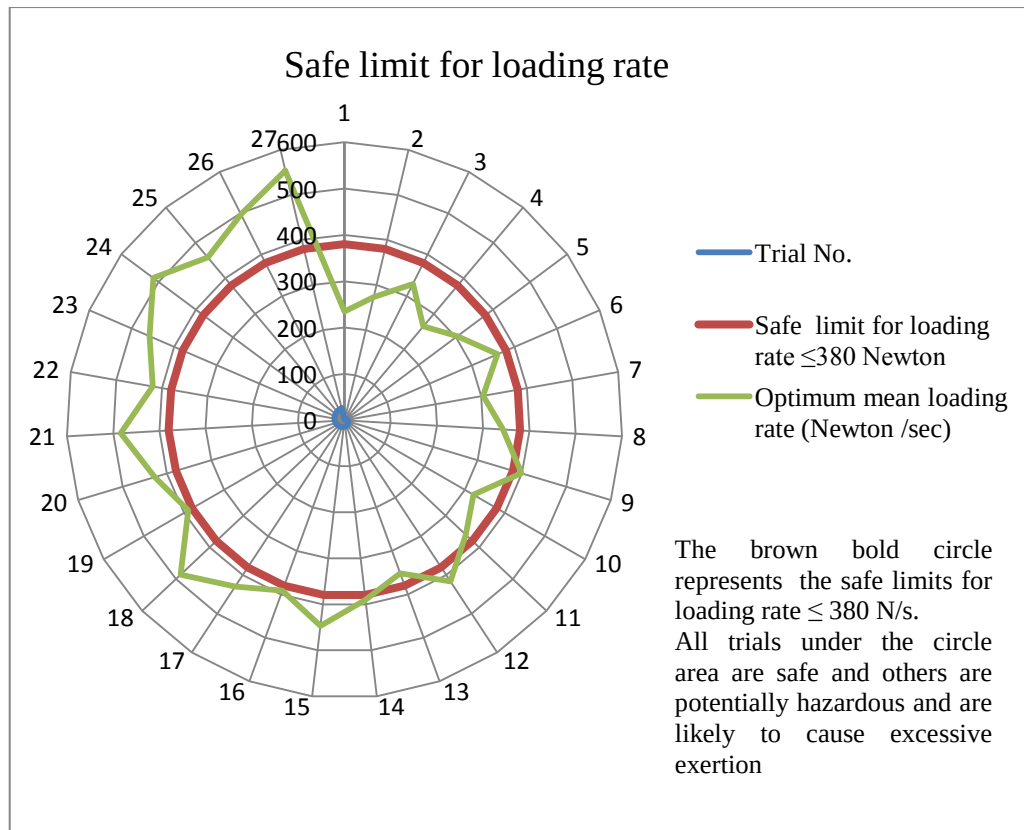


Figure 9.7: Optimum loading rate for different level setting of significant factors for identifying safe lifting task

