CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 ANALYSIS OF PUSH FORCE, HEART RATE, MUSCLE FORCE AND WRIST EXTENSION

Figure 4.1 shows the biometric sensors sEMG, electrogoniometer, heart rate monitor attached to the subject; push-pull gauge attached to the horizontal push-pull bar of the trolley.

Fig. 4.1 The push-pull gauge attached to the horizontal bar of the trolley and the sensors attached to the subject
4.1.1 EFFECT OF HANDLE HEIGHT

4.1.1.1 Push Force Analysis: Initial Push Force Analysis

Figure 4.2 shows the initial pushing force exerted by five male subjects at five different handle heights when the total weight of the trolley was 125 kg (weight of the empty trolley 50 kg and load in the trolley 75 kg). The maximum force recorded by all the subjects was in the range from 110 N to 125 N when the height of the handle was at 900 mm. It was observed that the exerted pushing force gradually decreased as the height of the handle increased from 900 mm to 1100 mm.

It was found that the pushing force exerted by all the subjects were ranging from 80 N to 95 N at the handle height of 1100 mm resulting in a reduction of 25.5% of the effort required for pushing the trolley. The handle height has to be below the elbow height according to Ferriera et al. (2004). It can be observed from Figure 4.2 that subject 1 exerted a force of 118 N when compared to Subject 5 who exerted a force of 125 N at the handle height 900 mm. The force exertion gradually decreased as the handle height increase from 900 mm to 1100 mm as shown in Figure below.

![Initial pushing force on 100 mm diameter caster wheel at load 125 kg](image)

**Fig.4.2 Initial pushing force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 125 kg**
Figures 4.2 and 4.3 show the effect of handle heights on forces required for pushing a trolley loaded with 125 kg and 156 kg by five subjects of varying stature and handle height depending on the stature of subjects.

![Initial pushing force on 100 mm diameter caster wheel at 156 kg load](image)

**Fig.4.3 Initial pushing force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 156 kg**

![Initial pushing force on 100 mm diameter caster wheel at 188 kg load](image)

**Fig.4.4 Initial pushing force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 188 kg**
Figures 4.4 to 4.6 show the values of initial pushing forces exerted by all subjects when the trolley was fitted with a wheel diameter of 100 mm and loaded with 188 kg, 219 kg and 250 kg respectively.

Fig.4.5 Initial pushing force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 219 kg

Fig.4.6 Initial pushing force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 250 kg

The use of manual material handling devices like four wheeled trolleys which are poorly designed consume a lot of energy from the industrial workers. Arun et al., (2014) reported that it was not clear what handle heights would be optimal for pushing and pulling.
The present experiment results revealed that 1100 mm handle height was the recommended value for the subjects tested which permits the minimum push forces for transporting loads as seen in figures 4.2 to 4.6. If the handle height was less than this value, the subjects have to exert more forces during pushing. The reason could be that when the handle was situated at a height of 1100 mm, the subjects were occupying comfortable postures at elbow level and with minimum effort they were able to overcome the inertia forces. The results agree with the findings of Ferreira et al. (2004): The optimum height of the handle should be between 910 mm and 1120 mm. Handle heights should not be less than 910 mm since taller subjects would stoop. Shorter subjects reported discomfort when pushing the trolley while the handle height was set more than 1120 mm. It was observed that the handle height of 1100 mm made all subjects to exert the least force while pushing the trolley loaded with different loads when the wheel diameter of 100 mm was used as evidenced from figures 4.2 to 4.6.

4.1.1.2 Sustained Force Analysis

Figures 4.7 and 4.8 show the effects of handle height on force required for sustaining the motion of the trolley while using 125 mm diameter wheel and trolley weight of 125 kg and 156 kg respectively. Subject 5 exerted less force compared to all other subjects. At the handle height of 1000 mm all subjects exert lesser force compared to other handle heights.
Fig. 4.7 Sustained force using 125 mm wheel diameter at all handle heights for all subjects when trolley loaded with 125 kg

Fig. 4.8 Sustained force using 125 mm wheel diameter at all handle heights for all subjects when trolley loaded with 156 kg

Figures 4.9, 4.10 and 4.11 show the effects of handle height on sustaining force while 125 diameter wheel was used and trolley weight of 188 kg, 219 kg and 250 kg. The sustaining forces are found to be lesser while a handle height of 1100 mm was used.
Fig. 4.9 Sustained force using 125 mm wheel diameter at all handle heights for all subjects when trolley loaded with 188 kg load.

