8-2006

Design Assessment of Two-Wheeled Luggage Based on Mechanical Models and a Usability Test

Jun-Seok Lee
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Jun-Seok Lee entitled "Design Assessment of Two-Wheeled Luggage Based on Mechanical Models and a Usability Test." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

Dongjoon Kong, Major Professor

We have read this dissertation and recommend its acceptance:

Jack Wasserman, Robert Ford, Myong K. Jeong

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a dissertation written by Jun-Seok Lee entitled "DESIGN ASSESSMENT OF TWO-WHEELED LUGGAGE BASED ON MECHANICAL MODELS AND A USABILITY TEST." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial and Information Engineering.

Dongjoon Kong

Major Professor

We have read this dissertation
and recommend its acceptance:

Jack Wasserman

Robert Ford

Myong K. Jeong

Accepted for the Council:

Anne Mayhew

Vice Chancellor and
Dean of Graduate Studies

(Original signatures are on file with official student records.)

DESIGN ASSESSMENT OF TWO-WHEELED LUGGAGE BASED ON MECHANICAL MODELS AND A USABILITY TEST

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Jun-Seok Lee
August 2006

To my deceased father and to my family

ACKNOWLEDGEMENTS

I have to admit that it is hard to find proper expressions to thank my great advisor, Dr. Kong. He is more than a thesis advisor as well as is a great person. He always accepts my ideas and encourages me with his academic enthusiasm and sincerity. This dissertation could not be finished without his experience, knowledge and patience.

I would also like to thank Dr. Ford. He provided me with invaluable guidance and insightful comments for my research.

I wish to thank the rest of my committee members, Dr. Wasserman and Dr. Jeong for their sincere advice, guidance, and support. Their advice and guidance encouraged me for believing I was capable.

I wish a special thanks to Dr. Kim. He always encouraged me with a warm heart.

I would like to thank Inho Kang, Sandra Rudd, Dr. Badiru, Jeanette Myers, Louise Sexton, and Christine Tidwell for their friendship and cooperation. I also wish to thank all Korean students who are studying at the University of Tennessee. Especially, I wish to thank Dr. Do-Kyung Kim, Dr. Jung-Hyun Kim, Dr. Choonggi Baek, Jongwook Park, and many more.

I would also like to thank the members of Knoxville Korean Catholic Community (KKCC).

Finally, I would like to thank my family. Without them, it would have been impossible for me to obtain the degree. I am forever grateful to my father, Seo-Kyu Lee, who passed away in 2003. I would like to thank my mother, Soon-Hee Jeong. I would like to thank my wife, Yeon-Hwa Jeong, my son, Chongho Lee, and my daughter, Eunsu Lee, who supported me. I appreciate their patience and trust toward me. I wish to express my love to my bother and sister: Ki-Young Lee and Nam-Jeong Lee.

ABSTRACT

The purpose of this study is to ergonomically assess two-wheeled luggage design based on mechanical models and a usability test.

Three mechanical models were developed for the pulling force estimation and important luggage design factor finding. Three pulling conditions with three motion stages were considered in the model. In addition, a set of pre-questionnaires and a set of post-questionnaires were prepared for the investigation of users' preferences for each design factor.

From the mechanical models, the minimum pulling force was found at the tilted angle of 65.56° in static staus, at the tilted angle of 30° in the initial phase, and at the tilted angle of 65.56° in the sustained phase. Based on the optimal tilted angle, several pole lengths were suggested (41.5" for 5%ile female, 45.5" for 5%ile male and 50%ile female groups, 49.5" for 50%ile male, 95%ile female groups, and 52.5" for 95%ile male group). In addition, some important design factors contributory to the minimum pulling force were found through the mechanical models. According to the results of mechanical models, tilted angles of luggage(α), the distance between center of mass and the bottom of luggage (b), and weight of luggage (W) significantly affected the pulling force.

Two luggage prototypes were developed by considering the important design factors resulted from the mechanical models and a usability test was conducted. For the usability test, two load weights (33 lbs and 50 lbs), six pole lengths (38.5", 41.5", 44.5", 45.5", 49.5", and 52.5"), four subject groups (5%ile female, 50%ile female, 50%ile male, and 95%ile male groups), and two luggage size (22"×14"×10" and 30"×21"×11.5") were

considered in experimental design. Subjects answered pre- and post-questionnaires as soon as they conducted the experiment. Test results demonstrated that most upper body parts were affected by load weights, pole length, and subjects' knuckle heights. In addition, pole lengths between 38.5" and 49.5" were selected from all subject groups. A pole should be adjustable within the range from 38.5" to 49.5" although the mechanical models suggested the pole lengths between 38.5" and 52.5". Tilted angle should be maintained from 30º to 50º in this range. This result indicated that there is a gap between the theoretical and practical results.

In conclusion, load weights, pole lengths, and subjects' knuckle heights should primarily be considered when luggage is designed. However, additional studies need to get deeper understanding of the gap between mechanical models and usability. In addition, more systematical survey questionnaires should be developed to provide any possible solutions to reduce the gap.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1 Problem statement 1

1.2 Study objectives 3

1.3 Thesis organization 3

1.4 Benefits of the research 4

CHAPTER 2 LITERATURE REVIEWS 5

2.1 Characteristics of material handling aids 5

2.1.1 Four-wheeled aids 7

2.1.2 Two-wheeled aids 17

2.2 Recommendations of material handling aids 23

2.2.1 Design characteristics 23

2.2.2 Load characteristics 26

2.2.3 Environmental conditions 27

2.2.4 Operational conditions 29

2.2.5 User characteristics 33

2.3 Summary 34

CHAPTER 3 WORK-RELATED MUSCULOSKELETAL DISORDERS 37

3.1 Introduction of Work-related Musculoskeletal Disorders (WMSDs) 37

3.2 WMSDs on push/pull activities 38

3.2.1 Risk factors on pushing/pulling 39

3.2.2 Accident-prone body parts from pushing/pulling activities 42

3.2.3 Symptoms of WMSDs 44

3.3 Anatomy of the hand and the wrist 45

3.3.1 Skeleton of the hand and the wrist 45

3.3.2 Joints of the hand 49

3.3.3 Muscles of the hand 53

CHAPTER 4 DEVELOPMENT OF MECHANICAL MODELS FOR PREDICTING PULLING FORCE ON A LUGGAGE CARRYING ACTIVITY .. 65

4.1 Mechanical models for pulling force prediction 65

4.1.1 Static status 66

4.1.2 Initial stage 69

4.1.3 Sustained stage 74

4.2 Model application 76

4.2.1 The effects of tilted angles, pulling heights, and handle heights in the static status… 76

4.2.2 The effects of tilted angles, pulling heights, and handle heights in the initial phase 82

4.2.3 The effects of tilted angles, pulling heights, and handle heights in the sustained phase 87

4.3 Statistical analysis 91

4.3.1 Regression and stepwise analysis for the static status 91

4.3.2 Regression and stepwise analysis for the initial phase 94

4.3.3 Regression and stepwise analysis for the sustained phase 96

4.4 Summary 98

CHAPTER 5 USABILITY TEST 101

5.1 Introduction 101

5.2 Subjects 102

5.3 Method 104

5.4 Test procedure 106

5.4.1 Pilot test 106
5.4.2 Main experiment 106
5.5 Statistical analysis 109
CHAPTER 6 RESULTS 110
6.1 Difficulties for two-wheeled luggage use 110
6.2 Risk assessment of body parts 110
6.2.1 Load weights vs. body parts 112
6.2.2 Pole lengths vs. body parts 113
6.2.3 Subject groups vs. body parts 117
6.2.4 Luggage size vs. body parts 119
6.3 Pulling force 121
6.3.1 Load weights vs. pulling force 121
6.3.2 Pole lengths vs. pulling force 122
6.3.3 Subject groups vs. pulling force 124
6.3.4 Luggage size vs. pulling force 126
6.4 Walking time 127
6.4.1 Load weight vs. walking time 127
6.4.2 Pole length vs. walking time 129
6.4.3 Subject groups vs. walking time 131
6.4.4 Luggage size vs. walking time 132
6.5 Trip/hit 134
6.5.1 Load weight vs. trip/hit 134
6.5.2 Pole lengths vs. trip/hit 135
6.5.3 Subject groups vs. trip/hit 137

6.5.4 Luggage sizes vs. trip/hit ... 138
6.6 Tilted angle approximation ... 140
CHAPTER 7 DISCUSSION ... 141
7.1 Difficulties for two-wheeled luggage use ... 141
7.2 Risk assessment of body parts ... 141
7.3 Pulling force ... 143
7.4 Walking time ... 145
7.5 Trip/hit ... 146
7.6 Tilted angle ... 147
CHAPTER 8 CONCLUSION ... 148
8.1 Research summary ... 148
8.2 Research Contributions ... 150
8.3 Future work ... 151
REFERENCES ... 153
APPENDIX ... 163
Appendix A Consent form ... 164
Appendix B Anthropometric and luggage Information ... 167
Appendix C Pre-Questionnaire ... 168
Appendix D Post-Questionnaire (33lbs/50lbs) ... 170
VITA ... 184

LIST OF TABLES

Table 2.1 Summaries for four-wheeled carrier study 8

Table 2.2 Coefficient of rolling friction for the different floor materials (Al-Eisawi et al., 1999a) 13

Table 2.3 Friction parameters and significant factors between high COF and low COF for two different coefficients of friction between floor and shoes (Ciriello et al., 2001)13

Table 2.4 Literatures related to two- wheeled cart 18

Table 2.5 Recommendations for design characteristics.. 24

Table 2.6 Recommendations for load characteristics 27

Table 2.7 Recommendations for environment conditions... 28

Table 2.8 Recommendations for operational conditions 30

Table 2.9 Recommendations for user characteristics 33

Table 4.1 Coefficients of static and kinetic friction between various common materials 72

Table 4.2 Coefficients of rolling friction between various common materials 75

Table 4.3 Knuckle height of civil population (Sanders & McCormick, 1993)................. 78

Table 4.4 The ratio F_y/W and F_y as a function of α (Case 1: fixed d = 38.5 in and maintained α =65.56°).. 79

Table 4.5 The ratio F_y/W and F_y as a function of α (Case 2: fixed d = 38.5 in and maintained h = user's knuckle height).. 80

Table 4.6 The ratio F_y/W and F_y as a function of α (in case of fixed h = user's knuckle height and α =65.56°).. 81

Table 4.7 The combined force as d and α are fixed in the initial phase.......................... 83

Table 4.8 The combined force as d and h are fixed in the initial phase............................ 84

Table 4.9 The combined force as h and α are fixed in the initial phase.......................... 86

Table 4.10 The combined force as d and α are fixed in the sustained phase.................. 87

Table 4.11 The combined force as d and h are fixed in the sustained phase 89

Table 4.12 The combined force as h and α are fixed in the sustained phase 90

Table 4.13 Summary of variables for pulling force prediction.. 92

Table 4.14 Summary of fit containing all predictors (the static status) 92

Table 4.15 Parameter estimates for all predictors (the static status)................................ 93

Table 4.16 Summary of fit containing α and b as predictors 94

Table 4.17 Parameter estimates for α and b 94

Table 4.18 Summary of fit containing all predictors (the initial phase) 95

Table 4.19 Parameter estimates for all predictors (the initial phase)................................ 95

Table 4.20 Summary of fit containing α and W as predictors 96

Table 4.21 Parameter estimates for α and W 96

Table 4.22 Summary of fit containing all predictors (the sustained phase)...................... 97

Table 4.23 Parameter estimates for all predictors (the sustained phase) 97

Table 4.24 Summary of fit containing α , b, and W as predictors 98

Table 4.25 Parameter estimates for α , b, and W 98

Table 5.1 The characteristics of usability test methods 103

Table 5.2 Profile of test subjects.. 104

Table 5.3 Independent variables and their levels for the experiments........................... 108

Table 5.4 Scales for rating 108

Table 6.1 The results of pre-questionnaires 111

Table 6.2 Results of Wilcoxon rank sum test for body complaints by load weights...... 114

Table 6.3 Results of Kruskal-Wallis rank sum test for body complaints by pole lengths 116

Table 6.4 Results of Kruskal-Wallis rank sum test for body complaints by knuckle heights 118

Table 6.5 Results of Wilcoxon rank sum test for body complaints by luggage sizes..... 120

Table 6.6 Results of Wilcoxon rank sum test for pulling forces complaints by load weights ... 122

Table 6.7 Comparisons for all pairs of pole lengths using Tukey comparison test........ 123

Table 6.8 Analysis of Variance for pole lengths... 124

Table 6.9 Results of Kruskal-Wallis rank sum test for force scores by subjects' knuckle heights ... 125

Table 6.10 Results of Wilcoxon rank sum test for force scores by luggage sizes.......... 127

Table 6.11 Comparisons for all pairs of load weights using Tukey comparison test..... 128

Table 6.12 Analysis of Variance for load weights... 128

Table 6.13 Comparisons for all pairs of pole lengths using Tukey comparison test...... 130

Table 6.14 Analysis of Variance for pole lengths... 130

Table 6.15 Comparisons for all pairs of subjects' knuckle heights using Tukey comparison test ... 132

Table 6.16 Analysis of Variance for subjects' knuckle heights... 132

Table 6.17 Comparisons for all pairs of luggage sizes using Tukey comparison test.... 133

Table 6.18 Analysis of Variance for luggage sizes... 133

Table 6.19 Results of Wilcoxon rank sum test for trip/hit complaints by load weights. 135

Table 6.20 Results of Kruskal- Wallis rank sum test for trip/hit complaints by pole lengths ... 136

Table 6.21 Results of Kruskal-Wallis rank sum test for trip/hit complaints by subjects' knuckle heights ... 138

Table 6.22 Results of Kruskal- Wallis rank sum test for trip/hit complaints by luggage sizes ... 139

Table 6.23 Summary of variables for tilted angle force prediction ... 140

Table 6.24 Parameter estimates for all predictors... 140

LIST OF FIGURES

Figure 2.1 Factors which are important to the usability of manual transport aids (developed from Mack et al., 1995) 6

Figure 3.1 Individual carpals, metacarpals, and phalanges (Source: Springhouse Corporation., 2001) 47

Figure 3.2 Joints of the hand (modified from Calais-Germain, 1993) 49

Figure 3.3 Extensors moving the wrist (left to right: Extensor carpi radialis longus, Extensor carpi radialis brevis, and Extensor carpi ulnaris) (modified from Anderson, 1983) 54

Figure 3.4 Flexors moving the wrist (left to right: Flexor carpi radialis, Palmaris Longus, and Flexor carpi ulnaris) (modified from Anderson, 1983) 54

Figure 3.5 Extrinsic extensors moving the fingers (left to right: Extensor pollicis longus, Extensor pollicis brevis, Abductor pollicis longus, Extensor indicis, Extensor digiti minimi, and Extensor digitorum) (modified from Anderson, 1983) 57

Figure 3.6 Extrinsic flexors moving the fingers (left to right: Flexor digitorum profundus and Flexor digitorum superficialis) (modified from Anderson, 1983) 58

Figure 3.7 Intrinsic thena muscles moving the fingers (left to right: Abductor pollicis brevis, Flexor pollicis brevis, and Opponens pollicis) (modified from Anderson, 1983) 60

Figure 3.8 Intrinsic hyperthenar muscles moving the fingers (left to right: Abductor Digiti minimi, Flexor digiti minimi, and Opponens digiti minimi) (modified from Anderson, 1983) 61

Figure 3.9 Intrinsic central muscles moving the fingers (left to right: Lubricals, Interossei - dorsal, and Interossei - palmar) (modified from Anderson, 1983) 63

Figure 3.10 Intrinsic adductor muscles moving the fingers (Adductor pollicis) 64

Figure 4.1 The free diagram of luggage with a tilted angle in the static status 67

Figure 4.2 The free diagram of luggage with a tilted angle in the initial and sustained stages 70

Figure 4.3 Graph of the ratio F_y / W as a function of α in static status. 77

Figure 4.4 The relationship between combined force and tilted angles while d and h are fixed in the initial phase 83

Figure 4.5 The relationship between combined force and tilted angles while d is fixed and h is maintained to user's knuckle height in the initial phase 85

Figure 4.6 The relationship between combined force and tilted angles while h is maintained to users' knuckle height and α is fixed in the initial phase 86

Figure 4.7 The relationship between combined force and tilted angles while d and h are fixed in the sustained phase 88

Figure 4.8 The relationship between combined force and tilted angles while d is fixed and h is maintained to user's knuckle height in the sustained phase.............................. 89

Figure 4.9 The relationship between combined force and tilted angles while h is maintained to users' knuckle height and α is fixed in the sustained phase............ 91

Figure 5.1 Two-wheeled prototypes (left: small luggage with 38.5" pole length, right: large luggage with 52.5" pole length).. 105

Figure 5.2 Angle finder.. 105

Figure 5.3 Actual pulling task on a tiled ground surface... 107

Figure 5.4 The hand and arm posture 108

Figure 6.1 Overall Least Squares Means (LSM) of body parts.................................... 112

Figure 6.2 The complaint scores of body parts between load weights.......................... 113

Figure 6.3 The complaint scores of body parts among pole lengths 115

Figure 6.4 The complaint scores of body parts among knuckle heights......................... 117

Figure 6.5 The complaint scores of body parts between luggage sizes......................... 119

Figure 6.6 Quantile box plot of pulling force score by load weights 121

Figure 6.7 Quantile box plot of pulling force scores by pole lengths............................ 123

Figure 6.8 Quantile box plot of pulling force scores by subjects' knuckle heights........ 125

Figure 6.9 Quantile box plot of pulling force scores by luggage sizes.......................... 126

Figure 6.10 Quantile box plot of walking time by load weights 128

Figure 6.11 Quantile box plot of walking time by pole lengths 129

Figure 6.12 Quantile box plot of walking time by subjects' knuckle heights 131

Figure 6.13 Quantile box plot of walking time by luggage sizes 133

Figure 6.14 Quantile box plot of trip/hit by load weights.. 134

Figure 6.15 Quantile box plot of trip/hit by pole lengths 136

Figure 6.16 Quantile box plot of trip/hit by subjects' knuckle heights 137

Figure 6.17 Quantile box plot of trip/hit by luggage sizes 139

CHAPTER 1 INTRODUCTION

1.1 Problem statement

With rapid technological advancement, automation and mechanization have been applied in many industries and in our daily activities. Manual material handling (MMH) is not an exception. In general, MMH recognized that objects are being lifted, lowered, carried, pushed and pulled by hand (Snook et al., 1978). Numerous studies were found in relation to lifting and carrying load. However, the studies regarding pushing and pulling were less published. Pushing and pulling activities have been estimated at nearly half of MMH (Baril-Gingras & Lortie, 1995; Kumar et al., 1995). In industrial sectors, many hand carts and trucks are used as excellent alternatives to reduce lifting and carrying activities. Various case studies have reported that well-designed handling aids can help to reduce workload and the risk of injuries (Das & Wimpee, 2002; de Looze et al., 1995; Kingma et al., 2003; Kuijer et al., 2003; Laursen & Schibye, 2002; Okunribido & Haslegrave, 1999; Resnick & Chaffin, 1995; Schibye et al., 2001). However, many epidemiological studies found that the handling aids still had various injury types such as strains, sprains, bruises, cuts, etc. and 9 % to 18 % of the low back injuries were associated with pushing and pulling (Garg & Moore, 1992; Lee et al., 1991; Snook et al., 1978). However, there are hardly any epidemiological data available to answer the question of whether pulling is related to musculoskeletal complaints (Burdorf & Sorock, 1997; Hoozemans et al., 1998; Kuiper et al., 1999).

Due to business expansion or other reasons, the population who frequently took long distance trips with the two-wheeled luggage has increased rapidly. In our daily life, two-wheeled luggage aids humans by reducing demands of physical capabilities due to elimination of lifting activities and improving their control over the environment. However, some literature was found in relation to four- and two-wheeled industrial carriers, but nothing to two-wheeled luggage. The handling of the industrial carriers mainly are handled by pulling backward and pushing forward with two-hands. Thus, the dynamic mechanism and properties of those carriers should be different from those of two-wheeled luggage. Two-wheeled luggage is the typical manual handling aid with pulling forward with one hand. In addition, the previous study focused on design factors of carriers and their effects through kinematical and biomechanical models. Despite their effort on the carrier design improvement in terms of human factors, there are still various injuries because users' preferences and reactions were not considered in the studies. Unfortunately, the luggage in the market has revealed negative results in its application due to its poor designs and misusages. A usability test is used to elicit qualitative and quantitative feedback on the products. Therefore, there is a need for a usability test with mechanical models for theoretical and practical satisfaction.