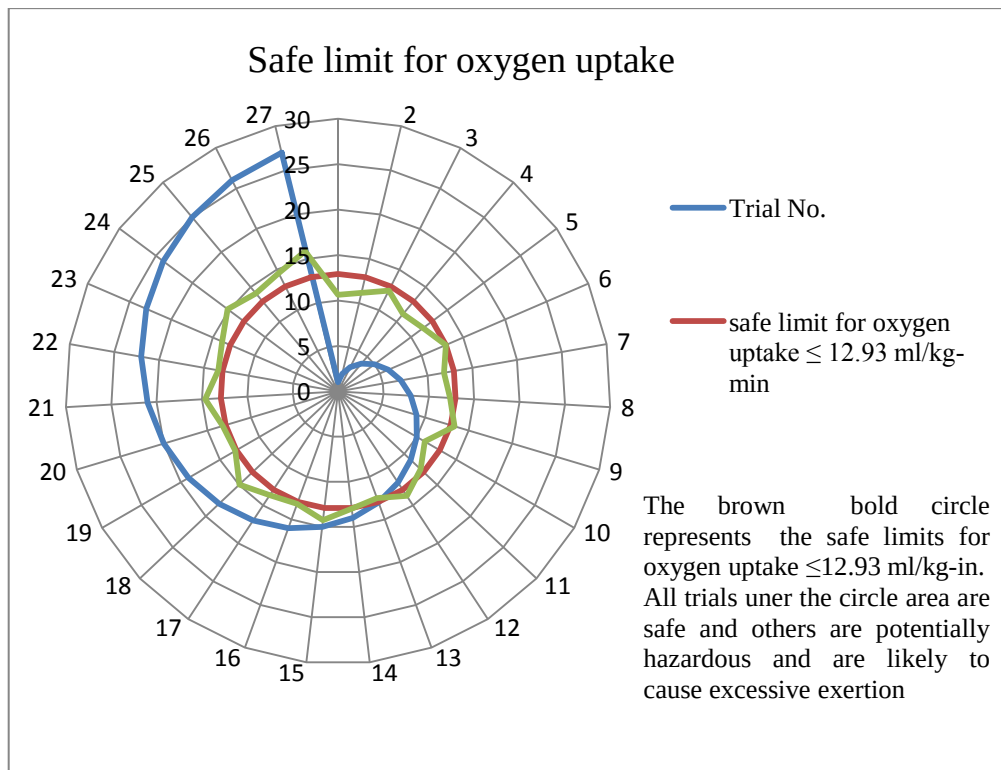


Figure 9.8: Optimum oxygen uptake for different level setting of significant factors for identifying safe lifting task

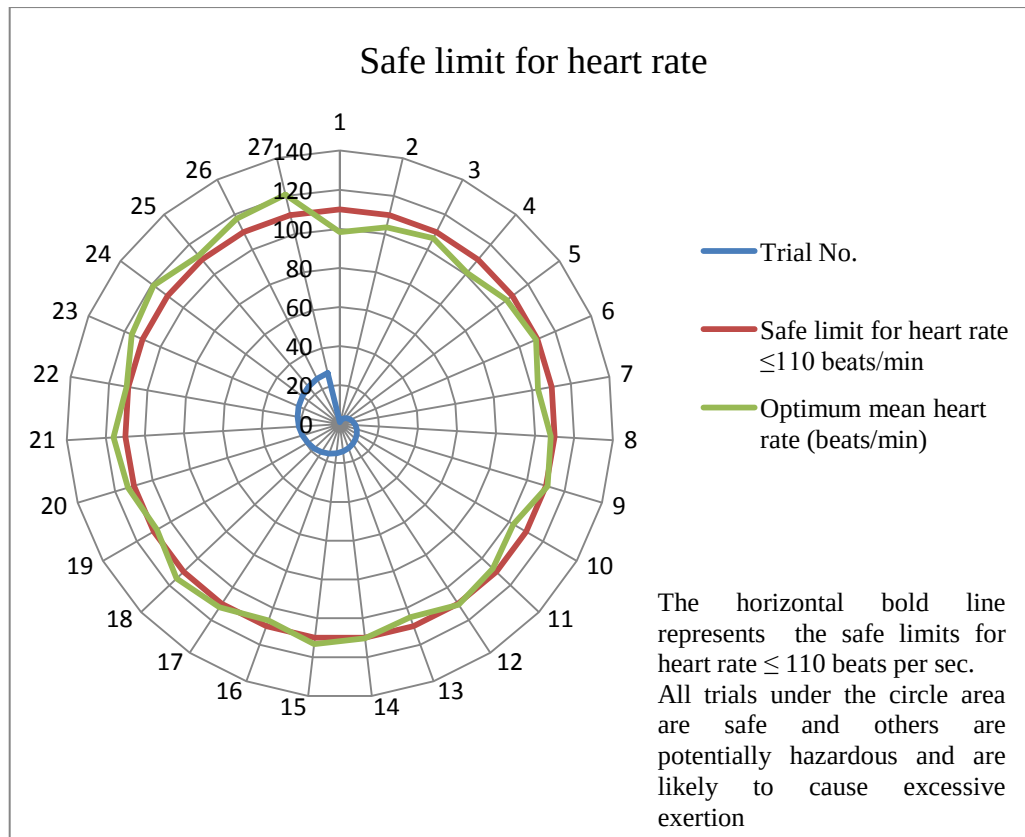


Figure 9.9: Optimum heart rate for different level setting of significant factors for identifying safe lifting task

- Different combinations of these significant factors were used to identify the least and the most exerting task conditions.
- The safe limits were established for various task parameters so as to prevent/reduce injuries to workers engaged in lifting and carrying tasks.