Fig. 4.10 Sustained force using 125 mm wheel diameter at all handle heights for all subjects when trolley loaded with 219 kg load.
4.1.1.3 Ending Force analysis

Figures 4.12 to 4.16 present the ending force required when different handle heights are used by different subjects. In general, ending forces decrease with increase in handle height. Subject 5 exerts the highest force at a handle height of 900 mm and exerts the least force while using a handle height of 1100 mm.
Fig. 4.13 Ending force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 156 kg

But subject 1 exerted the lowest force at a handle height of 900 mm and the highest force at a handle height of 1100 mm. All subjects exerted the same force when the handle height was around 1020 mm. The pattern of ending force exerted was reversed beyond 1020 mm until the maximum handle height of 1100 mm.

Fig. 4.14 Ending force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 188 kg
Fig. 4.15 Ending force using 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 219 kg

Fig. 4.16 Ending force on 100 mm wheel diameter at all handle heights for all subjects when trolley loaded with 250 kg

4.1.2 Effect of handle height on heart rate

The effects of handle height on heart rate are shown in figures 4.17 and 4.18 while subject 1 pushed trolley loaded with 125 kg as well as 156 kg
on 100 mm, 125 mm and 150 mm wheel diameters respectively. The heart rates were the lowest at the handle height of 1100 mm and a wheel diameter of 150 mm.

**Fig. 4.17** Heart rate (BPM) of Subject 1 at different handle heights while pushing 125 kg load on three different wheel sizes.

**Fig. 4.18** Heart rate (BPM) of Subject 1 at different handle heights while pushing 156 kg load on three different wheel sizes.
Figure 4.19 shows the heart rates of all the five subjects recorded on three different wheel diameters when the total weight of the trolley was 188 kg. It was observed that all the subjects experienced heart rate ranging between 78 to 89 beats per minute when the wheel diameter was 100 mm and the heart rate ranges from 73 to 84 bpm when the wheel diameter was 150 mm. Subjects 1 and 5 (the shortest and the tallest) experience lesser heart rate compared to subjects 2, 3 & 4 (with medium heights).

![Heart rate of five subjects at 1100 mm handle height at 188 kg load](image)

**Fig. 4.19 The effect of wheel diameter on heart rates (BPM) of five subjects at a load of 188 kg**

4.1.3 Effect of handle height on wrist extension

Figure 4.20 shows the wrist extension measured using the flexible goniometer for all the five subjects at five different handle heights. The wrist extensions for all the five subjects were found to be about 16° when the handle height was 900 mm. It was observed that the wrist extensions gradually decreased (8 to 12) degrees with the increase of the handle height from to 1100 mm. The optimum height of the handle should be in between 900 mm and 1120 mm. In general the handle should be little below the
elbow height. There should be at least 200 mm distance from the back edge of the trolley to the handle in order to provide comfortable leg room for normal walking according to Ferreira et al. (2004).

![Wrist extension on 100 mm diameter caster wheel at 125 kg load](image)

**Fig.4.20** Wrist extension (°) for five subjects during initial pushing of the trolley on 100 mm wheel at load 125kg in the trolley

### 4.1.4 Effect of handle height on muscle activity

Figure 4.21 shows the recorded muscle activity during initial pushing for the five subjects at five different handle heights. It was found that the muscle force was higher for the subjects 4 and 5 when the handle height was 900 mm. For subjects 1, 2 the maximum occurred at the handle height 950 mm and for subject 3 the maximum occurred at handle height 1000 mm. It was also found that the muscle activity for all the subjects decreased when the height of the handle is 1100 mm.
Fig. 4.21 EMG (%MVC) for the left arm flexor digitorum muscle during initial pushing of the trolley on 100 mm wheel at load 125 kg

4.1.5 EFFECT OF WHEEL DIAMETER

4.1.5.1 Effect of wheel diameter on push force

The relation between push force and wheel diameter is shown in figures 4.22 and 4.23. It was observed from the figures 4.22 and 4.23 that the push forces were the lowest while using 150 mm wheel diameter.

Fig. 4.22 Initial push force (N) at a handle height of 1100 mm with a load of 125 kg on three wheel diameters
**Fig.4.23** Initial push force (N) at a handle height of 1100 mm with a load of 156 kg on three wheel diameters

4.1.5.2 Effect of wheel diameter on muscle activities (sEMG analysis)

Figures 4.24 and 4.25 show the muscle force in % MVC while the trolley loaded with 125 kg and 156 kg fitted with 100, 125 and 150 mm diameter wheels pushed by 5 subjects. It was observed that the muscle activities were less when a wheel diameter of 150 mm was used.
It was found that the muscle activity was higher for the all subjects when the wheel diameter was 100 mm and varied between 26 and 36 % MVC. The muscle activity reduced from 22 to 23.5 % when 150 mm wheel diameter was used.

![Muscle force at handle height 1100 mm at 156 kg load](image)

**Fig. 4.25 Muscle force in % MVC at load 156 kg at handle height of 1100 mm using different wheel diameters.**

Figure 4.25 shows the muscle activity shown in % MVC during initial pushing for the five subjects on three different wheel diameters. The muscle activity for subject 1 was lower than other subjects at all wheel diameters.