In this study, the design of luggage was ergonomically investigated in terms of mechanical models and a usability test. With mechanical models and usability, design assessments of any types of carriers have not been studied so far. Therefore, not only work on the design of luggage based on mechanical models but also the assessment of their applications through a usability test should be conducted to enhance the value of the product for users. In this study, the adequate design of luggage and the satisfaction of luggage users can be achieved simultaneously through mechanical models and a usability test.

1.2 Study objectives

The purpose of this study was to ergonomically investigate luggage design through mechanical models for pulling force estimation and a usability test for users' preferences. This study suggested a luggage design criteria by comparing the various design factors of two-wheeled luggage through mechanical models and a usability test.

This thesis addressed the following research objectives:

1. To examine the pulling force in different motion phases of luggage through mechanical models.
2. To find important luggage design factors through the mechanical models.
3. To investigate usability of two-wheeled luggage by the effects of those design factors through a usability test.

1.3 Thesis organization

In chapter 1, the problem statement and objectives of the research were presented. In chapter 2, previously published literatures were reviewed in relation to four-wheeled carriers and two-wheeled carriers. In chapter 3, Work-related Musculoskeletal Disorders (WMSDs) including functional anatomy of hand and wrist, injury patterns and symptoms of WMSDs were reviewed. In chapter 4, a mechanical model was provided for estimating pulling force in three motion steps such as static, initial/ending, and sustained phases. This chapter included a study regarding the property of luggage in terms of motion phases and provided the mathematical models for estimating pulling force. A statistical analysis was conducted to find important factors for designing better luggage. In chapter 5, a usability test was conducted based on subjective ratings. In chapter 6, test results were provided including difficulties for two-wheeled luggage use, risk assessment of body parts, pulling force, walking speed, and trip/hit. In chapter 7, the results in chapter 6 were discussed. Finally, in chapter 8, a research summary and future work were presented.

1.4 Benefits of the research

From this study, we have several economical and ergonomical benefits.

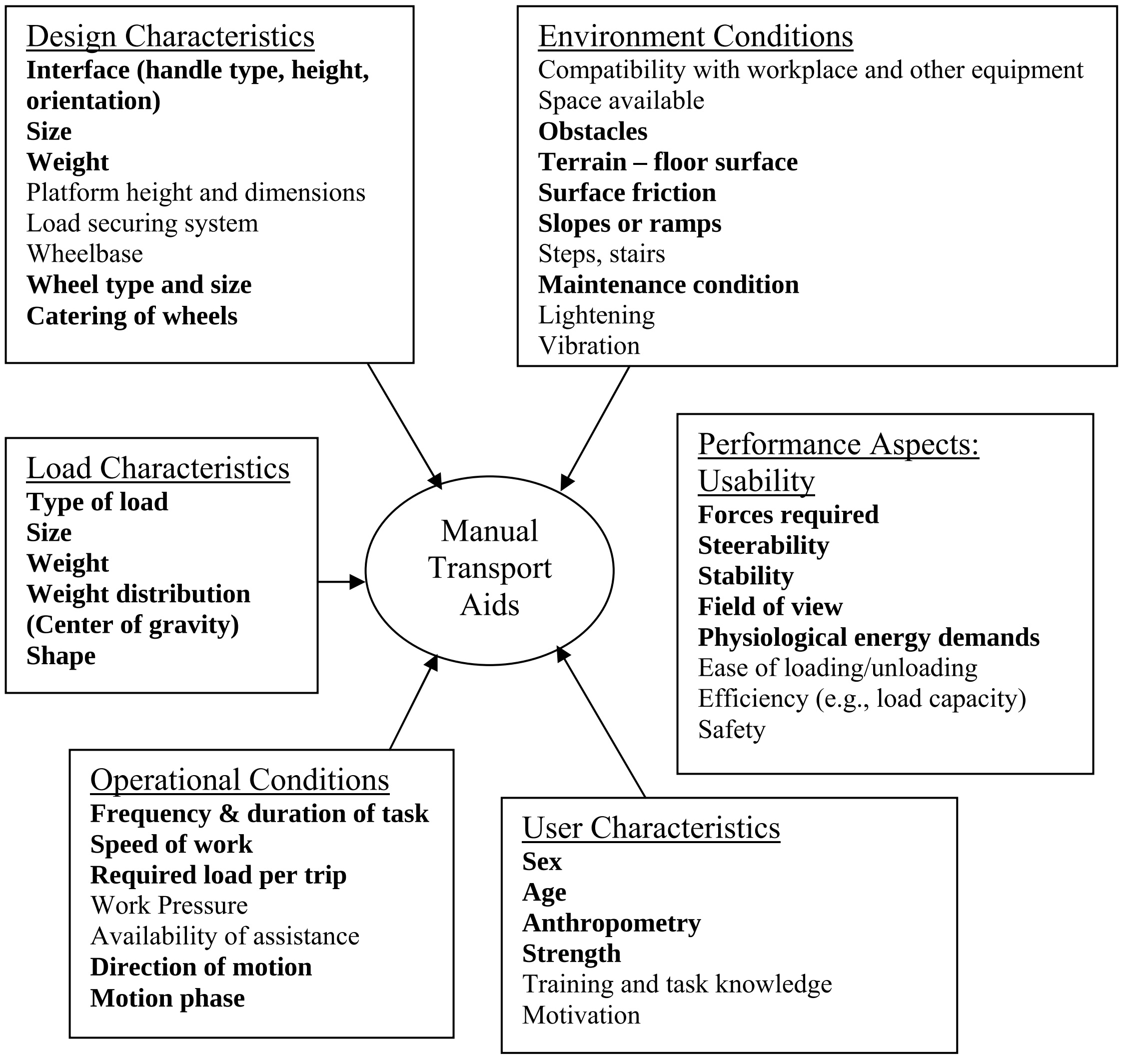
1. Provide study guidelines for the usability of two-wheeled luggage.
2. Provide important design factors for luggage industry.
3. Minimize the force and provide better hand posture required to perform tasks.
4. Continually improve the quality and reliability of luggage.
5. Minimize insurance and hospitalization cost by improving safety.
6. Maximize the safety, health, and well-being of all luggage users.

CHAPTER 2 LITERATURE REVIEWS

2.1 Characteristics of material handling aids

Many studies related to material handling aids have been conducted in various carriers such as four-wheeled carts, two-wheeled hand trucks, and one-wheeled barrows. The studies usually focused on different aspects for the same material handling aids. Design factors, environment factors, operator factors, task factors, and usability issues were included. Mack et al. (1995) found many of the aids were poorly designed or inappropriately used. To reduce and assess the risk of injury for any manual material handling tasks, they provided guidance for their selection and evaluation. In their study, the main parameters were defined based on information obtained during a survey, evidence from literature, and generally accepted ergonomic principles. Figure 2.1 showed the main parameters defined by Mack et al. (1995).

From Figure 2.1, the bold letters represented the factors shown in the literature reviews. The parameters shown in Figure 2.1 were applicable into all-type of manual material handling aids. However, particular factors which were marked with a bold letter should be important for two-wheeled luggage although the different motion dynamics were involved in luggage operation. According to Mack et al. (1995), the design characteristics included interface (handle type, height, and orientation), size, weight, platform height and dimensions, load securing system, wheelbase, wheel type and size, and catering of wheels. Environment conditions included compatibility with workplace and other equipment, space availability, obstacles, terrain, slope and ramps, steps and stairs, maintenance condition, lighting, and vibration. Load characteristics included type



(Note: Bold letters mean the factors to be shown in this review)

Figure 2.1 Factors which are important to the usability of manual transport aids (developed from Mack et al., 1995)

of load, size, weight, weight distribution, and shape. Operation conditions included frequency and duration of task, speed of work, required load per trip, work pressure, and availability and assistance. Finally, user characteristics included sex, age, anthropometry, strength, training and task knowledge, and motivation. After combining all aspects, the performance could be measured. The measurements included force required, steerabilty, stability, field of view, physiological energy demands, ease of loading/unloading, efficiency, and safety.

2.1.1 Four-wheeled aids

Ten studies related to four-wheeled carriers were found for the current research issues. At least two factors from factors in Figure 2.1 were considered in each reference. The dependant variables, independent variables, and type of each study were summarized in Table 2.1. Then detailed reviews by each factor were provided.

Design characteristics

One of the most important features of material handling aids is design characteristics. Interface as a design characteristic includes handle type, height, and orientation. Handle interface needs to be well placed and of the appropriate type, affecting both ease of steering and biomechanical stresses when exerting force. In addition, carts' size, weight, and wheel type and size should be considered as design characteristics.

Table 2.1 Summaries for four-wheeled carrier study

Study	Type of carrier	Dependent variables	Independent variables	Study type
Al-Eisawi et al., 1999a	Four-wheeled cart	Minimum push and pull forces	- Floor material - Cart load - Wheel width, diameter, and orientation	Experiment
Al-Eisawi et al., 1999b	Four-wheeled cart	Initial hand forces in cart pushing and pulling	- Handle height - Cart load	Experiment
Ciriello et al., 2001	Four-wheeled push cart simulator	Maximum acceptable horizontal and vertical forces	- Type of floors - Motion phase (initial and sustained) - Load weight - Push duration	Experiment
Das and Wimpee, 2002	Hospital meal cart	- Postural discomfort - Gender differences - Load weight - Push, pull, turning forces	- Maneuverability - Handle height and placement - Vision - Opening and closing of cart doors - Protection of the cart - Easy of stopping - Size of meal tray - Provision of hot meal - Direction of motion	Direct observation and survey
De Looze et al., 2000	Four-wheeled cart	- Force direction change - Load on the shoulder and low back	- Handle height - Force level - Direction of motion	Experiment
Haslam et al., 2002	Four-wheeled cart	Maximum acceptable forces	- Floor surface	Experiment
Jansen et al., 2002	Four-wheeled standard catering cart	External pushing forces	- Three type of catering carts (different handle height, width, orientation, net mass, diameter of castors and design) - Motion direction (straight and turning) - Surface (linoleum or carpet)	Experiment
Mack et al., 1995	Four-wheeled trolley	Usability	- Design factors - Environment conditions - Load characteristics - Operational condition - User characteristics	- Survey
Resnick, 1995	Four-wheeled cart	- Hand force - Velocities - Spinal compression	- Handle height - Cart load - Volitional exertion level	Experiment
Van der Beek et al., 2000	Four-wheeled mail cage	- Exerted force (initial, average, ending) - Oxygen uptake and heart rate	- Gender - Cage weight - Direction of motion - Exerted forces - Physiological load	Experiment

Al-Eisawi et al. (1999a) performed a laboratory experiment to find factors affecting minimum push and pull forces of the four-wheeled carts. As design characteristics, they compared different wheel sizes and orientations. The four-wheeled cart had a dimension of 610×1020×820 mm (width×length×height). The weight of the cart was 15.3 kg without the wheels. Their wheels had two different widths (25 mm and 38 mm). A diameter of 102 mm (hard rubber) was used to evaluate the effect of wheel width. In the following experiment, the cart had three different wheel diameters (51, 102, and 152 mm) with 25 mm wheel width for evaluation of the effect of the wheel diameter. F0R0 (all four wheels aligned in the forward direction), F0R90 (the two front wheels, the wheels furthest from the cart handle, aligned in the forward direction and the two rear wheels, the wheels closest to the cart handle, aligned at 90° to the forward direction), F90R0 (the two front wheels aligned at 90° to the forward direction and the two rear wheels aligned in the forward direction), and F90R90 (all four wheels aligned at 90° to the forward direction was tested as wheel orientations. In this study, they found the wheel width did not have a significant effect on the minimum pull forces on carpet and on concrete. In addition, as considering wheel diameter and orientation, they found that larger diameter and F0R0 had less pull forces.

Al-Eisawi et al. (1999b) conducted a study with three different handle heights; knuckle, elbow, and shoulder. In their study, they found the vertical forces were smallest at the elbow level. Handle height, interaction between handle height and cart load were also significant for the initial hand forces. However, Al-Eisawi and his colleagues did not provide the size of the carts in their study.

Das and Wimpee (2002) conducted a study for a better design of a meal cart. They used the horizontal, cylindrical cart handle with handle height of 121 cm. They found the placement of the handle did not allow a comfortable posture for the small (5^{th} percentile female) or a large (95^{th} percentile male) person.

De Looze et al. (2000) conducted an experiment for measuring the change of force direction and load on the shoulder and low back. In their study, the adjusting bar heights with 60%, 70%, and 80% of the shoulder height were used for the pushing operation. In addition, they used handle heights of 50%, 60%, and 70% of for pulling operation. In pushing, the direction ranged from pushing downward at the mean (SD) angle with respect to the downward vertical of 45.6 (3.3°) at the lowest force level and handle height, to pushing slightly upward at 96.1(2.6°) at the highest force level and handle height. The absolute shoulder torque was significantly and positively affected by handle height and horizontal force level. The mean decrease in total force exertion from the lowest to highest handle height was 36 N (= 22%), 26 N (= 10%), and 7.4 N (= 2%) at the low, middle, and high horizontal force level. A tripling of the horizontal force level in pushing yielded increases in the total force exertion of 2.2, 2.5, and 2.8 times for the three handle heights. In pulling, the effects of the force level and handle height were also significant but considerably smaller than pushing. Among conditions, the direction varied from pulling upward at 25.6 (15.3°) at the lowest force level and handle height to pulling slightly downward at 256.3 (6.1°) at the highest force level and handle height. The effect of the horizontal force level was positively correlated and the effect of handle height was negatively correlated to the absolute shoulder torque. However, the effects of handle height on the shoulder torque were generally much smaller than the effects of the force level. Finally, it was found that handle height clearly affected the direction of force exertion, which influences the shoulder and low back load.

Mack et al. (1995) found the handle height had the most serious effects on cart design and the dimension of trolleys made them difficult to push in their survey.

Load characteristics

Reports from Al-Eisawi et al. (1999a, 1999b) showed load characteristics according to two separate experiments. In 1999a study, they chose cinder blocks as the type of load and increased load weight from 0 to 181.4 kg in increments of 36.3 kg for investigating the effect of wheel width, diameter, and orientation. In another experiment, the load weights increased from 0 to 217.7 kg in increments of 36.3 kg for investigating the effect of floor material. In two experiments, they revealed that the minimum push/pull forces were linearly proportional to cart weight. In 1999b study, they investigated the effect of handle height and cart load on the initial hand forces in cart pushing and pulling. Handle heights were set to knuckle, elbow, and shoulder levels and cart loads were set to 73 kg and 181 kg. In this study, the results showed that higher force was applied as cart load increased. The statistical results also showed that cart load was significant ($p \leq 0.0001$) and the interaction between cart load and handle height was also significant ($p \leq 0.0001$).

In an additional test, Resnick and Chaffin (1995) measured five different cart loads to see biomechanical load on L5/S1. The results indicated subjects produced excessive spinal compression forces when the load reached 450 kg. In addition, they concluded that cart loads should be kept under 225 kg to avoid high back forces.

Van der Beek et al. (2000) found pushing and pulling a postal cage with 2450 N required the use of 50% physiological capacity of postal workers.

Environmental conditions

Environment conditions were usually categorized as space available, obstacles, floor surface, surface friction, and slopes or ramps. Mack et al. (1995) included more factors such as compatibility with workplace and other equipment, steps, stairs, maintenance condition, lightening, and vibration in their usability model. However, most current researches have focused on the first five factors in their study.

While people exert pushing or pulling forces with the cart, two frictions (shoes friction and rolling friction) are involved in the starting, sustained and ending phases. Those frictions were summarized on Table 2.2 and Table 2.3 based on the results of previous studies (Al-Eisawi et al., 1999a; Ciriello et al., 2001).

Al-Eisawi et al. (1999a) conducted an experiment to investigate the effect of environment conditions such as floor surface for minimum push and pull forces. They chose four different floor surfaces: smooth concrete, tile, asphalt, and industrial carpet. In their study, tile as a floor material had 1.07 times higher coefficient of friction (COF) than concrete. In addition, asphalt had 1.48 times higher and carpet had 2.06 times higher than concrete (Table 2.2).

Ciriello et al. (2001) psychophysically determined the maximum acceptable horizontal forces and load weights on the floors having different coefficients of friction with shoes as shown in Table 2.3. In their study, they distinguished two different coefficients of friction: high and low. The results showed the maximum acceptable

Table 2.2 Coefficient of rolling friction for the different floor materials (Al-Eisawi et al., 1999a)

Floor	Coefficient of rolling friction (mm)	95% confidence of interval (mm)	Comparison with concrete
Concrete	2.205	2.144-2.266	-
Tile	2.362	2.327-2.403	7% higher
Asphalt	3.261	3.139-3.383	48% higher
Carpet	4.541	4.440-4.648	106% higher

Table 2.3 Friction parameters and significant factors between high COF and low COF for two different coefficients of friction between floor and shoes (Ciriello et al., 2001)

Factors	High coefficient of friction (COF) floor	Low coefficient of friction (COF) floor
Measured coefficient of friction (MCOF)	0.68	0.26
Required coefficient of friction (RCOF)	0.321	0.193
Initial horizontal force (N)	403.8 (SD=129.4)	240.2 (SD=67.6)
Sustained horizontal force (N)	221.5 (SD=31.6)	136.8 (SD=21.1)
Cart weight (kg)	13 (SD=1.7)	21 (SD=7.8)

weights of push cart tasks on the low COF was significantly lower (31%) than those on the high COF. Initial and sustained horizontal forces on the low COF were also lower (41% and 38%, respectively) than those on the high COF. However, initial and sustained vertical forces were not significantly different between two floor surfaces. Finally, push duration on the low COF floor was longer (62%) than that on the high COF floor.

Das and Wimpee (2002) conducted an experiment on carpet and tile as floor materials. They found the higher push force of the carpet floor could be attributed to the higher coefficient friction of the carpet compared to the tile. The pull forces were basically the same as the push forces. However, they didn’t provide any specific mathematical results in their study although they found sustained push and pull forces were considerably less than initial push or pull forces.

In addition, Haslam et al. (2002) confirmed that a difference existed between the mean peak initial horizontal ground forces between slippery and non-slippery flooring conditions ($p < 0.05$). A significant difference ($p < 0.05$) was also found with the mean peak initial vertical forces associated with the maximum acceptable loads.

In other experiment conducted by Jansen et al. (2002), more detailed results were presented. Jansen et al. (2002) found that the initial forces had a small range from 147 N for the SCC on linoleum to 167 N for the SCC on carpet. Sustained forces were somewhat lower compared to the initial forces (-62 to -112 N).

Mack et al. (1995) pointed out that the condition of floor surfaces was a major problem for cart design from the result of their survey. Sticky and carpeted floors increased the forces required to move the aid, while rough surfaces and bumps or steps not only increased the force, but made it difficult to move at all.

Resnick and Chaffin (1995) reported that hand forces were affected by floor condition in their study. The peak velocities reached ranged only from 0.2 $m \times s^{-1}$ to 1.1 $m \times s^{-1}$ (MTM standard 1.80.$m \times s^{-1}$) for long distances. They concluded that these slower movement speeds were required for pushing of heavy loads, especially over short distances.

Operational conditions

Mack et al. (1995) suggested some factors such as frequency and duration of task, speed of work, required load per trip, work pressure, and availability of assistance as operational conditions. However, a few studies regarding those factors have been studied. For this study, direction and phases of motion have been added to operational conditions. Previous studies (Das & Wimpee, 2002; Jansen et al., 2002) revealed that the direction of motion greatly influenced both the maneuverability of trolleys and the required forces to move them.

The frequency of use of four-wheeled carts depends on the industry. Mack et al. (1995) surveyed 12 industries and found that 80% of four-wheeled carts were used more than once a day and 30% were used more than 10 times a day. However, only 20% of carts were four-wheeled in the trash-collecting industry (de Looze et al., 1995).