#### 9.4 PREDICTED LOADING RATE USING NEURAL NETWORKS

- ANN model was developed to establish a relationship between input and output parameters and to predict the loading rate.
- To estimate the relation between the experimental value and predicted value, paired-sample t-test and correlation test were used. The experimental and the predicted values are in close agreement at 99.8 percent. The variation in experimental value and predicted value of mean loading rate was 1.3311,  $t(17) = 1.121$ ,  $p=0.278 > 0.05$ . It shows that the experimental results and model predicted results are not significantly different at 95 percent confidence range.
- The maximum and minimum variations between the experimental and predicted value were 3.26 percent and 0.01 percent respectively and overall mean of percent relative error was 0.852, which shows a close relationship.

- The comparison of the experimental results and predicted results obtained by the neural network are plotted which shows a very close relationship between both the results in verifying the network generalization capabilities.
- The linear regression analysis was performed to check the capabilities of network for the network output and the experimental target value. The regression plot showed R values as follows; training (R=1), validation (R=0.93277), testing (R=0.68738) and overall (R=0.94705). Regression R values measure the correlation between outputs and targets. An R value of 1 means a perfect relationship.
- Once the vertical reaction forces of the body to the stress of performing a task are accurately predicted, risk assessment of lifting task will be feasible.
- The ANN modeling accurately predicted the ground reaction forces and can be used as a reliable tool for study of ground reaction forces.

## **9.5 OPTIMIZATION OF EXPERIMENTAL SETTING FOR SAFE LIFTING**

- Four output response parameters, namely oxygen uptake, heart rate, perceived exertion and ground reaction forces were optimized collectively using Analytical Hierarchy Process (AHP) for most suitable experimental settings for safe lifting for different lifting frequencies during manual lifting.
- The optimal parameter settings for each of the samples (three lifting frequency sets 110,140,180 per 20 minutes) were evaluated. The overall optimal process settings were for trials 6, 15, 21 which reveals that higher load, lower lifting frequency and vice versa for same vertical distance (shoulder), the best combination for safe lifting.
- Correlation plot of three optimal process settings shows that the lifting frequency decreases with increase the weight at constant vertical distance (shoulder height).

## **9.6 CONCLUSIONS**

In India, manual material handling (MMH) is widely practiced in industrial activities. Load lifting and carrying, a basic task executed by workmen engaged in manual material handling consists of lifting an object, carrying it some distance and then putting it down, still remains an indispensable resource in many industrial operations. The manual lifting task is directly concerned with the industry or construction workmen.

The main objective of the study has been to minimize the exertion on the workmen as well as to minimize the risk of subsidence using most appropriate levels of lifting parameters during such tasks performed in different environmental conditions and to determine the safe limits of

significant parameters to reduce/prevent any musculoskeletal or chronic injury. Following conclusions can be drawn from the study