4.1.5.3 Effect of wheel diameter on heart rate

The effects of wheel diameter on heart rate for all the 5 subjects are shown in figure 4.26. It was also observed that the heart rate was the lowest when 150 mm diameter wheel was used.
Heart rates of a subject when pushed the trolley with a handle height of 1100 mm and loads varying from 125 to 250 kg are shown in figure 4.27. In general, heart rates increase with increase in the load of the trolley. Heart rates varied for different wheel diameters but at loads ranging from 156 kg to 219 kg. There was minimal difference in heart rates for wheel diameters of 100 mm and 125 mm. Heart rates decreased when wheels of bigger diameter indicating that the discomfort has reduced by using larger wheels. This can be attributed to the fact that the push force as well as muscle force decrease with increase in wheel diameter as seen from Figures 4.24 and 4.25.

Fig. 4.26 Wheel diameter Vs Heart Rate at 1100 mm Handle Height at 156 kg load in the trolley
Fig. 4.27 Load Vs Heart Rate for Subject 2 at 1100 mm Handle Height

4.1.5.4 Effect of wheel diameter on wrist extension

Wrist extension analysis (Goniometer analysis) graphs at handle height 1100 mm at three different loads 188, 219 and 250 kg; for all five subjects are shown in figures 4.28 to 4.30.

Figures show the wrist extension measured using the flexible goniometer for all the five subjects at three different wheel diameters.

Fig. 4.28 Effect of wheel diameter on wrist extension at load 188 kg when the handle height is 1100 mm
The wrist extensions for all the five subjects were found to be about 15 degrees when the wheel diameter was 100 mm. It was observed that the wrist extensions have gradually decreased to around 13 degrees with the increase of the wheel diameter to 150 mm.

**Fig. 4.29 Effect of wheel diameter on wrist extension at load 219 kg When the handle height is 1100 mm**

**Fig. 4.30 Effect of wheel diameter on wrist extension at load 250 kg at handle height 1100 mm**
4.2 BIO-MECHANICAL ANALYSIS AND OPTIMIZATION

4.2.1 A Theoretical model for Bio-Mechanical analysis

The theoretical model proposed by Lee et al. (1991) has been employed for biomechanical analysis: Equation 4.1 shows the variables considered for the biomechanical model: subject's body weight, subject's stature, hand force, handle height and various interactions of these variables. The stature/ handle-height relationship is bio-mechanically more important to the compressive forces than the subject's stature alone. This ratio represents the relative height of the handle compared with the stature. Therefore a new variable, height factor, which represents this ratio is defined and used instead of stature and handle height as follows:
Height factor, \( H = (\text{stature} - \text{handle height})/\text{stature} \)

The following is the relationship between the peak compressive force at the L5/S1 disc and the independent variables as given by Lee et al. (1991).

\[ Y_{\text{pushing}} = 298 + 16.62W - 2261.86H + 0.0254WF + 12.67FH \quad \ldots (4.1) \]

Where
- \( Y_{\text{pushing}} \) = peak compressive force at L5/S1 disc in pushing
- \( W \) = subject weight (kg)
- \( H \) = height factor
- \( F \) = horizontal hand force (N)

4.2.2 Compressive forces at L5/S1 interface

The theoretical model proposed by Lee et al. (1991) for biomechanical analysis has been employed and the experimental results are verified. The results of the biomechanical analysis are presented in Figures
4.31 and 4.32, which show the compressive forces acting on the L5/S1 interface while five subjects were pushing trolleys loaded with 125 kg and 156 kg.

**Fig. 4.31** Compressive force (N) at L5/S1 interface at 125 kg load at different handle heights.

**Fig. 4.32** Compressive force at L5/S1 interface in N while pushing a trolley with 156 kg load for different handle heights.
The results shown in Figures 4.31 and 4.32 indicate that the compressive force acting at the L5/S1 interface is the least at a handle height of 1100 mm validating the experimental results reported in previous section. The trends of the resulting curves do not exactly match with the curves of the experimental study. In Figure 4.31, there is no variation in the compressive force on the spinal column between 900 mm and 1000 mm of handle height and the compressive forces reduce from 1000 mm to 1100 mm. Subject 4 is experiencing the highest compressive force on the low back and subject 5 is experiencing the lowest compressive force in while pushing 125 kg as well as 156 kg load. The reason for this is evident from Table 3.1; subject 4 has the highest weight and experiences the highest compressive load in the low back and subject 5 has the lowest weight and suffers the lowest compressive load in the low back. This finding is in agreement with the findings of Lee et al. (1991) that low body weight lowers the compressive load at L5/S1 interface.