For the direction of motion, Das and Wimpee (2002) conducted an experiment with a hospital meal cart. For pulling, this cart caused an awkward posture on the neck, back and trunk to move the cart. For pushing, the posture minimized health hazards especially neck, back, and trunk. The results should be correct in only this kind of job; however, direction of motion should be selected based on the purpose of tasks.

Jansen et al. (2002) investigated the effect of change of directions with four-wheeled carts; SCC, Hupfer, and Animo models. They found that pushing the SCC resulted in significantly higher values of $F_{initial, pushing}$ than pushing one of the prototypes, but the $F_{initial, pulling}$ was significantly lower for straight activities. In line with pushing straight, mean values for $F_{initial, pushing}$ were lowest in pushing the Hulfer cart on linoleum and highest in pushing the SCC on carpet.

User characteristics

User characteristics such as sex, age, anthropometry, strength, training and task knowledge, and motivation may be very important to usability (Al-Eisawi et al., 1999b; van der Beek et al., 2000). However, another study reported that the relationship between maximum acceptable trolley load and subject weight and height was not significantly related (Haslam et al., 2002).

Al-Eisawi et al. (1999b) studied initial hand force with five males and five females. The average age of the male group was 28.4 years with 3.6 years of standard deviation while average age of the female group was 21.6 years with 1.5 years of standard deviation. The average height of male group was 181.6 cm with 6.6 cm of standard deviation and the average height of female group was 169.6 cm with 9.7 cm of standard deviation. The study showed that strength capability and gender did not influence hand force. However, the difference among subjects within gender was significant ($p \leq 0.0001$).

Van der Beek et al. (2000) studied gender differences in exerted forces during pushing and pulling of wheeled cages by postal workers. Twelve experienced postal workers participated in the study. The participants were between 20 and 30 years of age with body weight ranging from 50 to 64 kg. However, individual anthropometry data was not provided in their study. The results showed gender differences were significant for all dependent variables (average force, initial force, ending force, oxygen uptake, and heart rate; $p= 0.030 \sim 0.000$). Male workers exerted significant higher average forces than females, while differences regarding initial forces and physiological load were not significant. Gender differences in exerted forces were not caused by differences in anthropometry and maximum capacity. These results confirmed those of Al-Eisawi et al. (1999b).

2.1.2 Two-wheeled aids

Studies related to two-wheeled carriers are comparatively fewer than those of four-wheeled carts. Eight studies related to two-wheeled carriers were found.
The dependant variables, independent variables, and type of each study were summarized in Table 2.4, and then detailed reviews by each factor were provided.

Design characteristics

Laursen and Schibye (2002) conducted an experiment with seven waste collectors. The two-wheeled container were pushed and pulled on three different surfaces: flagstones, paving stones, and grass. The empty weight of the container was 15 kg and the wheel size was 0.25 m diameter and 0.045 m width. The results showed that container weight affected the magnitude of push/pull forces and the load on the shoulders but not the load on the lumbar spine.

Mack et al. (1995) found the handle height had the most serious effects on cart design and the dimension of trolleys made it difficult to push.

Okunribido and Haslegrave (1999) investigated the effect of handle design. Handle orientation was compared with 35°, 50°, and 70°. Handle length was set to 1.0, 1.1, and 1.2 m. The weight of the cylinder was 37 kg. In this study, they found that the height and angle of the handles affected the tilted angle of the trolley. In turn, the angle of handles affected the position of the handles and of the center of mass (COM) with respect

Table 2.4 Literatures related to two- wheeled cart

Study	Type of carrier	Dependent variables	Independent variables	Study type
De Looze et al., 1995	Two-wheeled trash container	- Biomechanical load	- Vehicle type and size - Handle height - Load weight - Direction of motion	Experim-ent
Kingma et al., 2003	Two-wheeled trash container	- Force - Joint loading	- Handle height - Center of mass (COM) - Direction of motion	Experim-ent
Kuijer et al., 2003	Two-wheeled trash container	- Biomechanical load	- Handle height - Horizontal distance between handle and the wheel-axis - Diameter of wheels	Experim-ent
Laursen and Schibye, 2002	Two-wheeled container	- Biomechanical load - Torque at the shoulder joint	- Type of floor - The container weight - Motion phases - Direction of motion	Experim-ent
Mack et al., 1995	- Two-wheeled trolley	- Usability	- Design factors - Environment conditions - Load characteristics - Operational condition - User characteristics	Survey
Okunridido and Haslegrave, 1999	Two-wheeled cylinder trolley	- Force at the feet - Biomechanical load - Posture (the wrist angle, elbow flexion)	- Handle angle and height - Load weight - Subjective rate (effort, discomfort, and stability)	Experim-ent and survey
Schibye et al., 2001	Two-wheeled trash container	- Force - Biomechanical load	- Load weight - Direction of motion - Motion phase	Experim-ent
Suherman and Plaut, 1997	Two-wheeled suitcase	-Human response time	- The magnitude time delay - The coefficient of the puller's restoring moment - The amplitude and frequency of the excitation moment	Simulati-on

to the axis of the wheels, thereby influencing the required forces at the handle and the resulting joint loading. As a result, the elbow stresses were significantly affected by the design of the trolley handle, as was the degree to which the trolley was tilted while moving forward with the load.

Suherman and Plaut (1997) measured the magnitude of the time delay, the coefficient of the puller's restoring moment, and the amplitude and frequency of the excitation moment with a two-wheeled suitcase. In their study, they concluded that the average side-to-side frequency of a person walking was approximately 1 Hz, which corresponds to **Ω** (excitation frequency) = 1.37, and the average response time was about 0.1 sec, which corresponds to δ (time delay) = 0.46. The results showed, with no time delay, the suitcase did not overturn during 20 cycles of excitation. If $\delta = 0.1$, the suitcase fell down after 11 impacts. With $\delta = 0.5$, overturning occurred after one impact, and with $\delta = 1.0$ the suitcase exhibits "immediate overturning" in one direction with no rocking back and forth.

Kuijer et al. (2003) investigated effects of the redesigned two-wheeled container for refuse collection on mechanical loading of low back and shoulders. They conducted an experiment by changing the height of the handle, horizontal distance between the handle and the wheel-axis, and diameter of the wheels. The handle was displaced at 0.1 rearwards in the horizontal and 0.1 m upwards in the vertical direction. The volume of the container was 0.24 m^3 and the wheel axis was lengthened from 0.55 m (standard) and 0.69 m (redesigned). The diameter of the wheel was also increased from 0.2 to 0.3 m. The results indicated that the redesigned two-wheeled container resulted in lower peak and sustained exerted hand forces for the activities of pulling and pushing and lower peak value for the turning (all $p < 0.001$). The peak moment at the low back for pulling with the redesigned container was lower than for pulling the standard container ($p = 0.03$). The same effect was found for peak moment at the low back for turning ($p = 0.02$). However, the type of two-wheeled container did not affect the compression force at the low back. These effects were caused by the change of handle height, the change of horizontal distance between handle and wheel-axis, and the change of wheel diameter.

Kingma et al. (2003) investigated the effect of the hand force and joint loading by horizontal and vertical center of mass (COM) and handle locations. They considered 8 different COMs and 11 different handle locations. The dimension of the container was 0.240 m^3 and the bottom of the container was 0.49 × 0.56 m (width × depth). Wheel diameter was 0.2 m. The study reported a 0.1 m increase of the handle height slightly reduced the required vertical force without adverse effects on joint loading.

In Okunribido and Haslegrave's study (1999), for starting, the best configuration proved to be 35° handle angle and a 1.0 m handle length. However, the results were less clear in determining the best configuration for pushing the trolley forward. Mean wrist flexion was least (1.5°, 2.51 SD) with 50° handle angle and 1.2 m handle length, the highest (8.0°, 10.84 SD) with 35° handle angle and 1.0 m handle length. Mean wrist extension was least (17.1°, 12.16 SD) with the 35° handle angle and 1.0 m handle length, the highest (32.5°, 13.63 SD) with 35° handle angle and 1.2 m handle length, and (27.3°, 7.87 SD) with 50° handle angle and 1.1 m handle length. Mean radial deviation was least (4.0°, 5.10 SD) with the 35° handle angle and 1.0 m handle length, and highest (12.1°, 8.37 SD) with the 70° handle angle and 1.2 m handle length.

Load characteristic

Not many studies regarding the load characteristics were found. Lausen and Schibye (2002) in their study reported that the force was 10 - 30% larger on grass compared to flagstones and it could be caused by a reduction in the acceleration when the container weight was increased for at least the tilting and initial phase.

Another study by Kingma et al. (2003) used concrete blocks as loads controlling by foams and straps to prevent slipping. The load weight was 59.4 kg (SD= 0.9 kg) and 9 conditions of COM was considered. In their study, they revealed that backward displacement of the COM increased low back loading and forward displacement of the COM increased shoulder and elbow loading. However, a COM displacement in the direction of wheel axis did not have negative effects on joint loading and reduced the forces, needed to tilt the container.

Environmental conditions

Laursen and Schibye (2002) conducted an experiment on three different floor surfaces as environment conditions. Flagstones, paving stones, and grass floor surfaces were compared in their study. In their study, the type of surface affected the magnitude of the push/pull forces during initial and sustained phases, and affected the load on the shoulder in the sustained phase. However, it did not affect the compression in the lumbar spine. The largest force found in the initial phase when pushing the heaviest container on grass. In the initial phase, the force was 10 - 30% larger on grass compared to flagstones.

Kuijer et al. (2003) categorized the motion of the container as four different activities: (1) tilting the two-wheeled container and pulling it with the one hand; (2)

tilting the two-wheeled container and pushing it with two hands; (3) turning the two-wheeled container around; and (4) pulling the empty two-wheeled container up onto the pavement in their study.

Operational conditions

Okunribido and Haslegrave (1999) reported high stresses at the elbow and considerable wrist deviations were found to occur during the initial phase. Higher forces were required in the vertical direction when the weight of the trolley was tilted to free the wheels for movement.

Schibye et al. (2001) in their study reported that the compression at L4/L5 is from 605 to 1445 N during pushing and pulling. The extension torque at L4/L5 produced by the push/pull force was counteracted by the forward leaning of the upper body. The shear force was below 202 N in all situations. The torque at the shoulders was between 1 and 38 Nm. In their experiment the torques at the low back and the shoulders were low during pushing and pulling. No relation was found between the size of the external force and the torque at the low back and the shoulder.

Kuijer et al. (2003) in their study emphasized the effect of experience of collecting activity and reported the experienced workers had better control of the load. However, any comparison tests were not provided.

User characteristics

Kingma et al. (2003) recruited three different subject groups (a 5th percentile male, a 95th percentile male, and two participants of intermediate body height) for the study.

The effect of the participant and the push versus pulling indicated that there was a significant effect of the participant due to body height variations on most of the dependant variables for COM conditions and handle conditions.

2.2 Recommendations of material handling aids

This section included the recommendations of material handling aids with each factors mentioned in section 2.1. To avoid argument about the results of each study, the recommendations were developed by the characteristics of the studies. Therefore, practitioners should investigate the recommendations by the systematic classification of carriers as well as by the number of wheels as those are applied into the real workplace. The recommendations were presented based on the guidelines in Figure 2.1.

2.2.1 Design characteristics

Recommendations for design characteristics were categorized broadly into three interesting factors: Dimension of carrier, handle, and wheel. The study for design characteristics were summarized in Table 2.5.

Dimension of carrier

Chengalur et al. (2004) provided the general dimension of the truck or carts. They reported those aids should be 1.3 m (4 ft.) long and 1 m (3 ft.) wide. They emphasized bigger dimension made it more difficult to maneuver in a standard aisle. In addition, they reported the preferred height should be less than 127 cm (50 in.). Based on their report, this height kept the handling of parts on the carts within the safer range of below shoulder

Table 2.5 Recommendations for design characteristics

Design characteris-tics	Study	Carrier type	Comparisons	Recommendations
Dimension of carrier	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	1.3 m (4 ft.) × 1 m (3 ft.) × 1.27 m (50 in.) (Length × Width × Height)
	Das and Wimpee (2002)	Four-wheeled hospital meal cart	145 cm × 60 cm× 152 cm (Length × Width × Height)	136 cm × 66 cm× 139 cm (Length × Width × Height)
Handle	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	- Adjustable T-handle: long enough and at least 20 cm (8 in.) of horizontal extension - Fixed handle: at least 91 cm (36 in.) but not grater than 112 cm (44 in.) - Vertical handle: ranged from 15 cm (6 in.) to 127 cm (50 in.)
	Al-Eisawi et al. (1999b)	Four-wheeled cart	Knuckle, elbow, and shoulder level	Elbow level
	Das and Wimpee (2002)	Four-Wheeled hospital meal cart	121 cm of handle height	- 94 -115.3 cm - Vertical handle instead of horizontal handle
	Jansen et al. (2002)	Four-wheeled catering cart	SCC: horizontal push bar Hupfer: two vertical push bars Animo: vertical push bars	Vertical bar
	Mack et al. (1995)	Two-wheeled sack truck and cylinder truck	Vertical bar and vertical handles with a horizontal bar	Vertical handles with a horizontal bar
	Kingma et al. (2003)	Two- wheeled container	Eleven handle locations	(-0.176, 1.00) m
Wheel	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	- Larger diameter
	Al-Eisawi et al. (1999a)	Four-wheeled cart	- Width: 25 and 35 mm - Diameter: 51, 102, and 152 mm - Orientation: F0R0, F0R90, F90R0, F90R90	- Larger diameter - F0R0 wheel caster - No difference between wheel widths
	Das and Wimpee (2002)	Four-wheeled hospital meal cart	N/A	Larger diameter (20 cm) wheel width (4 cm)
	Jansen et al. (2002)	Four-wheeled catering cart	4 casters, 4 casters and a fixed wheel, 3 normal casters and a fixed wheel	Both types with a fixed wheel
	Mack et al. (1995)	Four- and two-wheeled cart	N/A	- Suitable wheel type and tyre pressure - Should provide good wheel bearing and maintenance

height for most people. In another study for hospital meal carts, Das and Wimpee (2002) recommended 136 cm × 66 cm× 139 cm (length × width × height). In their study, they explained this dimension had better maneuverability and vision.

Handle

Chengalur et al. (2004) suggested several different guidelines for different types of carriers. If an adjustable T-handle is used, the handle height should be long enough and at least 20 cm (8 in.) of horizontal extension is required. A fixed horizontal handle should be 91 cm (36 in.) or more above the floor but not greater than 112 cm (44 in.). Vertical handles should be within the range from 15 cm (6 in.) to 127 cm (50 in.). For the handle height evaluation, many studies were published. Al-Eisawi et al. (1999b) found the smallest vertical forces at the elbow level. Handle height significantly affected initial hand push/pull forces ($p<=0.000.1$). Das and Wimpee (2002) stated that the proposed handle height for pushing or puling should be about 91-115.3 cm. Das and Wimpee (2002) and Jansen et al (2002) revealed that vertical handles were proposed instead of horizontal cart handles because the vertical handles caused a decrease in a range of operators accommodated horizontally or with respect to shoulder/elbow width. However, Mack et al. (1995) stated vertical handles with a horizontal bar found to be more helpful in tilting the truck. Kingma et al. (2003) suggested the height of handle compared with eleven handle locations for pulling activity. For pulling force, 100 cm were suggested for the height of handle while horizontal distance between handle and side of carts were -0.176 cm.

Wheel

For the wheel type and size, the specific information was not given. Most studies provided general information of wheel characteristics. For instance, most studies (Al-Eisawi et al., 1999a; Chengalur et al., 2004; Das & Wimpee, 2002) emphasized larger diameter of wheels for moving cart handling while Mack et al. (1995) recommended suitable type of wheel and tire pressure depending on task place. Hard material and high pressure tires were also recommended (Chengalur et al., 2004; Das & Wimpee, 2002). Al-Eisawi et al. (1999a) stated that wheel width did not have any significant effects on the minimum pull forces on carpet and on concrete. The cart with larger diameter and F0R0 (all four wheels were aligned in the forward direction) had less pull force. However, another study (Jansen et al., 2002) provided a contradictory result that a cart with a fixed wheel resulted in lower integrated pushing force despite the location of the wheel. In addition, Mack et al. (1995) underlined good wheel bearing and maintenance as other considerations.

2.2.2 Load characteristics

Heavier loads required higher force (Al-Eisawi et al., 1999b; Chengalur et al., 2004) and minimum push/pull forces were linearly proportional to cart weight (Al-Eisawi et al., 1999a). Chengalur et al. (2004) suggested that the load should be reduced or power assist should be provided when load reached to 227 kg (500 lb.). In additional tests, Resnick and Chaffin (1995) indicated that cart loads should be kept under 225 kg to avoid high back forces. Kingma et al. (2003) reported the relationship between center of mass (COM) and handle force. In their study, they concluded that the force was highly dependent on COM and reported the center of mass should be aligned on the midline of the container. The summary of literature regarding load characteristics was shown in Table 2.6.

2.2.3 Environmental conditions

In the current research, environmental condition has been mainly focused on obstacles, floor surface, surface friction, and slope and ramps. Table 2.7 showed the summary of the study for environmental conditions.

Obstacles

In Suherman and Plaut's study (1997), obstacles caused response time delay and this time delay increased the likelihood that the suitcase became unstable and fell onto one of its sides.

Table 2.6 Recommendations for load characteristics

Load characteristics	Study	Carrier type	Comparisons	Recommendations
Load	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	Heavier load, higher force Recommended load: under 227 kg (500 lb.) on a hand cart or truck
	Al-Eisawi et al. (1999a)	Four-wheeled cart	0 to 217.7 kg in increment of 36.3 kg	Minimum push/pull forces were linearly proportional to cart weight
	Al-Eisawi et al. (1999b)	Four-wheeled cart	73 and 181 kg	Heavier load, higher force
	Resnick and Chaffin (1995)	Four-wheeled cart	45 to 450 kg	Maximum load: under 225 kg
	Kingma et al. (2003)	Two-wheeled container	Eight different center of mass locations	Midline of the container

Table 2.7 Recommendations for environment conditions

Environment conditions	Study	Carrier type	Comparisons	Recommendations
Obstacles	Suherman and Plaut (1997)	Two-wheeled suitcase	Time delay = 0.1, 0.5, 1.0	More time delay, more unstable and fell down
Floor surface	Al-Eisawi et al. (1999a)	Four-wheeled carts	Concrete, tile, asphalt, and carpet	Concrete = 1.07 tile = 1.48 asphalt = 2.06 carpet
	Laursen and Schibye (2002)	Two-wheeled containers	Flagstones, paving stones, and grass	Grass needed highest force while flagstones needed lowest force in any phase.
Surface friction	Ciriello et al. (2001)	Four-wheeled push cart simulator	Low COF and High COF	Appropriate friction was necessary.
	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	The coefficient of friction between shoes and floor: about 1.0.
	Haslam et al. (2002)	Four-wheeled trolley	Slippery and non-slippery floor surface	No differences between slippery and non-slippery surface due to subjects' modified posture, but they concluded further research was required.
Slope and ramps	Chengalur et al. (2004)	Four-wheeled truck and cart	N/A	Ideal: flat floor

Floor surface

Al-Eisawi et al. (1999a) found concrete had less push and pulling force. Compared to concrete, tile, asphalt, and carpet had 1.07 times, 1.48 times, and 2.06 times more forces, respectively. Laursen and Schibye (2002) investigated the effect of three different floor surfaces (flagstones, paving stones, and grass) on biomechanical load with two-wheeled containers. They found that grass needed 50% - 100% larger hand forces in sustained phase as well as 10% - 30% larger in initial phase. Therefore, they concluded that the smooth surface needed less biomechanical load on hand in any motion phase.

Surface friction

Ciriello et al. (2001) compared high with low coefficient of friction (COF) to investigate horizontal and vertical components of maximum acceptable initial and sustained forces. With high coefficient of friction, the maximum acceptable weights increased. Contrary, initial and sustained horizontal forces decreased and duration was longer on the low COF. There was a trade-off between rolling friction and slippery. Therefore, they concluded that appropriate friction was necessary. Chengalur et al. (2004) clearly recommended the coefficient friction of the handler's shoes with the floor is about 1.0. Controversially, Haslam et al. (2002) reported that no differences were found between the slippery and non-slippery conditions for maximum acceptable trolley loads due to subjects' modified posture, but they recommended further study on this case.