- i. Lifting and carrying tasks cause more physiological stress in winters than summers. The lifting tasks performed in winters must have different relaxation or fatigue allowances built into the cycle time of the task to compensate for higher exertion experienced during winter.
- ii. In case of controlled temperature conditions, the limits for the load weight, lifting frequency and vertical distance can be increased without causing increased exertion to the workers.
- iii. The physiological effects of load weight, lifting frequency, coupling, asymmetric angle, vertical distance, horizontal distance and travel distance on the workmen were evaluated. It was seen that lifting loads with higher vertical distance increase the physiological workloads. The tasks become even more stressful when the heavy load (23 kg) is lifted above the shoulder level at high frequency (9 lifts/minute).
- iv. The interaction of load and frequency has some affect on the responses. The Borg perceived exertion scale increases linearly with physiological measures like oxygen uptake and heart rate as the work intensity increases.
- v. In continuous lifting, some appropriate rest periods should be incorporated to ease the task. The safe combinations of significant parameters could be used to evolve job designs of manual lifting tasks. Empirical model and MRSN equations for responses could be used to generalize the task conditions.
- vi. The neural network model accurately predicts the loading rate and can be used as a reliable tool for study of loading rate in case of complex problems that involve both qualitative and quantitative factors.
- vii. Analytical Hierarchy Process was used for most suitable experimental settings for safe lifting for three samples of lifting frequencies during manual lifting. It is believed that such a technique will enhance the reliability of the results thus obtained.

## **9.7 SCOPE FOR FUTURE WORK**

- The study can be extended to identify higher levels of lifting parameters to lower the cardiovascular risks and metabolic energy expenditure of the workers.
- Further investigations on interaction effects among lifting parameters are needed for better understanding of the physiological risks involved in lifting operations.

- The temperature multiplication factor can be included in lifting equation to study the environmental effect for Indian male workers.
- Since the laboratory has only two force platforms, the maximum travel distance (or carrying distance) that could be studied was 60 cm. It can be further increased with more number of force platforms for better effect of travel distance.
- The safe combinations of significant parameters can be practiced in construction work, shop floor of manufacturing unit and transportation of food product etc.

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## APPENDIX-I

### MAT LAB CODE

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```
clear all
close all
clc
%x1=mean O2 uptake
% x2 Heart rate
i=0; j=1;
for x1=4:0.1:17
i=i+1; j=0;
X1(i)=x1;
for x2=72:1:130
j=j+1;
X2(j)=x2;
%Y(i,j) = -173546.393412899+2736339.39798865/x1+3068.16601442343*x2-
13325442.2065023/x1^2-17.666791713359*x2^2-
33278.2454670191*x2/x1+14025031.4296505/x1^3+0.035915684254075*x2^3+88.74313089
12327*x2^2/x1+97318.9916386506*x2/x1^2;
% Y (i,j) = 813.161265148912+-
2581.30134984514*log(x1)+600.028459362827*log(x1)^2+477.320667910033*log(x2);
Y(i,j) = -157.218254953488-
29.384737944934*x1+2.5486849605223*x1^2+4.46101060027548*x2;
end
end
Y=Y';
surf(X1,X2,Y)
hold on
xlabel('Oxygen uptake (ml/kg-m^2)')
ylabel('Heart rate (beats/min)')
zlabel('Loading rate (N/sec)')
x1=12.93; x2=110;
```

$$\begin{aligned}
Y1 &= -173546.393412899 + 2736339.39798865/x1 + 3068.16601442343*x2 - \\
&13325442.2065023/x1^2 - 17.666791713359*x2^2 - \\
&33278.2454670191*x2/x1 + 14025031.4296505/x1^3 + 0.035915684254075*x2^3 + 88.74313089 \\
&12327*x2^2/x1 + 97318.9916386506*x2/x1^2 \\
Y1\_1 &= -2739048.55940387 - 559213.435504459*\log(x1) + 2090502.98180547*\log(x2) + \\
&275852.822864438*\log(x1)^2 - \\
&604035.352800083*\log(x2)^2 + 546789.217539954*\log(x1)*\log(x2) - \\
&11548.5085907239*\log(x1)^3 + 62364.2581047992*\log(x2)^3 - \\
&102161.318033885*\log(x1)*\log(x2)^2 + 78365.5927580589*\log(x1)^2*\log(x2) \\
Y1\_2 &= 813.161265148912 + -2581.30134984514*\log(x1) + 600.028459362827*\log(x1) \\
&^2 + 477.320667910033*\log(x2) \\
Y2 &= -157.218254953488 - \\
&29.384737944934*x1 + 2.5486849605223*x1^2 + 4.46101060027548*x2
\end{aligned}$$