### 4.2.3 Optimization Using Genetic Algorithm (GA)

Genetic Algorithm (GA) tool box of Matlab was used to find the optimized height of the handle. The objective function was formulated considering a mathematical relationship relating force applied by different subjects using different handle heights, the mathematical model proposed by Lee et al. (1991) and by specifying lower and upper limits for the handle height.

### 4.2.4 Optimization of handle height

The optimum value is obtained through Genetic Algorithm. Figure 4.33 shows the convergence of the value of load acting at L5/S1 interface ($Y_{\text{pushing}}$) in Newtons. The optimum handle height is obtained as 1090 mm
after 300 generations in Figure 4.34. These results validate the findings through experimental studies.

![Graph showing convergence of load acting on L5/S1 interface](image1)

**Fig. 4.33** Convergence of load acting on L5/S1 interface ($Y_{pushing}$) in Newtons

![Graph showing optimum handle height](image2)

**Fig. 4.34** Optimum handle height
4.3 DISCUSSIONS

An observational study has been made in a gear manufacturing company in Coimbatore, Tamil Nadu, South India. Workers in the company have expressed their difficulties in using the existing trolleys. The newly developed trolley has been used for finding out the height of handle and size of wheels which would reduce the force required to push the trolley which would lower the discomfort experienced by them.

The preferred heights for pushing or pulling vary with different workers according to Worksafe (2004). Only in a few carts, height adjustable handles are provided. Preferable Handle height has to be between elbow and hip for pushing. Worksafe (2004) also suggests handle heights in the range of 760 mm to 1200 mm for pushing. Darcor and Ergoweb (2001) reported that there is no single recommended handle height for pushing. A range of handle height from 740 mm to 1200 mm may be suitable for 90% or the American working population. Amy et al. (2016) highlighted that nearly 50% of all manual materials handling tasks are pushing and pulling. Andreas et al. (2017) reported that better handle positions ranged from hip to shoulder height. Best practices in handling to reduce musculoskeletal problems are to be checked in work places involving pushing and pulling.

In this work, it was found that the usage of handle height of 1100 mm reduced 25 to 35% of the pushing efforts (including force and heart rate) exerted by the subjects when compared to 900 mm handle height. It can be taken as the most comfortable height for the selected population whose anthropometric data provides the range of height (stature) from 1650 mm to 820 mm. The initial push forces, sustaining forces and ending forces exerted,
the heart rate experienced, the muscle activity generated and the wrist extensions were considerably low at a handle height of 1100 mm when compared to the other handle heights. Pushing and pulling tasks can be ergonomically evaluated at the workplace through the assessment of the magnitude of forces exerted by the subject/worker on the trolley. The push or pull forces are often distinguished as initial forces which are required to move the object from initial position as reported by Jansen Jorrit et al. (2002). Heart-rate methodology has been shown to be cost-effective method of an ergonomics intervention to reduce workload and improve working conditions. This is a practical approach as opposed to the energy expenditure technique that is difficult to implement in natural settings. The simplicity and objectivity of this approach are useful to solve the problem of the economic evaluation of ergonomics interventions according to Gregory et al. (2001). Surface electromyography (sEMG) was used as a stand-alone acquisition tool in order to emphasize the possibilities of sEMG utilization as a screening tool for ergonomic purposes according to Aleksander et al. (2010).

The results of the present study have shown that there is a decrease in the initial push force, sustaining force, ending force, heart rate, wrist extension and muscle activity by using the new trolley with wheels having 150 mm diameter and a handle height of 1100 mm for the selected population. The results agree with Chih-Long Lin et al. (2009) who found that the pushing and pulling force at 1150 mm handle height was less compared to 1015 mm and 880 mm handle heights. 150 mm wheels required less force compared to 200 mm wheels. The results of this work also agree with Lee et al. (1991), who found that a Handle height of 1090 mm was found to be better than other handle heights in pushing.
Theoretical verifications of experimental results are always good since they help researchers to make sure the experimental results are correct. Formulation of a theoretical model is a difficult task and it requires vast experimental results for checking the validity of such a model. Once the model is accepted by scientific community, it is easier to use the model as a standard for checking the experimental results of new experiments. The model proposed by Lee et al. (1991) has been used for verifying the experimental results of this research work and found to agree with the theoretical model.

Through optimization of the handle height using Genetic algorithm, optimum handle height was found to be 1090 mm within the range of handle heights ranging from 900 mm to 1100 mm, which agree reasonably with the experimental findings. The range of handle heights is fixed in agreement with the findings of Ferreira et al. (2004). The optimum height of the handle should be between 910 mm and 1120 mm. Handle heights should not be less than 910 mm since taller workers would stoop. A handle height which is more than 1120 mm would cause more discomfort to shorter workers.