Slope and ramps

Chengalur et al. (2004) in their book stated that uneven or sloped floors require greater force exertions.

2.2.4 Operational conditions

Operational conditions included push versus pull, motion phase, frequency and duration of task, speed of work, required load per trip, work pressure, and availability of assistance according to Mack et al. (1995). However, most studies focused on direction of force exerted, motion phase, frequency and duration of task, and speed of work. The summary of operational conditions was provided in Table 2.8.

Table 2.8 Recommendations for operational conditions

Operational conditions	Study	Carrier type	Comparisons	Recommendations
Direction of motion	Al-Eisawi et al. (1999a)	Four-wheeled cart	Push versus pull	Either push or pull should be selected by swiveling wheels and tasks.
	Al-Eisawi et al. (1999b)	Four-wheeled cart	Push versus pull	Push force = 0.935 × pull force on the average total horizontal hand force (initial phase)
	Chengalur et al. (2004)	Four-wheeled truck and cart	Push versus pull	Pushing is the preferred method of handling handcarts and trucks
	Das and Wimpee (2002)	Four-wheeled hospital meal cart	Push versus pull	Pushing was recommended using both hands
	De Looze et al., 2000	Four-wheeled cart	Push versus pull	Straight-line pushing and pulling were recommended
Motion phase	Jansen et al., 2002	Four-wheeled standard catering cart	Initial, sustained, and ending forces	Sustained force was lower than initial force while initial force and ending force were not significantly different.
	Mack et al. (1995)	Four- and two-wheeled cart	Initial, sustained, and ending forces	Consider the initial starting due to its largest force requirement among the motion phases.
	Chengalur et al. (2004)	Four-wheeled truck and cart	Initial, sustained, and ending forces	- Initial force: 23 kg-f (225.6 N) or less - Sustained force (general): less than 18 kg-f (176.5 N). - Ending force: less than 36 kg-f (353 N).
Frequency and duration	Chengalur et al. (2004)	Four-wheeled truck and cart	Sustained and ending forces	Frequent and long transfers should be done by powered equipment.
Speed of work	Eastman Kodak (1986)	Four wheeled truck and cart	N/A	Less than 1.1 m/s
	Resnick and Chaffin (1995)	Four-wheeled cart	MTM standard (1.8 m/s)	Slower speed of work: ranged from 0.2 m/s to 1.1 m/s

The direction of motion

Chengalur et al. (2004) stated that most carts or hand trucks can be pushed as well as pulled. Pulling is often done with one hand and with a twist in the trunk, so pushing is the preferred method of handling handcarts and trucks. Previous studies (Al-Eisawi et al., 1999a; Das & Wimpee, 2002; Jansen et al., 2002) revealed that the direction of motion such as push or pull was greatly influenced by both the maneuverability of trolleys and forces required to move them. Al-Eisawi et al. (1999a) reported that the minimum pull forces at the F90R0 wheel orientation were, on average 28% less than the minimum push forces. On the other hand, the minimum pull forces at the F0R90 wheel orientation were, on average, 19% higher than the minimum push forces. Therefore, they suggested that pull or push should be selected by swiveling wheels while wheel orientation should be selected by tasks. However, they did not present the relationship between pull or push in turning. In a later study, Al-Eisawi et al. (1999b) reported that the push forces were slightly higher (93.5%) than the pull forces on the average total horizontal hand force in the initial phase. Das and Wimpee (2002) recommended that the cart must be pushed using two hands. In addition, straight-line pushing and pulling were recommended to preserve balance (de Looze et al., 2000).

Motion phase

Jansen et al. (2002) reported that initial forces had a small range from 147 N to 167 N while sustained forces were somewhat lower (62 N to 112N) for catering carts. However, initial and ending forces were not significantly different. The initial starting phase should be considered to determine the limits of maximum acceptable force and load weight due to its largest force requirement among the motion phases (Mack et al., 1995). The general set of guidelines for pushing and pulling phases were suggested in Chengalur et al.'s book (2004). The initial force should be maintained to 23 kg-f (225.6 N) or less. The sustained force should be less than 18 kg-f (176.5 N). Finally, the ending force should be less than 36 kg-f (353 N).

Frequency and duration

Generally, the sustained force was recommended to be maintained less than 18 kg-f (176.5 N). However, sustained force should be set by different circumstances such as frequency and duration. As the force had to be sustained for a minute, it should drop to 11.5 kg-f (112.8 N). As it was sustained without a break for 4 minutes, the acceptable force dropped to about 3.5 kg-f (34.3 N) (Chengalur et al, 2004). They concluded that long transfers were better done with powered equipment.

Speed of work

Compared to the methods time measurement (MTM) standard, slower speed of work was recommended (Resnick and Chaffin, 1995) for long distance and jobs that requiring the pushing of heavy load. In their paper, the peak velocities reached by subjects ranged from 0.2 m/s to 1.1 m/s. This result was consistent with the recommendations of less than 1.1 m/s (Eastman Kodak, 1986).

2.2.5 User characteristics

User characteristics were defined by sex, age, anthropometry, strength, training and task knowledge, and motivations. However, the recommendations for user characteristics are fairly limited. Only sex and anthropometry were dealt with and recommended in current literature. Table 2.9 summarized the recommendations of user characteristics.

Sex

Al-Eisawi et al. (1999b) studied initial hand force with five males and five females. The study showed that strength capability and gender did not influence on the hand force. However, the difference among subjects within gender was significant ($p \leq 0.0001$). Van der Beek et al. (2000) studied gender differences in exerted forces during

Table 2.9 Recommendations for user characteristics

User characteristics	Study	Carrier type	Comparisons	Recommendations
Sex	Al-Eisawi et al. (1999b)	Four-wheeled cart	Five males and five females	No gender difference between strength capability and genders on the hand forces
	Van der Beek et al., 2000	Four-wheeled mail cage	Three postal worker groups: Four female (50 to 64 kg), four females (65 to 75 kg), four males (65 to 75 kg)	Limiting the initial forces was the first priority to reduce musculoskeletal disorders.
Anthropometry	Kingma et al., 2003	Two-wheeled trash container	5^{th} percentile male, 95^{th} percentile male, and two participants of intermediate body height	Handle height should be designed by the user's height.
	Mack et al., 1995	Four- and two-wheeled trolley	Survey from 61 males and 29 females	Trolleys and trucks should be designed by considering the individual user.

pushing and pulling of wheeled cages by postal workers. The results showed gender differences were significant for all dependent variables (average force, initial force, ending force, oxygen uptake, and heart rate; $p = 0.030 \sim 0.000$). Findings from the study showed that limiting the initial forces should be given highest priority to reduce the risk of musculoskeletal disorders.

Anthropometry

Kingma et al. (2003) recruited three different subject groups (a 5^{th} percentile male, a 95^{th} percentile male, and two participants of intermediate body height) for the study. The effect of the participants and the push/pull indicated that there was a significant effect of participants due to body height variations on most of the dependant variables for COM conditions and handle conditions. They stated that the handle height should be determined by the user's height. In the Mack et al.'s survey (1995), some users indicated that handles were too low so that they had to stoop when pushing. Frequently, with tall cage trolleys, the user tended to pull rather than push them. Those complaints were caused by the negligence of anthropometry when the trolleys were designed. Conclusively, the design of trolleys and trucks should allow the individual user to maintain a comfortable posture.

2.3 Summary

In the previous two chapters, various design factors for four- and two-wheeled carriers and their recommendations were identified. From the literature review, several important conclusions were found.

First, initial push/pull forces should be considered for carts and truck design to reduce musculoskeletal disorders (van der Beek et al., 2000). The initial forces were affected by several important factors. For instance, Al-Eisawi et al. (1999b) found that the minimum required initial forces increased with smaller wheel diameters and that those forces proportionally increased with cart weight. Handle height and interaction between handle height and cart load were also significant for the initial hand forces.

Second, dimension of carriers should be considered. Dimension of carriers affected both easy of steering and stability. Chengalur et al. (2004) and Das and Wimpee (2004) had close recommendations. The recommended dimensions of trolley and meal carts were 1.3m ×1m×1.27m and 136cm×66cm×139cm, respectively.

Third, wheel diameter also improved steerability and stability as well as biomechanical stress. Wheels with larger diameter produced less push/pull forces. Most studies suggested 20 to 25 mm for wheel diameter. However, wheel width was not significant enough to reduce push/pull force.

Fourth, handle location should be considered. Mack et al. (1995) reported that handle height had the most serious effects on cart design. Particularly, the height was most critical on four-wheeled trolley since the handle height is usually fixed. They suggested trolleys and trucks should be designed by considering the individual user. Wheel orientation was also important. Okunridibo and Haslegrave (1999) found that the best configuration proved to be 35° handle angle and 1.0m handle length.

Fifth, friction of floor surface should be considered. A hard dry floor decreases the operator’s physical stress. However, there was not perfect floor surface. In the slippery and non-slippery surface comparisons, Haslam et al. (2002) reported that no difference was found on both surface. Ciriello et al. (2001) also stated appropriate friction was necessary as considering rolling friction and friction between shoes and floor surface. However, further research would be necessary.

Finally, load should be considered. Load was one of the most important factors for all vehicle types because higher load required higher force (Chengalur et al, 2004; Al-Eisawi et al., 1999b). Chengalur et al. (2004) and Resnick and Chaffin (1995) recommended under 227 kg and 225 kg. These recommendations were close enough for four-wheeled trucks and carts.

After review of the literature, it was found that two-wheeled carriers have been researched fairly less than four-wheeled carriers. This article was undertaken to provide very important factors to reduce push/pull force. Factors presented in this study should be important to assess usability of material handling aids including luggage. In addition, they should be helpful to identify the most important design features for the different types of carriers and the different tasks to be conducted by the users.

CHAPTER 3 WORK-RELATED MUSCULOSKELETAL DISORDERS

3.1 Introduction of Work-related Musculoskeletal Disorders (WMSDs)

Work-related Musculoskeletal disorders (WMSDs) have been prevalently reported in manufacturing and other facilities. The disorders are associated with physical and psychosocial risk factors of the jobs and can affect almost all parts of the body including the hand, wrist, elbow, shoulder, neck, and back, depending on the physical movement characteristics, and the ergonomic and mechanical design of work tasks (Hales & Bernard, 1996; Winkel & Mathiassen, 1994). In addition, Work-related Musculoskeletal Disorders represented approximately one third of workers' compensation costs in U.S. private industry. In 2001, approximately 34% (522,528) of all illness cases were due to musculoskeletal disorders when looking specifically at cases involving days away from work (Bureau of Labor Statistics, 2003). Further information by U.S. Department of Labor reveals the following:

- Operators, fabricators, and laborers are dominant occupations (40.7%; total 212,701 cases).
- Strains and Sprains (76.5%; total 399,722 cases) dominate among workplace injuries.
- Workers who are serving as employers for 1 to 5 year and more than 5 years tend to suffer more musculoskeletal disorders (49.1 %; 180,974 and 147,326 cases respectively).
- White people dominate among racial groups (51.2%; 267,711 cases).

- Manufacturing and service employers suffer more musculoskeletal disorders (48.7 %; 119,458 and 134,851 cases respectively).
- Trunk (mostly back) is more susceptible area followed by upper extremities (mostly wrist).
- Most causation of the injury is due to overexertion (75%; mostly overexertion in lifting), awkward posture (13.3%), and repetitions (11.5%).

WMSDs do not happen as a result of single accident or injury. They gradually develop as a result of repeated trauma. Job or working conditions that combine risk factors will increase the risk for musculoskeletal disorders. Excessive force can lead to short-lasting injuries while repeated motion can cause injuries that last a long time. In addition, environmental conditions such as vibration and temperature, and motion with prolong awkward postures are broadly known as risk factors. The next sections specified WMSDs on push/pull activities.

3.2 WMSDs on push/pull activities

In most industries, mechanized assistances such as trolleys, carts, and hand trucks are used as a control measure to alleviate the physical stress and risk of musculoskeletal injury associated with manual materials handling. However, manual material handling continues to be a hazardous activity, leading to a very significant number of severe overexertion injuries. Neal (1997) pointed out that most workers knew the best way to lift, however, they had less knowledge of the best way to push or pull. In addition, many tests were found in the literature concerning lifting, but only a few concerning pushing and pulling. Of course, the risk factors of pushing and pulling were not well-known. The following section was to investigate the risk factors of WMSDs regarding pushing and pulling activities and the symptoms of this disease.

3.2.1 Risk factors on pushing/pulling

WMSDs can broadly be caused by excessive force, repetition of motion, awkward posture, and environmental conditions as physical factors (Arvidsson et al., 2003; Bernard, 1997; Molteni & De Vito, 2001).

Force is the mechanical effort for accomplishing an action. Voluntary motions and exertions are produced when internal forces are generated from active muscle contraction in combination with passive action of the connective tissues. Internal forces produce torque about the joints and tension, compression, torsion, or shear within the anatomical structures of the body. External forces act against the human body and can be produced by an external object or in reaction to the voluntary exertion of force against an external object. Force is transmitted back to the body and its internal structures when opposing external forces are applied against the surface of the body. Localized pressure against the body can transmit forces through the skin to underlying structures, such as tendons and nerves. Pressure increases directly with contact force over a given area and decrease when the contact area is proportionally increased. Contact stress is produced when forces compress the soft tissues between anatomical structures and external objects. It was reported from various sources that overexertion due to lifting, pushing, pulling, and carrying objects accounted for about 27 percent of all compensable industrial injury and illness in the United States (Chaffin, 1979). Handle height and the magnitude of the exerted force were found to be significantly related to the net moment at the shoulder (Hoozemans et al., 1998).

Repetition is the frequency or rate and duration corresponds to the time that one is exposed. Repetitive work of the upper extremities implies the performance of movements and muscle contraction of the shoulder, arm or hand. The physiological and biomechanical characteristics of repetitive work can be categorized as either intermittent static (i.e. external movements are small or negligible) or dynamic (i.e. movements around joints are easily distinguishable). This type of motion usually relates to the external force or load. Injuries of the wrist and hand constitute the majority of repetitive motion injuries of the upper limb and are also the most disabling and costly. According to a recent study of approximate 186,000 federal workers during the period form 1993 to 1994, for example, carpal tunnel syndrome (CTS) accounted for 93% of all mononeuritis claims and for 67% of all direct medical costs, with an average of $2,948 per claim (Feuerstein et al., 1998).

Awkward posture is the most frequently cited risk factor of WMSDs. Awkward posture at any articulation can result in transient fatigue and discomfort. The awkward posture can be categorized by elevation/abduction for the shoulder, pronation/supination for the elbow and forearm, flexion/extension and ulnar/radial deviation for the wrist, the hand, and pinch grips. In addition, working with stooped posture was one of several occupational risk factors that have been associated with spinal disorders (Friedrich et al., 2000). They concluded that non-neutral static work postures and frequent bending often have been implicated in the risk of occupational-related low back troubles. Subjects who also worked with their hands above shoulder level for 15 minutes were also at an increased risk of shoulder pain. For instance, postal workers had more shoulder pain (32%) than other workers (Harkness et al., 2003). In other study by Harkness et al. (2004), the rates of new-onset widespread pain were 15% at 12 months and 12% at 24 months. Several work place mechanical and posture exposures predicted the new onset of widespread pain: lifting > 15 lbs with 1 hand, lifting > 24 lbs with 2 hands, pulling > 56 lbs, prolonged squatting, and prolonged working with hands at or above shoulder level. Most studies found maximum exerted (horizontal) push forces for handle heights from one meter to shoulder height (Hoozemans et al., 1998; Snook et al., 1978).

Environmental conditions can be described in terms of vibration, excessive temperature, etc. Vibration can cause vasospastic disease (Reynaud's disease) and contributes to carpal tunnel syndrome (Wassermann et al., 1997). Acute and prolonged exposures to heat stress and cold stress reduce the ability of a person physiologically. The loss of blood volume effectively reduces work capacity or fitness, causing fatigue. Short-term fatigue and discomfort have been considered for musculoskeletal syndromes, and have therefore been used as criteria in ergonomic guidelines and standards.

As a result, excessive force, repetition, awkward posture, and environmental factors are generally well-known risk factors for WMSDs. However, those risk factors are sometimes too general to explain the potential risks of pushing and pulling.

Chaffin (1987) reported two types of hazard for pushing and pulling activities. Firstly, the musculoskeletal system could become physically overexerted. Secondly, pushing and pulling were accompanied by an increased risk of accidents due to slipping or tripping. Overexertion was claimed by 60% of low back pain patients as the cause of injury (Pope, 1989). According to him, 66% patients implicated lifting and 20% patients involved in pushing or pulling. Snook et al. (1978) found that 7% of low back injuries were associated with slipping, tripping, and falling. Manning (1983) reported that of 122 accidents causing back pain, 47% were associated with slipping. The percentages mentioned above do not reflect the actual cause of slipping or tripping. However, Manning et al. (1984) showed that 13% of the slipping accidents that resulted in low back pain were associated with pushing and pulling.

Personal factors including age, gender, anthropometry, and previous history of WMSDs are well-known as a risk factor. However, none of the personal factors were significantly related to any of the dependent variables of a pushing activity (van der Beek et al., 2000). It was concluded that gender differences in exerted forces were not caused by differences in anthropometry and maximum capacity, but due to application of different work methods by women in order to balance work demands and work ability.

Of the occupational risk factors studies, physical activities were more strongly associated with neck/shoulder pain than psychosocial variables (Smedley et al., 2003)

3.2.2 Accident-prone body parts from pushing/pulling activities

Several studies have reported that pushing, pulling, and lifting caused back, neck, shoulder complaints (Bernard, 1997; Frymoyer et al., 1980; Garg & Moore, 1992; Hoozemans et al., 1998). Manual material handling (MMH) tasks have been associated with the majority of lower back injuries (Snook et al., 1978). Low back injuries represented the most common and most costly musculoskeletal disorder experienced in the workplace (Marras, 2000). Jobs involving lifting, lowering, pushing, pulling, carrying, and holding; body movements such as frequent bending, twisting, and sudden movements; and working in bent-over postures appeared to have a significant potential for producing low-back pain. A combination of lifting, bending, and twisting appeared to be most hazardous on the back (Garg & Moore, 1992). An increased risk of a new episode of low back pain was found in those whose jobs involved lifting/pushing/pulling objects of at least 25 lbs, or whose jobs involved prolonged periods of standing and walking (Macfarlane et al., 1997). Of ergonomic significance was the finding that the estimated spine compression was substantially greater when asymmetric pulls imposed twisting loads about the spine compared to equivalent symmetric pulls, reflecting the additional muscle activities required to equilibrate the twisting moments (Thelen et al., 1996). In general, the literature of back injuries associated with MMH has been well published. However, the relationship between pushing and pulling and musculoskeletal disorders other than low back pain has not been extensively studied.

The shoulder region and upper extremities could also be at risk. Van der Beek et al. (1993) found a significantly increased risk for pain or stiffness in the neck/shoulder, upper and lower extremities when lorry drivers who regularly pushed and pulled wheeled cages were compared to those who only had a driving task. Physical tasks that required pulling or pushing with the outstretched arm/shoulder carried the highest risk of neck and shoulder symptoms (Smedley et al., 2003). Resnick and Chaffin (Resnick & Chaffin, 1995) measured the rate of perception (RPE) during pushing and pulling of material handling devices. The arm and leg were the body part most stressed, but fatigue or stress of the back was not reported. Garcin et al. (1996) reported the subjects complained of muscle pain in the arm and the back and of articular pains in the shoulders and wrists. In another report (Garg & Beller, 1990), the shoulder was perceived as most stressed during one handed pulling tasks. In conclusion, the shoulder was subjectively perceived as the body part most stressed during pushing and pulling. With respect to shoulders, wrists and elbows, net moments on antagonistic muscles established the required direction for the push/pull force and this can result in mechanically (physiologically) stressful situation.

3.2.3 Symptoms of WMSDs

The term of work related musculoskeletal disorder has been defined by OSHA as a disorder of the muscles, nerves, tendons, ligaments, joints, cartilage, blood vessels, spinal disks, ankle, and foot associated with exposure to risk factors (US Dept of Labor, 2000). The symptoms are various. Pain, weakness, swelling, burning, dull ache, numbness, and tingling are usual symptoms.

Pain is the most common symptom associated with WMSDs. Resulting strain/sprain injuries account for over 50 percent of workman's compensation claims in many industries. Almost two-thirds of these involve back pain, with reported compensation and medical payments totaling well over one billion dollars annually in the United States (Chaffin, 1979). According to previous report, 1505 hospital workers responded that the main cause of sick leave was musculoskeletal disorders and affected 16% of women. Back pain was described by 47% of the women, and treatment for musculoskeletal disorders by 28% (Estryn-Behar et al., 1990).

According to OSHA, these disorders may include muscle strains and tears, ligament sprains, joint and tendon inflammation, pinched nerves, spinal disk degeneration, and medical conditions such as low back pain, tendon neck syndrome, carpal tunnel syndrome, rotator cuff syndrome, DeQuervain syndrome, trigger finger, tarsal tunnel syndrome, sciatica, epicondylitis, tendonitis, Reynaud phenomenon, hand-arm vibration syndrome, carpet layer's knee, and herniated spinal disk (US Dept of Labor, 2000). Data from epidemiological and field studies suggested that there is a relationship between the onset and severity of WMSD and the performance of highly repetitive or forceful work tasks, particularly in harsh (ie, cold or vibrating) environments (Armstrong et al., 1993; Bernard, 1997; Crumpton-Young & Killough, 2000; Garg & Moore, 1992; Kuiper et al., 1999; Latko et al., 1999; Macfarlane et al., 2000; Ranney, 1993; Schoenmarklin et al., 1994; Silverstein et al., 1986; Stock, 1991).

3.3 Anatomy of the hand and the wrist

3.3.1 Skeleton of the hand and the wrist

The hand is composed of many small bones called carpals, metacarpals, and phalanges. The skeleton of the hand consists of the lower end of the forearm articulated with the carpals. The arrangements of those bones form 3 arches that are critical for successful object manipulation. The three arches of the hand, the proximal transverse arch, distal transverse arch, and longitudinal arch, allow the hand to conform to objects being held. This maximized the amount of surface contact which enhances stability and increases sensory input. Loss of these arches results in severe impairment in the functional use of the hands. The proximal transverse arch is at the level of the carpometacarpal joint with the keystone being the capitate. It is a relatively fixed arch, remaining arched even when the hand is open. The distal transverse arch is at the level of the metacarpophalangeal joints with the keystone being the 2^{nd} and 3^{rd} metacarpals. It is relatively mobile. The 1st, 4th, and 5th metacarpals rotate around the 2nd and 3rd metacarpals to either flatten or increase its arc. The carpals are articulated with the metacarpals, and the metacarpals are articulated with the phalanges. The carpals are eight small wrist bones; scaphoid, lunate, triquatral, pisiform, trapezium, trapezoid, capitate, and hamate. The metacarpals are a total of five and phalanges consist of fourteen bones (Figure 3.1).

Carpal bones

The carpals are arranged in two rows (proximal and distal). Each row contains four bones. The bones of the proximal row, from literal to medial, consist of the following four bones; scaphoid, lunate, triquetral, and pisiform. The bones of the distal row, from literal and medial, contains following four bones; the trapezium, trapezoid, capitate, and hamate. The concavity on the palmar side is formed by the tubercles of the scaphoid and trapezium on the radial side and by pisiform and the hook of hamate on the ulnar side. Transverse and longitudinal arches are formed by ligaments and bones.

Metacarpal bones and phalanges

Metacarpal bones consist of a series of five cylindrical shape bones that articulate proximally with the distal row carpal bones and distally with the base of the proximal phalanges of the digits. Each of metacarpal bones has a base (proximal), shaft, and head (distal). Each base of the metacarpal bones is roughly quadrangular, with facets for articulation with the carpal bones of the distal row and the adjacent metacarpals. The carpus and the metacarpals represent an anterior longitudinal and transverse concavity

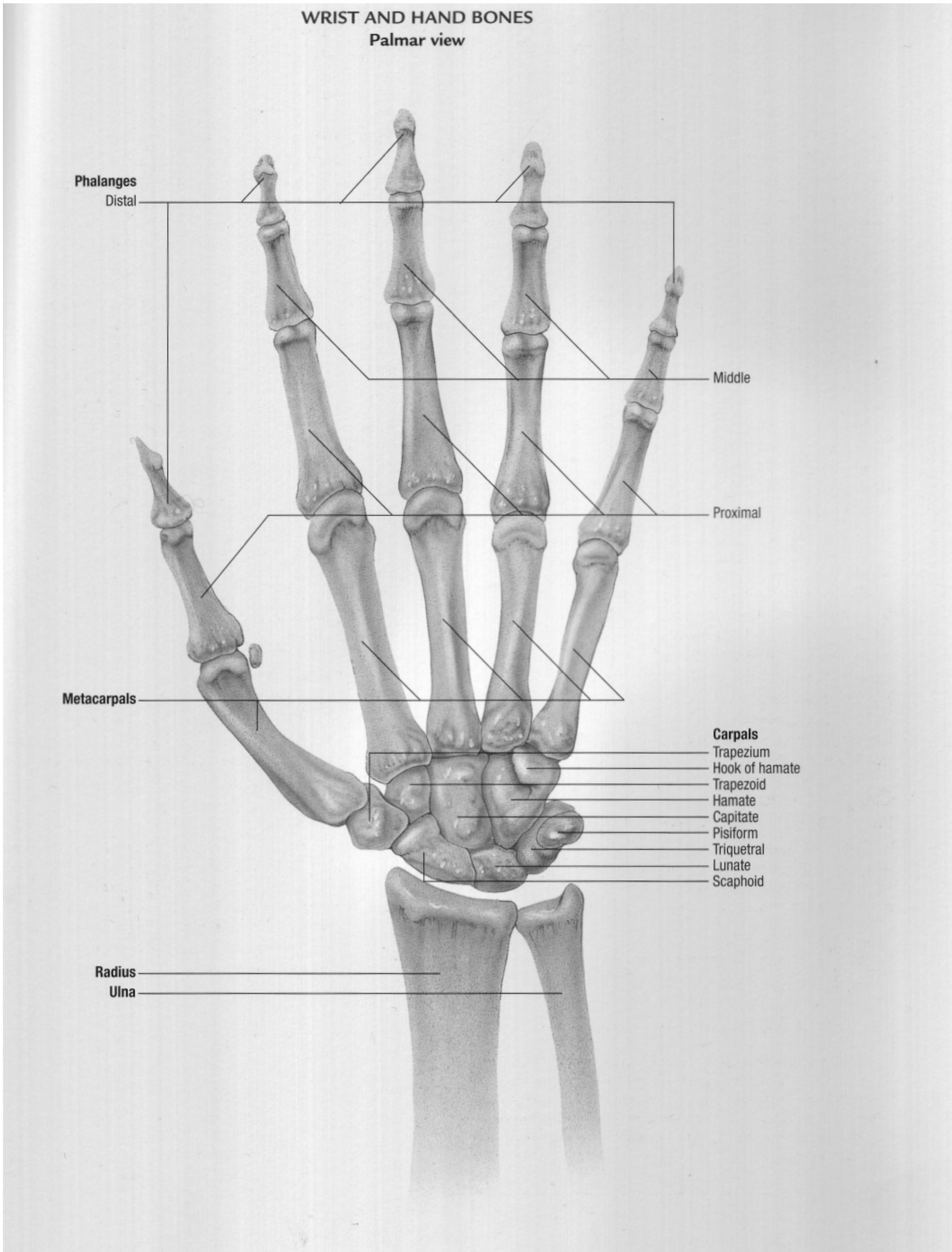


Figure 3.1 Individual carpals, metacarpals, and phalanges (Source: Springhouse Corporation., 2001)

which is filled with all important structures responsible for flexion of the fingers in all the interphalangeal and the metacarpophalangeal joints and also for extension of the 2 distal phalanges. It contains the greatest part of the important nerve supply and blood supply of the hand. The concavity of the carpus and the metacarpals is due to the configuration of the osseous parts and also to the ligamentous apparatus, and is maintained and controlled by the intrinsic muscles of the hand.

All the phalanges represent transverse and longitudinal volar concavities adapted to the transmission of the tedius apparatus controlling flexion of the digits. The body of the phalanx is relatively long and smooth. The proximal end of the phalanx is its base and is concave in shape. The distal end of phalanx is the head and relatively convex. The distal articular surface is smaller than the proximal articular surface. The longest finger is middle and shortest one is ring. Among the phalanges, the proximal phalanx is longer than middle, and the middle is longer than the distal. The general appearance of the proximal and the middle phalanges do not differ much. The heads of the proximal and middle phalanges resemble the distal end of the fumur with the biocondylar type, which generally facilitates flexion and extension and circumduction. The shafts of the phalanges are fairly smooth and convex throughout its length and width. It is somewhat semi-circular in transverse-section, unlike the cylindrical shape of metacarpals. The base is wider than the shaft. The end of the base of each proximal phalanx consists of a concave condyle that articulates with the head of its corresponding metacarpal to form a metacarpophalangeal joint. However, the volar aspect of the shaft of middle phalanx is not as concave as that of the proximal phalanx. The dorsal aspect of the shaft is somewhat narrower proximal to the head and widens toward the base. The distal phalanges differ in contour from the proximal and the middle phalanges. The length of the distal phalanx, with the exception of the thumb, is almost the same for all fingers of the same hand. The base of the phalanx is similar to the base of the middle phalanx.

3.3.2 Joints of the hand

The hand has four joints in each finger (Figure 3.2). From proximal to distal, the joints are distinguished as follows: Carpometacarpal, Metacarpophalangeal, Proximal interphalangeal and Distal interphalangeal joints. The range of motion varies from the different shapes of the joints. However, the motion is possible without difficulty. It is smooth, continuous and powerful. However, the configuration of the joints is changed if the burden of prolonged use or excessive prolonged use or excessive demand is added.

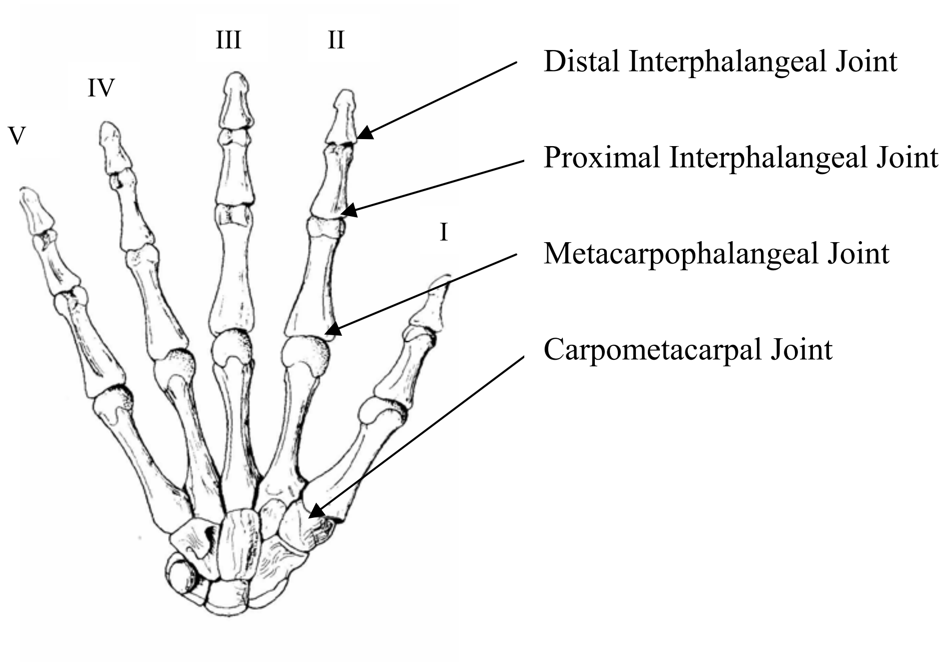


Figure 3.2 Joints of the hand (modified from Calais-Germain, 1993)

Carpometacarpal joint (CMC)

The carpometacarpal joints are the articulations between the distal row of carpal bones and the proximal ends of metacarpal bones of the hand. This joint is a synovial plane joint and limited motion is permitted at this carpometacarpal joint. The carpometacarpal joint is reinforced by dorsal and palmar ligaments. The carpometacarpal joint I (thumb joint) is the articulation between the proximal end of the metacarpal bone of the thumb and the trapezium. This joint is a well-developed saddle joint, and this articulation permits two planes of motion: flexion/extension and abduction/adduction which may be combined to produce circumduction. The base of metacarpal I is rotated 90° from that of metacarpal II. The metacarpal II articulates primarily with the trapezoid and secondarily with the trapezium and capitate. The metacarpal III articulates with the capitate. The metacarpal IV articulates with the capitate and hamate. The metacarpal V articulates with the hamate. Both carpometacarpal joints I and V are saddle joints allowing primarily two degrees of freedom of movement. The carpometacarpal joints II through IV are plane synovial joints allowing one degree of freedom of movement. They allow slightly sliding/gliding and flexion/extension movements. The range of these movements increases progressively from metacarpal II through V. As a result of the anterior curvature of the carpals, the plane of carpometacarpal joints IV and V is oblique to that of joints II and III. Thus, flexion of phalanx V moves it toward the thumb. Likewise, the orientation of metacarpal I causes the thumb to move toward the little finger during flexion. These movements, and orientations of the metacarpals, result in the anterior depression of the palm (Calais-Germain, 1993).

Metacarpophalangeal joint (MP)

The Metacarpophalangeal joints consist of the convex heads of the metacarpals articulating with the concave bases of the proximal phalanges. These are synivial condyloid joints with two degrees of freedom of movement. There are essentially hinge joints for active extension. Limited abduction/adduction and rotation are also possible. When the metacarpophalangeal joints are in extension or slight flexion, passive abduction/adduction and rotation allow the hand to adapt itself to grasp a variety of shapes. When these joints are in a more flexed position, they become less flexible but also stable, which is helpful for feats requiring strength or force (Calais-Germain, 1993). Flexion and extension take place in the sagittal plane and have a range of 100 -120° (90° in flexion and 20-30° in extension from the natural position, respectively). The range of flexion differs among individuals and fingers (i.e., the index finger has the smallest flexion range (about 70°), while the little finger demonstrates the most flexed angle (about 95°)) (Batmanabane & Malathi, 1985). The range of extension from the neutral position also varies considerably among population and individuals depending on joint laxity (Steindler, 1955).

Radial and ulnar deviation occurs in the frontal plane and can be performed voluntary. Although a general range of this movement is 40-60°, it has different ranges with the individual fingers. For example, the range of the index finger is up to 60° abduction and adduction, middle and ring fingers, about 45° and little finger, about 50° of mostly abduction (Steindler, 1955). The range of motion at the MP joint decreases as the flexion angle increases due to the fact that the head of the metacarpals have a biocondylar structure on the palmar side (Schultz et al., 1987; Youm et al., 1978).

The third movement, the axial rotation is much less noticeable and is not usually under voluntary control. When the fingers go from flexion into extension, they rotate axially from a pronated position to a supinated position, and vice versa. This is related to spreading of fingers as in extension, and with cupping and crowding together as they go into flexion (Steindler, 1955).

Distal and proximal interphalangeal joints

The phalanges are the finger bones. The type of articulation between adjacent phalanges is a hinge joint. The proximal interphalangeal joints (PIP) are the articulation between the proximal and the middle phalanges. The distal interphalangeal joint (DIP) is the articulation between the middle and the distal phalanges. These joints are strengthened by volnar and collateral ligaments. Volar ligaments blend with the collateral ligaments such that they pass the flexor tendons. The collateral ligaments of theses joints prevent any side to side translation, and are connected with the expansion sheaths of the extensor tendons.

The largest ranges of flexion from the fingers in neutral position, 100-110°, take place in the PIP joints, while flexion of less than 60-70° occurs in the DIP joints. Extension beyond the neutral position, deemed hyper extension, is a regular feature of the DIP and PIP joints, although it depends considerably on ligament laxity, especially in the PIP joint (Steindler, 1955)

3.3.3 Muscles of the hand

Muscles moving the wrist

Muscles moving the wrist can be divided into those whose primary action is wrist extension (extensor carpi radialis longus, extensor carpi radialis brevis, and extensor carpi ulnaris) and those whose primary action is wrist flexion (flexor carpi radialis, palmaris longus, and flexor carpi ulnaris).

Extensor carpi radialis longus originates from the lateral epicondyle and supracondylar ridge of the humerus. Its tendon passes under the extensor retinaculum and inserts on the posterior base of 2^{nd} metacarpal. It extends and abducts hand at wrist (Fig 3.3).

Extensor carpi radialis brevis arises from the common extensor origin on anterior aspect of lateral epicondyle of humerus. It inserts on the posterior base of 3^{rd} metacarpal. It extends and abducts hand at wrist (Fig 3.3).

Extensor carpi ulnaris originates from the common extensor origin on anterior aspect of lateral epicondyle of humerus. It inserts on the posterior base of 5^{th} metacarpal via groove by ulnar styloid. It extends and adducts hand at wrist (Fig 3.3).

Flexor carpi radialis is a muscle of the human forearm that acts to flex and abduct the hand. This muscle starts at the medial epicondyle of the humerus, passes along the groove of the trapezium, and inserts on the base of metacarpals II and III. It flexes and adducts the wrist, acting on both the radiocarpal and midcarpal joints (Fig. 3.4)

Palmaris longus is a muscle arising from the lateral edge of the radius, in its middle third, lateral to flexor digitorum superficialis and deep to pronator teres. Its tendon passes beneath the flexor retinaculum (carpal canal or tunnel) (to the radial side of

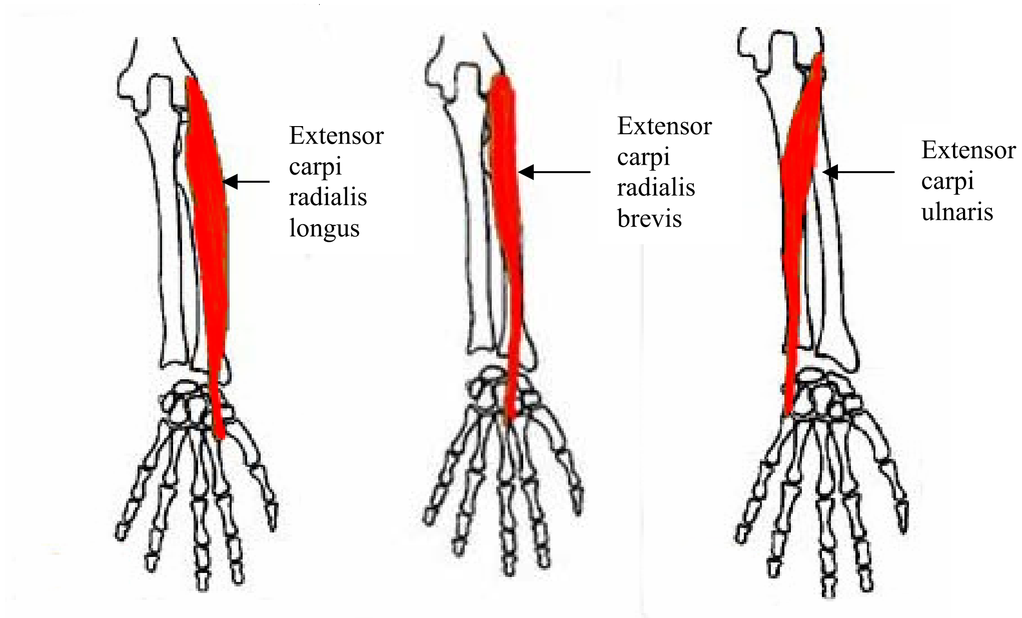


Figure 3.3 Extensors moving the wrist (left to right: Extensor carpi radialis longus, Extensor carpi radialis brevis, and Extensor carpi ulnaris) (modified from Anderson, 1983)

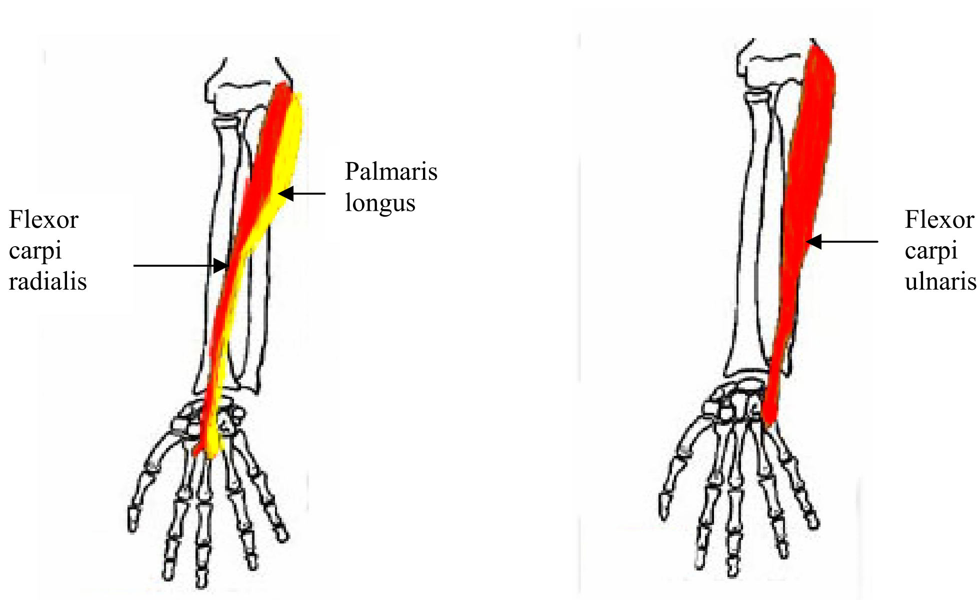


Figure 3.4 Flexors moving the wrist (left to right: Flexor carpi radialis, Palmaris Longus, and Flexor carpi ulnaris) (modified from Anderson, 1983)

the median nerve) and broadens in the palm of the hand to insert into the deep side of the palmar aponeurosis. It is a weak wrist flexor and takes no part in abduction or adduction because of its central location. It is absent in some individuals (Fig. 3.4) (Calais-Germain, 1993).

Flexor carpi ulnaris runs from the common flexor origin along the medial ulna, and inserts on the pisiform, hook of hamate, base of 5^{th} metacarpal via pisohamate and pisometacarpal ligaments. It flexes and adducts the wrist (Fig 3.4).

Muscle moving the fingers

The muscles producing movement of the fingers are divided into two groups, extrinsic and intrinsic, based on an origin of the muscles. The extrinsic muscles are originated from the arm and forearm while the intrinsic muscles are entirely confined to the hand. Therefore, extrinsic muscles are long and provide strength, while intrinsic muscles are short and provide precise coordination of the finger. Each finger is controlled by these two muscle groups. Although the function of each muscle group is different, coordination of the intrinsic and extrinsic muscles is essential for the proper hand movement.

Extrinsic muscles of the hand are divided into two groups based on location and function: the dorsal aspect of the forearm (extensors) and the palmar aspect of the forearm (flexors). The extensors can be divided into those whose primary action is the digit extension (abductor pollicis longus, extensor pollicis brevis, extensor pollicus longus, extensor indicis, extensor digiti minimi, and extensor digitorum) and the flexors can be divided into those whose primary action is the digits flexion (flexor digitorum profundus and flexor digitorum superficialis).

Abductor pollicis longus arises from upper posterior surface of ulna, middle surface of radius, and interosseous ligament, inferior to supinator. The tendon passes under the extensor retinaculum and inserts on the lateral base of 1st metacarpal and trapezium. This muscle abducts and extends thumb at carpometacarpal joint (Calais-Germain, 1993).

Extensor pollicis brevis originates on the lower third of posterior shaft of radius and interosseous membrane, inferior to abductor pollicis longus. The tendon passes under the extensor retinaculum and inserts on the base of the proximal phalanx of the thumb. It extends metacarpophalangeal and carpometacarpal joints of thumb (Fig 3.5).

Extensor pollicus longus originates middle third of posterior ulna and adjacent interosseous membrane, inferior to abductor pollicis longus and superior to extensor indicis. The tendon passes under the extensor retinaculum and inserts on the base of distal phalanx of thumb via Lister's tubercle. It extends interphalangeal and metacarpophalangeal joints of thumb (Fig 3.5).

Extensor indicis arises from the lower posterior shaft of ulna and adjacent interosseous membrane, below the origin of extensor pollicis longus. Its tendon joins that of extensor digitorum leading to 2nd finger and extends all joints of index finger.

Extensor digiti minimi arises from the common extensor origin on anterior aspect of lateral epicondyle of humerus. Its tendon joins that of extensor digitorum leading to 5th finger. It extends all joints of little finger (Fig 3.5).

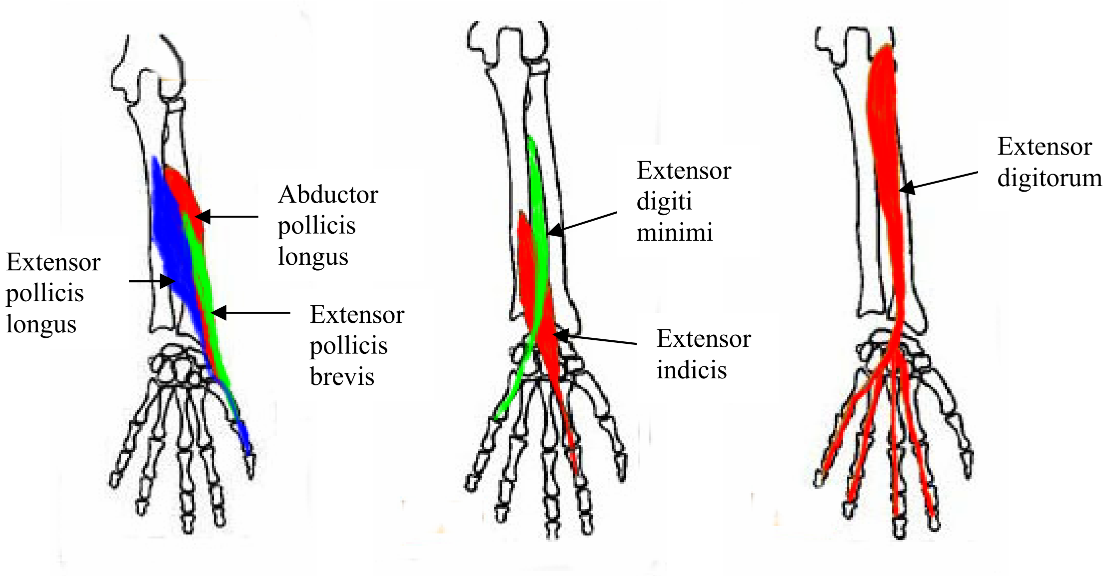


Figure 3.5 Extrinsic extensors moving the fingers (left to right: Extensor pollicis longus, Extensor pollicis brevis, Abductor pollicis longus, Extensor indicis, Extensor digiti minimi, and Extensor digitorum) (modified from Anderson, 1983)

Extensor digitorum originates from the common extensor origin on anterior aspect of lateral epicondyle of humerus and deep fascia of the forearm. It splits into four tendons which pass under the extensor retinaculum. Each tendon in turn splits into three bands, of which the central band inserts on the posterior base of the proximal and middle phalanges, while the two lateral bands reunite at the base of the distal phalanx. It extends all interphalangeal joints of 2nd finger through 5th, as well as the metacarpophalangeal and wrist joints (Fig 3.5) (Calais-Germain, 1993).

Flexor digitorum profundus originates from medial olecranon, upper three quarters of anterior and medial surface of ulna as far round as subcutaneous border and narrow strip of interosseous membrane which connects the ulna and radius. It splits into four tendons which pass through the carpal tunnel and inserts on the distal phalanges of

2nd through 5th fingers. It flexes distal interphalangeal joints, and then secondarily flexes proximal interphalangeal and metacarpophalangeal joints and wrist (Fig 3.6).

Flexor digitorum superficialis has three heads: humeral head from common flexor origin of medial epicondyle humerus, medial ligament of elbow, and ulnar head from anterior oblique line. It splits into four tendons which pass through the carpal tunnel and redial border of coronoid process and fibrous arch, and radial head from whole length of inserts bilaterally on the middle phalanges of 2nd through 5th finger. It flexes proximal interphalangeal joints and secondarily metacarpophalangeal joints and wrist (Fig 3.6). Intrinsic muscles originate at wrist and hand structures. They are divided into four

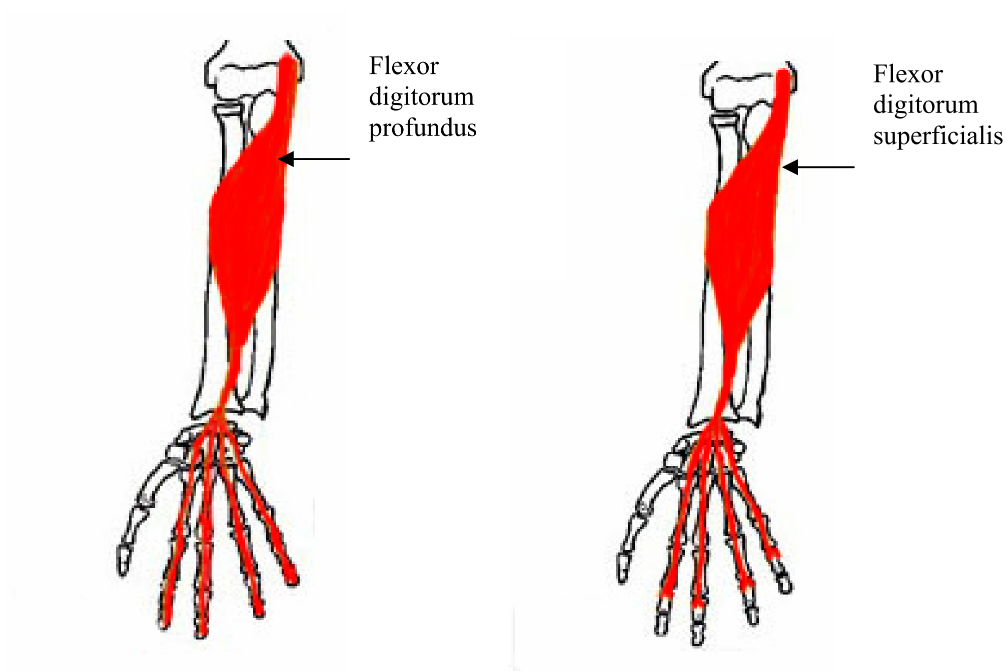


Figure 3.6 Extrinsic flexors moving the fingers (left to right: Flexor digitorum profundus and Flexor digitorum superficialis) (modified from Anderson, 1983)

compartments: the thenar, the hypothenar, the central, and the adductor compartments. The thenar muscles are chiefly responsible for opposition of the thumb and resides in the thenar eminence. The thenar muscles consist of abductor pollicis brevis, flexor pollicis brevis, and opponens pollicis. The hyperthenar muscle group of the medial side of the hand act on the little finger. This muscle group consists of abductor digiti minimi, flexor digit minimi, and opponens digiti minimi. The central compartment includes lumbricals and interossei associated with long flexor tendons. This muscle group acts on all the phalanges except the thumb. The adductor compartment includes adductor pollicis.

Abductor pollicis brevis arises from the flexor retinaculum, scaphoid, and trapezium, and inserts on the lateral base of the proximal phalanx of the thumb next to the flexor pollicis brevis. It acts abduction at the 1^{st} metacarpophalangeal and carpometacarpal joints, plus some medial rotation (Fig 3.7).

Flexor pollicis brevis lies medial to abductor pollicis brevis and originates from flexor retinaculum and tubercle of trapezium. It inserts on the lateral base of the proximal phalanx of thumb via radial sesamoid located at the 1^{st} metacarpophalangeal joint. It flexes the metacarpophalangeal joint of thumb (Fig 3.7).

Opponens pollicis has an origin from flexor retinaculum and tubercle of trapezium. It inserts on lateral shaft of the 1^{st} metacarpal. It draws the 1^{st} metacarpal bone laterally to oppose thumbs toward center of palm and rotates it medially. This action is important in grasping movements (Fig 3.7).

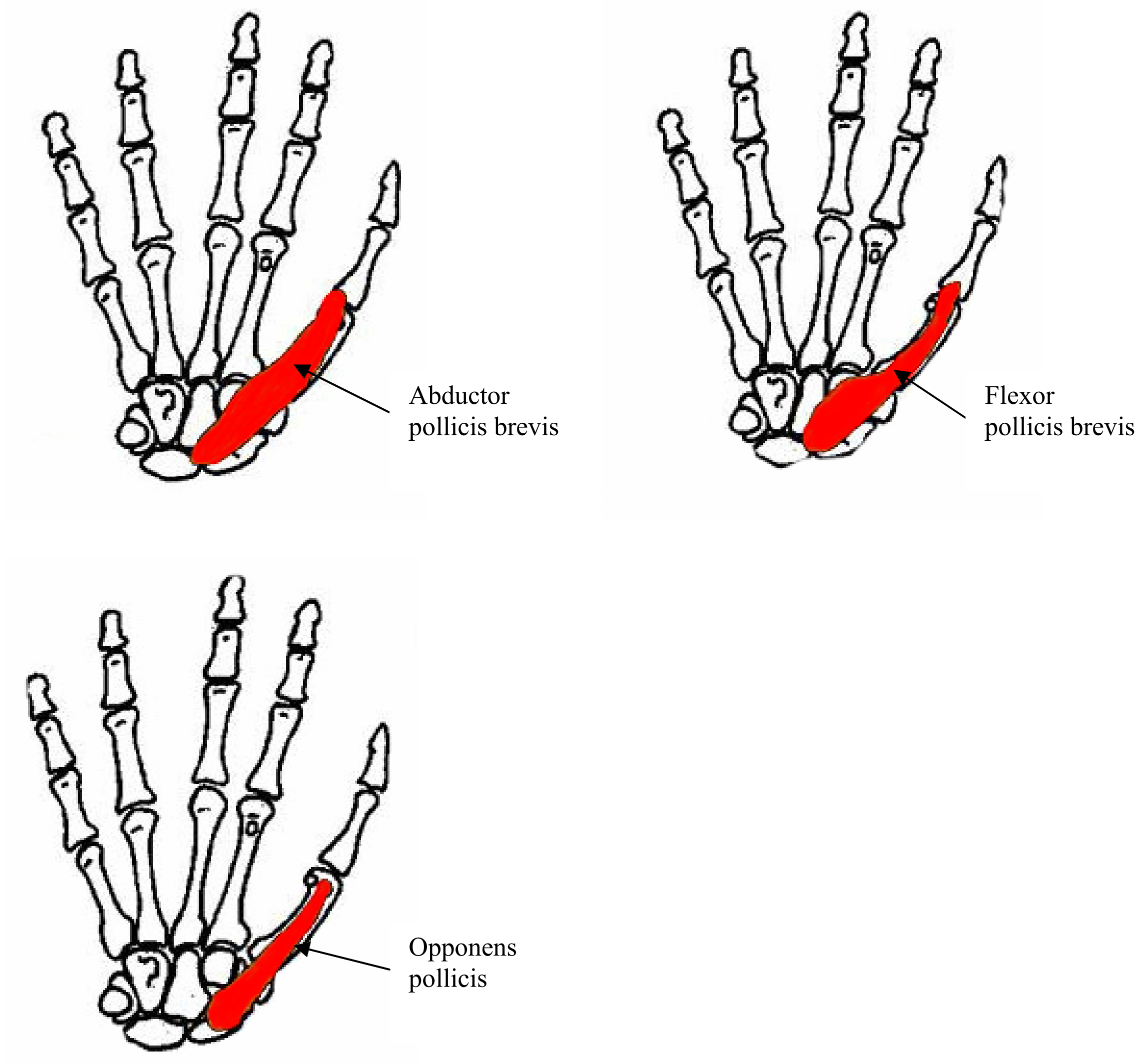


Figure 3.7 Intrinsic thena muscles moving the fingers (left to right: Abductor pollicis brevis, Flexor pollicis brevis, and Opponens pollicis) (modified from Anderson, 1983)

Abductor digiti minimi originates from the pisiform bone, pisohamate ligament and flexor retinaculum. It inserts on the ulnar side of base of proximal phalanx of the little finger and extensor expansion. It abducts the little finger at metacarpophalangeal joint (Fig 3.8).

Flexor digit minimi arises from the flexor retinaculum and the hook of hamate. It inserts on the ulnar side of the base of proximal phalanx of the little finger. It flexes the metacarpophalangeal joint of the little finger (Fig 3.8).

Opponens digiti minimi originates from the flexor retinaculum and the hamates hook, and inserts on the ulnar surface of the 5th metacarpal. It draws the 5th metacarpal anteriorly and rotates it, bringing digit 5 into opposition with the thumb (Fig 3.8).

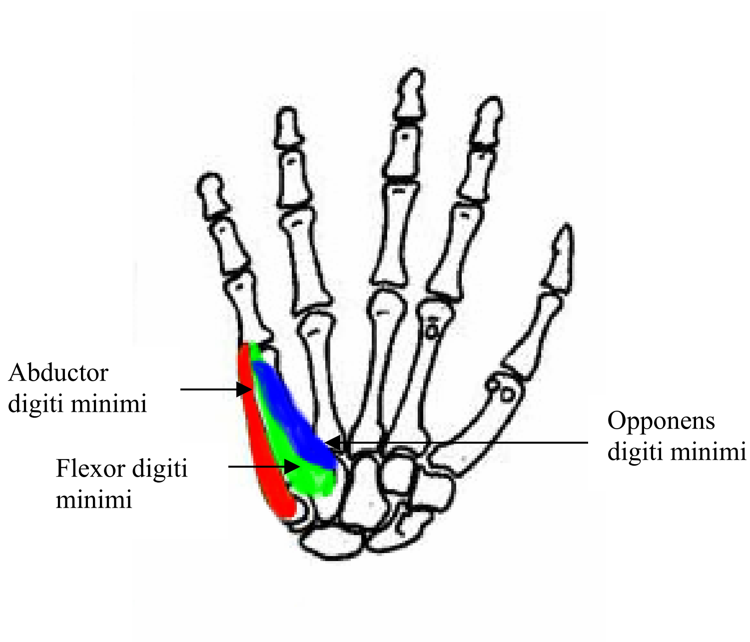


Figure 3.8 Intrinsic hyperthenar muscles moving the fingers (left to right: Abductor Digiti minimi, Flexor digiti minimi, and Opponens digiti minimi) (modified from Anderson, 1983)

Lumbricals associated with long flexor tendons originates from tendons (2 radial sides and 2 ulnar sides) of flexor digitorum profundus. It inserts on the tendons of extensor digitorum. They flex metacarpophalangeal joints and extend interphalangeal joints of the fingers (Fig 3.9).

The interossei are small muscles originating from the metacarpals and inserting on the phalanges. There are four dorsal and three palmar interossei. Four dorsal interossei insert on the proximal phalanges and the dorsal extensor expansion on the radial side of the index and middle fingers and the ulnar side of the middle and ring fingers. They abduct from the axis of the middle finger and flex metacarpophalangeal joint while extending interphalangeal joints. On the other hand, three palmar interossei insert on the proximal phalanges and dorsal extensor expansion on the ulnar side of the index and the radial side of the ring and little fingers and to the ulnar sesamoid of the thumb. They adduct to the axis of middle finger and flex the metacarpophalangeal joint while extending the interphalangeal joints (Fig 3.9). The interossei and lumbricals put the fingers in position for holding a pencil or small object.

Adductor pollicis lies deep to the flexor tendons in the palm and has two origins: oblique head from the base of 2^{nd} and 3^{rd} metacarpals, trapezoid and capitate and transverse head from the anterior surface of body of the 3^{rd} metacarpal. It inserts on the ulnar side of base of the proximal phalanx of the thumb. It adducts the carpometacarpal joint of thumb toward the middle digit (Fig 3.10). These intrinsic muscles make possible the fine and precise finger movements and independent action of each phalanx such as abduction/adduction of the fingers, thumb and little finger movements and also flexion/extension of the fingers.

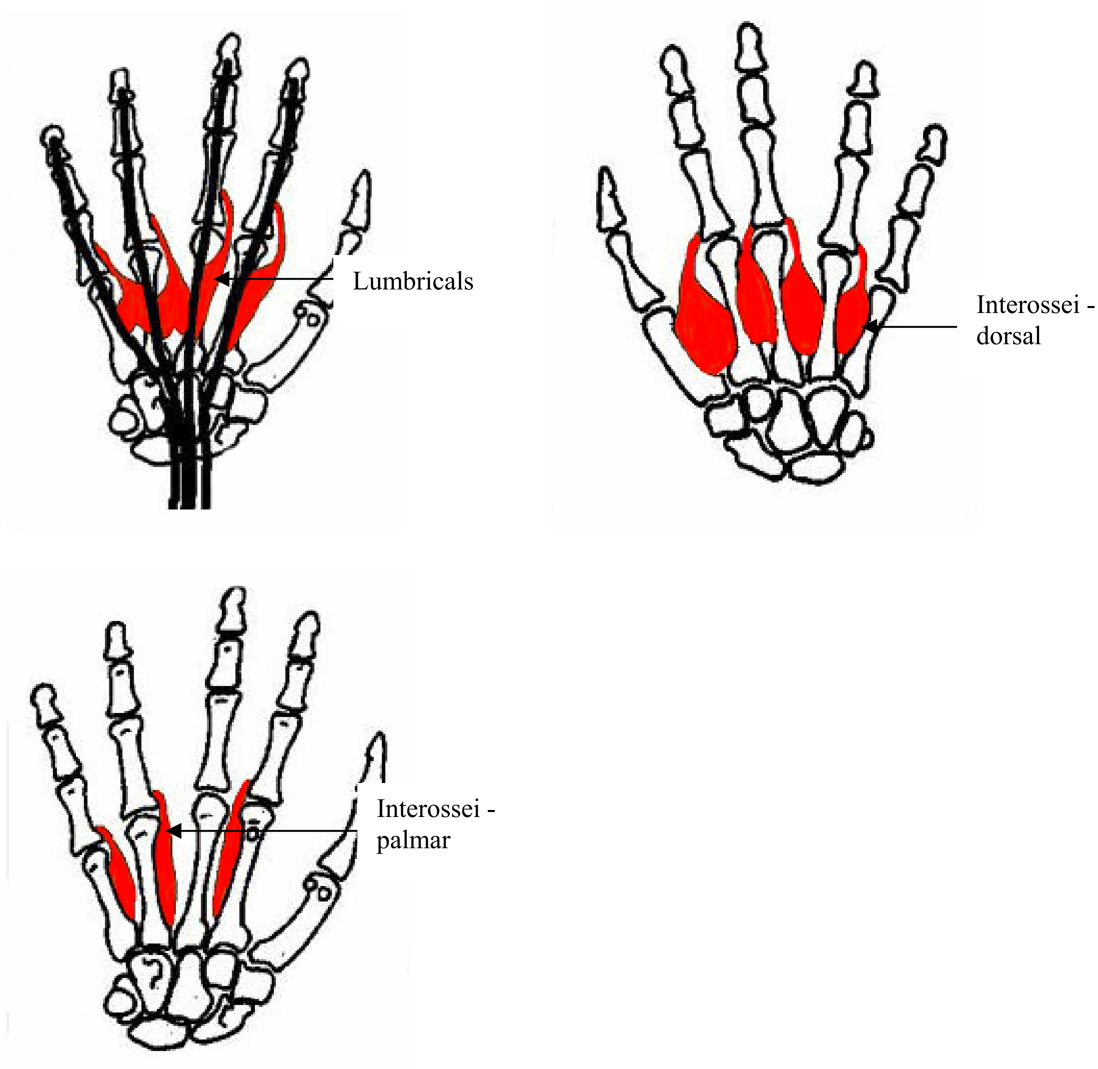


Figure 3.9 Intrinsic central muscles moving the fingers (left to right: Lubricals, Interossei - dorsal, and Interossei - palmar) (modified from Anderson, 1983)

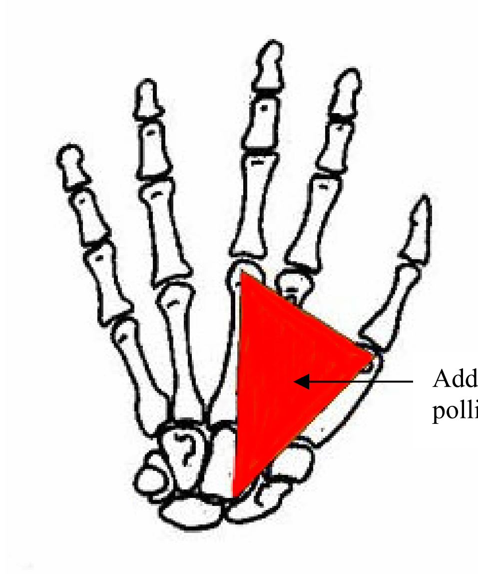


Figure 3.10 Intrinsic adductor muscles moving the fingers (Adductor pollicis) (modified from Anderson, 1983)

CHAPTER 4 DEVELOPMENT OF MECHANICAL MODELS FOR PREDICTING PULLING FORCE ON A LUGGAGE CARRYING ACTIVITY

4.1 Mechanical models for pulling force prediction

Luggage is an example of simple transportation methods which multiply forces. Thus, one can transport a heavy load with a smaller force than is required to lift the load using one's body. Once the load is lifted off the ground, the luggage uses wheels to expedite moving the load elsewhere. Well-designed luggage allows the traveler to comfortably apply pulling force without any potential injury source.

The operation of luggage pulling can be described in five steps:

1. Pushing down luggage. The luggage is stabilized after luggage is tilted.
2. Initial pulling force is exerted to start movement of a luggage. The force of surface friction placed on the loaded luggage by the floor.
3. Apply pulling force on balanced and loaded luggage to move in the forward direction. The rolling force placed between wheels and floor.
4. When the destination is reached, the luggage will be stopped.
5. The luggage is positioned to upright.

The following mechanical models were focused on the static, initial, and sustained stages. Ending stage was not considered in this study since the luggage generates similar pushing force compared to pulling force in initial stage (Jansen et al., 2002). The mechanical models were developed with three steps. First, a mechanical model on static status was developed to find the optimal luggage tilted angle based on a ratio of force by weight (F/W). Second, other mechanical models for predicting pulling force in initial and sustained stages were developed. Finally, the three cases were evaluated with the mechanical models and the important influent factors to minimize the pulling force in each motion stages were found.

4.1.1 Static status

In the static stage, the luggage was considered at a stand position without any horizontal movement. For a mechanical model, we assumed that loads were evenly distributed because the modeling is impossible to be developed if the center of mass is changed by different loading distribution. Figure 4.1 showed an airport luggage and its free-body diagram when it was held in equilibrium in the tilted position. The force F_y that the user should exert to maintain luggage balanced can be calculated by following equations.

$$\sum M_{(point\,C)} = d\left(F_y \cos\alpha\right) + a\left(W \sin\alpha\right) - b\left(W \cos\alpha\right) = 0,$$

and solving for F_y, we obtained

$$F_y = \frac{\left(b - a\tan\alpha\right)W}{d} \tag{4.1}$$

Equation (4.1) was ideal for finding an optimal tilted angle (α) with less vertical force (F_y) as d was fixed. If d is fixed, more or less tilted angles have influence on pulling force and more or less arm angles result in awkward arm posture. Those factors

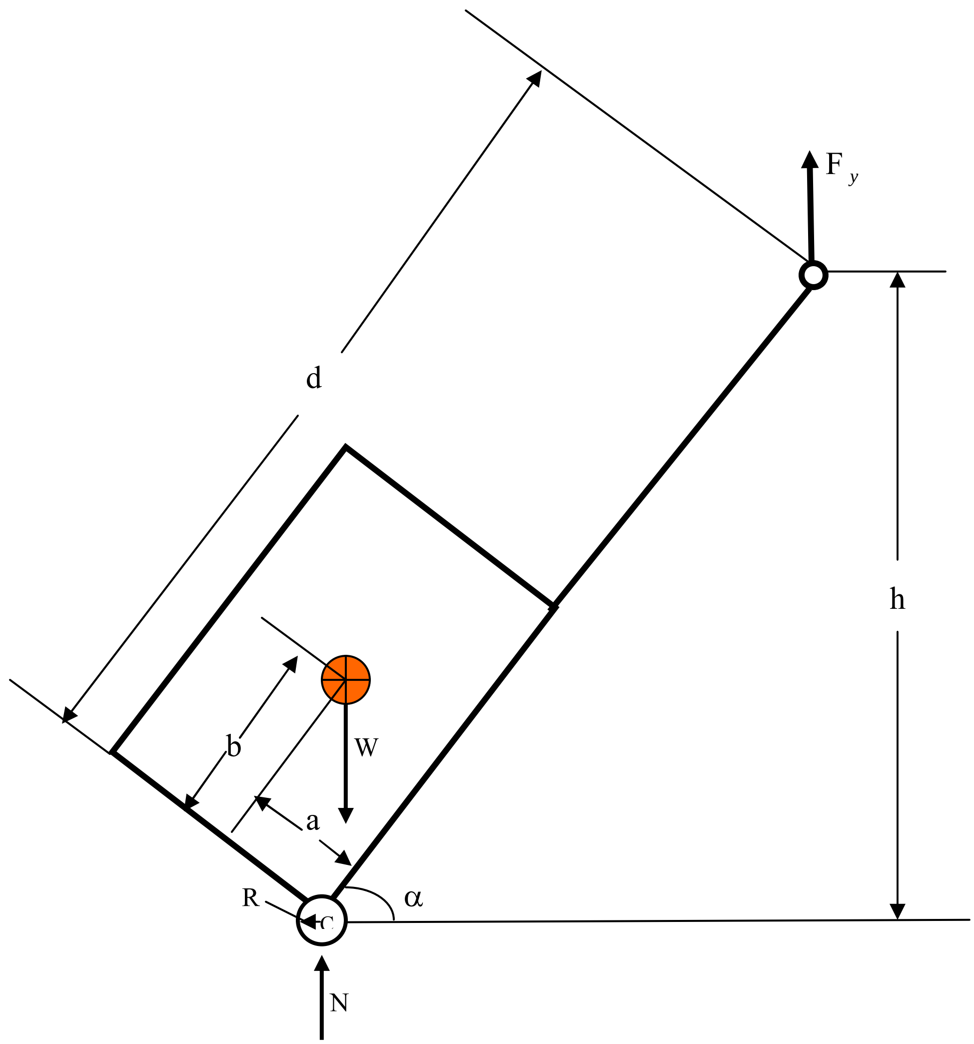


Figure 4.1 The free diagram of luggage with a tilted angle in the static status

may be sources of musculoskeletal disorders. Thus, the users tend to adapt their posture to a comfortable level while they pull the luggage. The height of the handle from the ground (the dimension h) needs to be adjusted by the users. Therefore, the equation (4.1) should be reconstructed by user characteristics (anthropometry) for better application.

Since $h = R + d\sin\alpha$, we obtained a relationship between the length of the handle (d) on upright position and the tilt angle (α):

$$d = \frac{h - R}{\sin\alpha} \tag{4.2}$$

substituting this expression for d into (4.1), we obtained

$$F_y = \frac{\sin\alpha(b - a\tan\alpha)W}{h - R} \tag{4.3}$$

where

M = Moments

F_y = Vertical force due to normal force

N = Normal force exerted by ground

α = Tilted angle of luggage

W = Total weight of luggage

d = Handle length on upright position

a = Distance between center of mass and the side of luggage

b = Distance between center of mass and the bottom of luggage

h = Height between the ground and the handle with tilted angles (pulling height)

R = Radius of a wheel

4.1.2 Initial stage

In the initial stage, initial force is exerted to start movement of a luggage. The initial force is significantly higher than the force exerted to sustain movement. The minimum combined force is required to initiate luggage movement. The minimum horizontal force is better from a physics point of view, but a minimum combined force should be considered for users since the combined force affects to a user's hand and arm rather than horizontal force (Figure 4.2).

The following model was proposed to find minimum combined force as considering luggage tilted angles, pole length, and users' anthropometry data. To develop the model, we assumed that the unknown reactions on the free-body diagram were the vertical force F_y horizontal force F_x, combined force F_c and the normal force N exerted by the floor. In this stage, a friction affected only horizontal force. General properties of the static friction are as follows:

1. The maximum force of static friction that exists between two surfaces is proportional to the normal force and the object's weight. Thus, if the weight of the object is increased by 20 percent, then the required horizontal force is also increased by 20 percent.

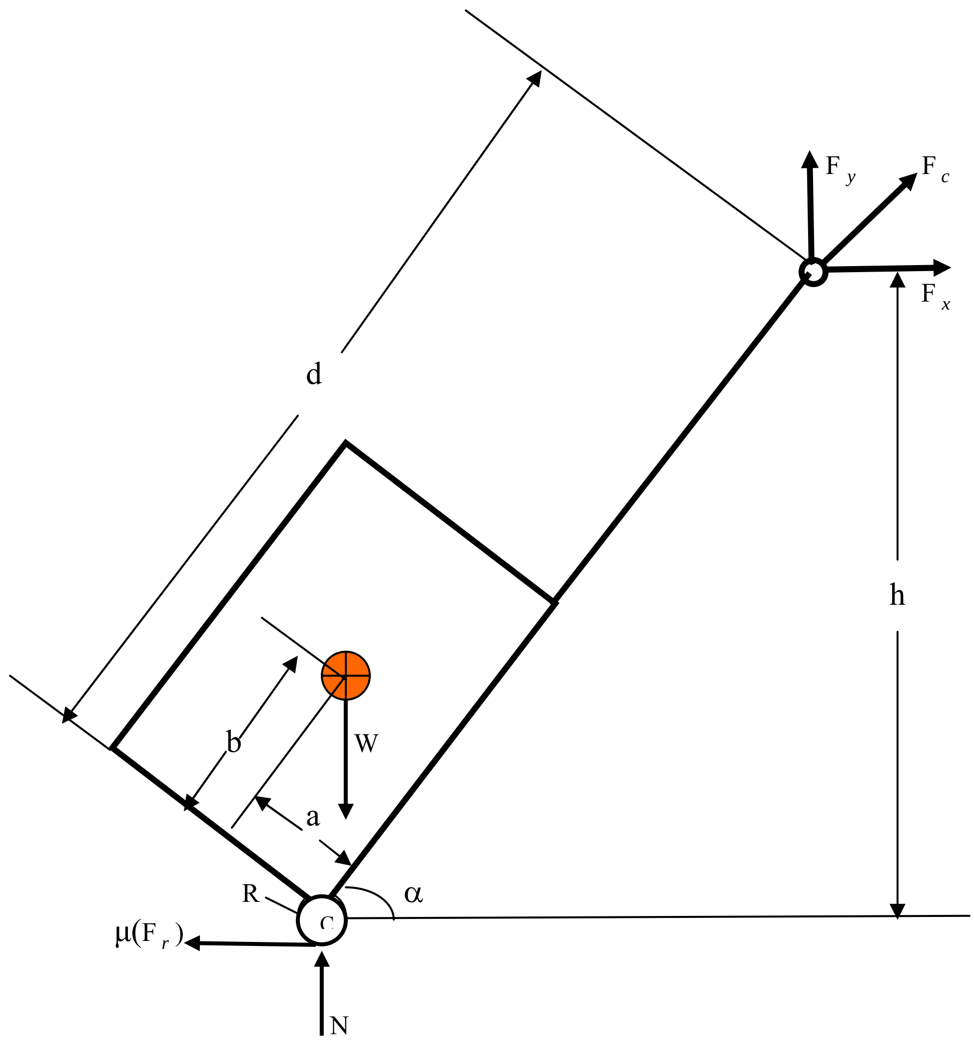


Figure 4.2 The free diagram of luggage with a tilted angle in the initial and sustained stages

2. The magnitude of the static friction force has a maximum value $f_{s,\max}$ that is given by $f_{s,\max} = \mu_s N$, where μ_s is the coefficient of static friction and N is the magnitude of the normal force. If the magnitude of the component of F that is parallel to the surface exceeds $f_{s,\max}$ then the body begins to slide along the surface.
3. Dynamic friction is lower than static friction. If the body begins to slide along the surface, the magnitude of the frictional force rapidly decreases.
4. The friction force does not depend on how much area of the object is in contact with the surface.
5. The friction force does not change when velocity changes. Thus, the friction force at a higher sliding speed would be the same as that at a lower sliding speed.
6. The friction force does not change when the temperature changes. That is, the friction force is the same for an object sliding over a surface at 80º F as it is at 20º F.

In the mechanical model, the static friction (maximum value $f_{s,\max}$) used was 0.9 with the assumption of the friction between rubber and concrete. Therefore, the maximum possible load on the surface was calculated in the mechanical model. Table 4.1 showed coefficients of friction between various common materials (Serway & Faughn, 2003).

In considering the friction force, the summing of moments about c was as follows.

$$\sum M_{(po\operatorname{int} C)} = d\left(F_y \cos\alpha\right) + a\left(W \sin\alpha\right) - b\left(W \cos\alpha\right) - d\left(F_x \sin\alpha\right) = 0,$$

Table 4.1 Coefficients of static and kinetic friction between various common materials

	Static friction (μ_s)	Kinetic friction (μ_k)
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Wood on wood	0.25-0.50	0.2
Glass on glass	0.94	0.4
Rubber on concrete (dry)	0.9	0.8
Rubber on concrete (wet)	0.3	0.25
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	---	0.04
S teel on ice	0.10	0.06
Metal on metal (lubricated)	0.15	0.06
Ice on ice	0.1	0.03
Teflon on Teflon	0.04	0.04
Synovial joints in humans	0.01	0.003

and general terms of F_y and F_x were expressed as

$$F_y = W - N$$

$$F_x = \mu N$$

Then, $W - N$ and μN was replaced into F_y and F_x, respectively.

$$d(W - N)\cos\alpha + aW\sin\alpha - bW\cos\alpha - d\mu N\sin\alpha = 0$$

From this equation, we obtained

$$N = \frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + \mu\sin\alpha)} \tag{4.4}$$

Therefore, F_y and F_x were expressed as follows:

$$F_y = W - \frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + \mu\sin\alpha)} \tag{4.5}$$

$$F_x = \mu\frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + \mu\sin\alpha)} \tag{4.6}$$

$$F_c = \sqrt{F_x^2 + F_y^2} \tag{4.7}$$

where

F_y = Vertical force on the handle

F_x = Horizontal force

F_c = Combined force

μ = Coefficient of friction

4.1.3 Sustained stage

In the sustained stage, users exert force through the handle while the wheel has fully rotated. In this stage, the friction on the ground was not considered anymore. A new friction, rolling friction, was introduced while luggage is moving. The rolling friction is significantly lower than the friction on the ground. Therefore, the pulling force in this stage should also be significantly decreased. General properties of the static friction are as follows:

1. When the wheel rolls, it requires a certain amount of frictional force, at least, some force which can make the wheel not slip.
2. Assume that a wheel is rolling without slipping, the surface friction does not work against the motion of the wheel and no energy is lost at that point.
3. When the wheel has fully rotated, but where the wheel touches the ground surface, there is, momentarily, no movement relative to the ground surface. Compared to the luggage's speed, the speed of the wheel in contact with the ground is then 0 percent.

The following equations were rewritten considering the new friction. In the mechanical model, the static friction used was 0.01 with the assumption of the friction between hardrubber and concrete. Table 4.2 showed coefficients of friction between various common materials (Serway & Faughn, 2003).

Summing moments about c,

$$\sum M_{(po\operatorname{int}C)} = d\left(F_y \cos\alpha\right) + a\left(W \sin\alpha\right) - b\left(W \cos\alpha\right) - d\left(F_x \sin\alpha\right) = 0,$$

Table 4.2 Coefficients of rolling friction between various common materials

	Rolling friction (f_r)
Steel on steel	0.0005
Wood on steel	0.0012
Wood on wood	0.0015
Iron on iron	0.00051
Iron on granite	0.0021
Iron on wood	0.0056
Polymer on steel	0.002
Hardrubber on steel	0.0077
Hardrubber on concrete	0.01-0.02
Rubber on concrete	0.015-0.035

and general terms of F_y and F_x were expressed as

$$F_y = W - N$$

$$F_x = f_r N$$

Then, $W - N$ and $f_r N$ were replaced into F_y and F_x, respectively.

$$d(W - N)\cos\alpha + aW\sin\alpha - bW\cos\alpha - df_r N\sin\alpha = 0$$

From this equation, we obtain

$$N = \frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + f_r\sin\alpha)} \tag{4.8}$$

Therefore, F_y and F_x were expressed as follows:

$$F_y = W - \frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + f_r \sin\alpha)} \tag{4.9}$$

$$F_x = f_r \frac{W(d\cos\alpha + a\sin\alpha - b\cos\alpha)}{d(\cos\alpha + f_r \sin\alpha)} \tag{4.10}$$

$$F_c = \sqrt{F_x^2 + F_y^2} \tag{4.11}$$

where

F_r = Coefficient of rolling friction

4.2 Model application

4.2.1 The effects of tilted angles, pulling heights, and handle heights in the static status

This example was used to find a proper tilted angle. The proper angle makes luggage balanced and requires minimum pulling force. Suppose that, based on statistical data on human dimensions, we decided to design the luggage for convenient use by persons up to 6 ft 2 in. tall. Let R = 1.5 in, a = 5 in, b = 11 in, and d = 38.5 in. The resulting value of F_y / W as a function of α was shown in Figure 4.3. At $\alpha = 65.56^\circ$, the user must exert zero force, which means the weight of the luggage acts at a point directly

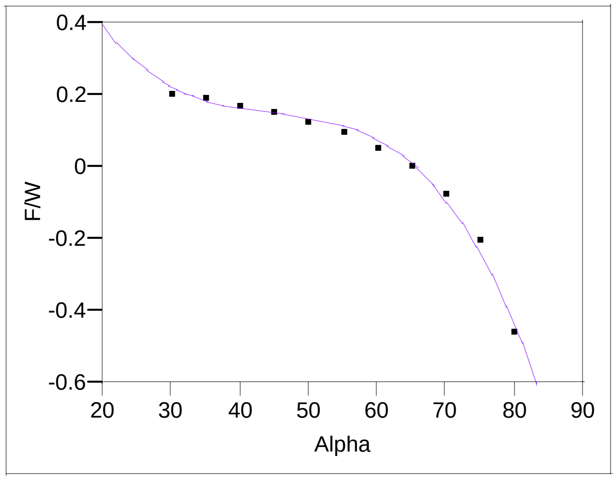


Figure 4.3 Graph of the ratio F_y / W as a function of α in static status.

above the wheels. This would be the optimum solution if the user could maintain exactly that value of α . However, the optimal pulling height for all users (h =36.547 in) were severely higher than users' knuckle heights while they maintained the optimal tilted angle. In this study, we assumed that the optimal pulling height is user's knuckle height since the user did not have any awkward arm posture at the level in his standing position. Thus, the height of inclined luggage should be close to users' knuckle height, but not lower (Table 4.3). If the height is lower than users' knuckle height, the upper body should be inclined to right or left. This motion substantially results in musculoskeletal disorders. If the height is severely higher than users' knuckle height, the upper arm needs more flexion.

The flexion results in more stress on upper arms. Therefore the pulling height is an important factor for substantial injuries.

Table 4.3 Knuckle height of civil population (Sanders & McCormick, 1993)

Subjects	5%ile male	5%ile Female	50%ile male	50%ile Female	95%ile male	95%ile Female
Knuckle height	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in

To find the important factors affecting the minimum F_y / W, we conducted analysis with three cases.

For the first case, we had assumptions as following.

1. The optimal tilted angle (α) is maintained with 65.56°.
2. The luggage should be balanced (F_y=0).
3. The pulling height (h) is set by the luggage height (d) and the tilted angle (α).
4. The load is 50 lbs.
5. The dimension of luggage is 22"×14"× 10" with d = 38.5".

The decision to either accept or not accept was done by comparing the pulling height and user's knuckle height. If the calculated pulling height was lower or severely higher than the user's knuckle height, the design of the luggage was not accepted. The result showed that the luggage was totally balanced when d and tilted angles (α) were fixed. However, the pulling height was absolutely higher than the users' knuckle heights. The result was shown in Table 4.4.

For the second case, the dimensions of luggage were not changed, but the pulling force was set to the users' knuckle height. Here were the assumptions for the second analysis.

1. The optimal tilted angle should be variable depending on user's knuckle height.

Table 4.4 The ratio F_y/W and F_y as a function of α (Case 1: fixed d = 38.5 in and maintained α =65.56°)

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle*	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree
h*	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in
d*	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
F_y (lbs)	0	0	0	0	0	0
F_y/W	0	0	0	0	0	0
Decision	Do not accept	Do not accept	Do not accept	Do not accept	Do not accept	Do not accept

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; *: fixed variables)

2. The pulling height is set to user’s knuckle height.
3. The load is 50 lbs.
4. The dimension of luggage is 22"×14"× 10" with d = 38.5”.

The decision making of acceptance was done by F_y value comparing to balanced force (F_y=0). If the vertical force was exceeded to balanced force, the design of luggage was not accepted. The result showed that luggage was balanced for all user groups. However, the vertical force resulted since the tilted angle was not optimal. The result was shown in Table 4.5.

For the last case, the height of the handle from ground (the dimension *h*) to the users’ knuckle height was fixed while tilted angles were maintained with the optimal angle. The handle height on the upright position was calculated by h and α values.

Table 4.5 The ratio F_y/W and F_y as a function of α (Case 2: fixed d = 38.5 in and maintained h = user's knuckle height)

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle	Approxima-tely 42.5degree	Approxima-tely 38.2 degree	Approxima-tely 47.1 degree	Approxima-tely 42.7 degree	Approxima-tely 51.7 degree	Approxima-tely 47.6 degree
h*	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
d*	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
F_y (lbs)	8.51	9.36	7.44	8.3	6.07	7.18
F_y/W	0.1668	0.1836	0.146	0.166	0.1215	0.1438
Decision	Do not accept	Do not accept	Do not accept	Do not accept	Do not accept	Do not accept

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; *: fixed variables)

The assumptions for last analysis were following.

1. The optimal tilted angle (α) is 65.56°.
2. The optimal pulling heights are users' knuckle heights.
3. The load is 50 lbs.
4. The dimension of luggage is 22"×14"× 10".
5. The handle length should be variable based on user's knuckle height.

The decision making of acceptance was done by F_y value comparing the balanced force (F_y=0). If the vertical force exceeded the balanced force, the design of luggage was not accepted. The result showed that the luggage was totally balanced while the optimal tilted angle was maintained. The result was shown in Table 4.6.

Table 4.6 The ratio F_y/W and F_y as a function of α (in case of fixed h = user's knuckle height and α =65.56°)

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle *	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree
h*	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
D	28.6 in	26.1 in	31.0 in	28.7 in	33.2 in	31.2 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
F_y (lbs)	0	0	0	0	0	0
F_y/W	0	0	0	0	0	0
Decision	Accept	Accept	Accept	Accept	Accept	Accept

Note: Suggested luggage design (The dimension of luggage: 22"×14"×10" with an adjustable handle;
*: fixed variables)

Based on three cases, users are less comfortable if they are restricted with a fixed handle height (d) and a specific tilted angle (α) (case 1 and case 2). To maintain the optimal tilted angle while d was fixed, the awkward arm posture was not avoidable (case 1). If users maintained the pulling height to their knuckle levels with a fixed d, the vertical force should result (case 2). The results showed users need more force to hold luggage. Providing an adjustable handle was very important for the users' health (case 3). The vertical force was zero while the optimal angle can be maintained. For 5 %tile females, a 26.1 inch-handle was suitable while a 28.6 inch-handle was suggested for 5 %ile males and 50 %ile females. In addition, a 31 inch-handle was suggested for 50 %tile males and 95 %tile females while a 33.2 inch-handle was suggested for 95 %tile males. As a result, different handle height should be suggested depending on users' characteristics. Particularly, installation of four holes on the handle should be helpful to reduce vertical force for maintaining luggage balance for all user groups.

4.2.2 The effects of tilted angles, pulling heights, and handle heights in the initial phase

In 4.2.2, the effects of tilted angles, pulling heights, and handle heights for luggage users in the initial stage were investigated. Three cases (fixed d and maintained the optimal angle, fixed d and maintained pulling height to the user's knuckle height, and maintained pulling height to the user's knuckle height and the optimal tilted angle) were compared. The assumptions for each case were still valid. The results were provided as a combined pulling force rather than a vertical force since the pulling force is generated horizontally and vertically as soon as luggage is pulled.

In the analysis of case 1, a fixed d (= 38.5 in) while maintaining the optimal angle (α = 65.56°) were assumed. The combined force was 36.493 lbs (= 162.321 N) for all user groups (Table 4.7). However, this combined force had different effects to each group users' wrist and arm since the pulling height was positioned above their knuckle heights. This pulling force resulted in the user's awkward wrist and arm posture. Figure 4.4 showed the relationship between combined force and tilted angles when d was fixed. The combined force was least at a tilted angle of 25° (F_C = 33.451 lbs for all user groups). However, the pulling height at 25° was lower than the user's knuckle height. Thus, the combined force (F_C = 34.627 lbs) was minimum at α = 50° by considering optimal pulling heights.

Table 4.7 The combined force as d and α are fixed in the initial phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle*	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree
H	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in
d*	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lbs)	33.223	33.223	33.223	33.223	33.223	33.223
Horizontal Force (lbs)	15.1	15.1	15.1	15.1	15.1	15.1
Combined Force (lbs)	36.493	36.493	36.493	36.493	36.493	36.493

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; *: fixed variables)

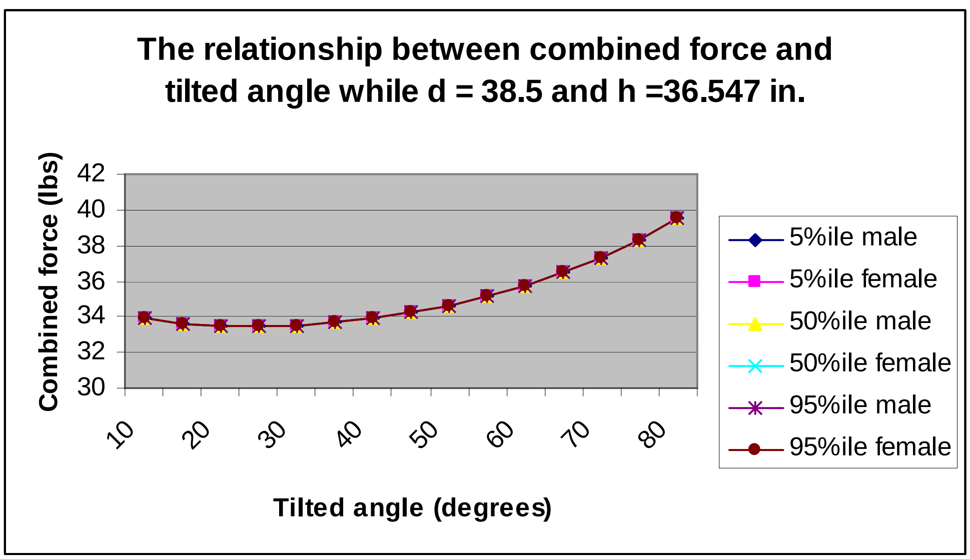


Figure 4.4 The relationship between combined force and tilted angles while d and h are fixed in the initial phase

In the analysis of case 2, the combined force ranged from 33.822 to 34.782 lbs (150.44 to 154.71 N) when users maintain their knuckle heights as pulling heights with a fixed d (=38.5 in) (Table 4.8). The combined force was slightly lower than in case 1. Figure 4.5 showed the relationship between combined force and tilted angles when d was fixed. The combined force was least at a tilted angle of 25° (F_C = 33.451 lbs for all user groups). However, the pulling height was lower than the user's knuckle height. Thus the combined force was minimum at α = 42.5° for 5%ile males, 38.2° for 5%ile females, 47.1° for 50%ile males, 42.7° for 50%ile females, 51.7° for 95%ile males, and 47.6° for 95%ile females by considering the optimal pulling height.

Table 4.8 The combined force as d and h are fixed in the initial phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle	Approxima-tely 42.5degree	Approxima-tely 38.2 degree	Approxima-tely 47.1 degree	Approxima-tely 42.7 degree	Approxima-tely 51.7 degree	Approxima-tely 47.6 degree
h**	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
d**	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lb)	27.166	26.101	28.307	27.216	29.465	28.432
Horizontal force (lb)	20.55	21.509	19.523	20.506	18.481	19.411
Combined force (lb)	34.064	33.822	34.387	34.076	34.782	34.426

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; **: fixed variables)

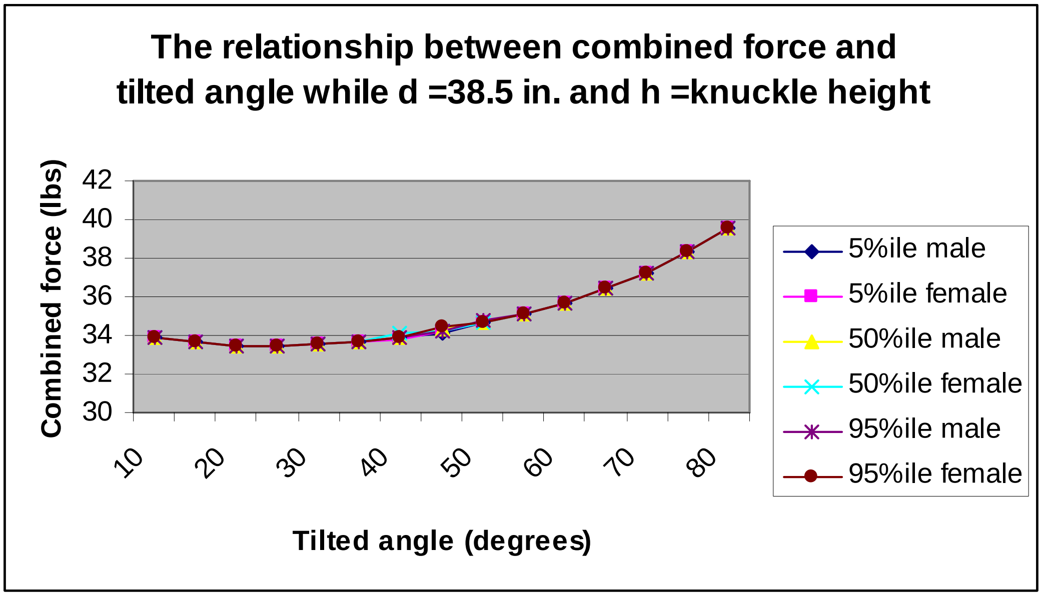


Figure 4.5 The relationship between combined force and tilted angles while d is fixed and h is maintained to user's knuckle height in the initial phase

In the analysis of case 3, the combined force is 36.493 lbs (162.321 N) for all users with different handle height (d) while users maintained their knuckle heights as pulling heights and the optimal tilted angle (Table 4.9). The combined force was the same as in case 1, but slightly higher than in case 2. Figure 4.6 showed the relationship between combined force and the tilted angle when d was fixed. The combined force is least at a tilted angle of 30° (33.449 lbs for 5%ile males, 33.451 lbs for 5%ile females, 33.456 lbs for 50%ile males, 33.449 lbs for 50%ile females, 33.46 lbs for 95%ile males, and 33.457 lbs for 95%ile females). Those combined forces are slightly lower than in case 1 and 2. The suggested handle heights are 45.5 in for 5%ile males, 41.5 in for 5%ile females, 49.5 in for 50%ile males, 45.5 in for 50%ile females, 52.5 in for 95%ile males, and 49.5 in for 95%ile females.

Table 4.9 The combined force as h and α are fixed in the initial phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle ***	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approximately 65.56 degree
h***	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
D	28.6 in	26.1 in	31.0 in	28.7 in	33.2 in	31.2 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lb)	33.222	33.222	33.222	33.222	33.222	33.222
Horizontal force (lb)	15.1	15.1	15.1	15.1	15.1	15.1
Combined force (lb)	36.493	36.493	36.493	36.493	36.493	36.493

Note: Suggested luggage design (The dimension of luggage: 22”×14”×10” with an adjustable handle; ***: fixed variables)

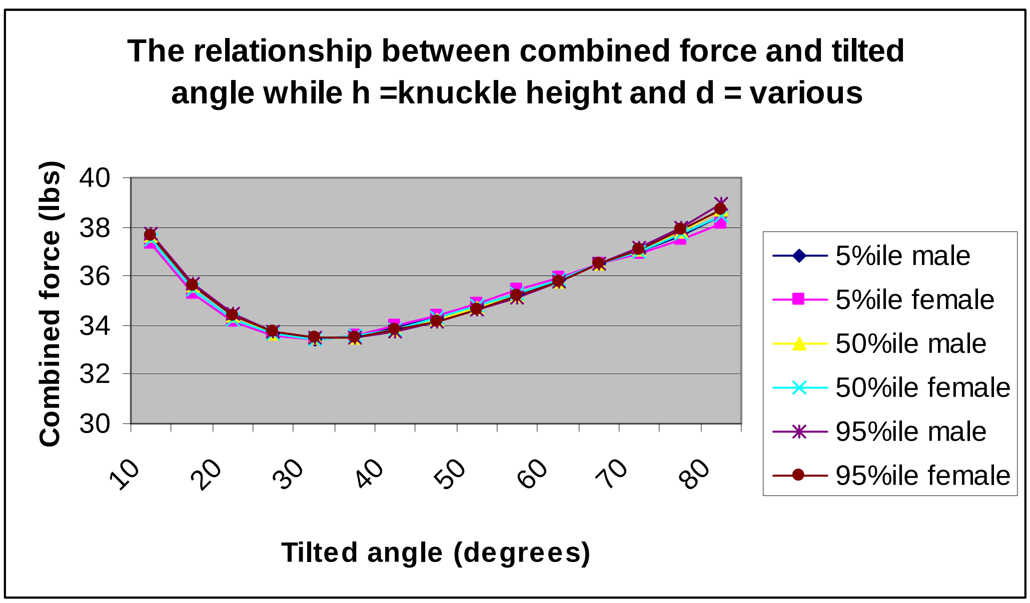


Figure 4.6 The relationship between combined force and tilted angles while h is maintained to users’ knuckle height and α is fixed in the initial phase

4.2.3 The effects of tilted angles, pulling heights, and handle heights in the sustained phase

In 4.2.3, the effects of tilted angles, pulling heights, and handle heights for luggage users were investigated in the sustained stage. Three cases (fixed d and maintained the optimal angle, fixed d and maintained the pulling height to user's knuckle height, and maintained the pulling height to user's knuckle height and the optimal tilted angle) were still compared and their assumptions were still valid. The results were also provided as a combined pulling force rather than a vertical force.

In the analysis of case 1, the combined force was 1.18 lbs (= 5.25 N) for all user groups at α = 65.56° when d was set to 38.5 in (Table 4.10). However, the pulling height (= 36.55 in) was considerably higher than the users' knuckle height. This pulling force results in the user's awkward wrist and arm posture.

Table 4.10 The combined force as d and α are fixed in the sustained phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle*	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree	Approxima-tely 65.56 degree
H	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in	36.547 in
d*	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lbs)	1.074	1.074	1.074	1.074	1.074	1.074
Horizontal Force (lbs)	0.4893	0.4893	0.4893	0.4893	0.4893	0.4893
Combined Force (lbs)	1.1801	1.1801	1.1801	1.1801	1.1801	1.1801

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; *: fixed variables)

Figure 4.7 showed the relationship between combined force and tilted angles when d was fixed. The combined force was least at a tilted angle of 67.2° (F_C = 0.5 lbs for all user groups). Thus, more force was generated by rolling friction if the same optimal angle was maintained.

In the analysis of case 2, the combined force ranged from 6.6271 to 9.5032 lbs (29.48 to 42.27 N) when users maintained their knuckle heights as a pulling heights with a fixed d (=38.5 in) (Table 4.11). The combined force was considerably higher than in case 1. Figure 4.8 showed the relationship between the combined force and tilted angles when d was fixed. The combined force was least at a tilted angle of 67.2° (F_C = 0.5 lbs for all user groups). However, the pulling height was higher than user's knuckle height.

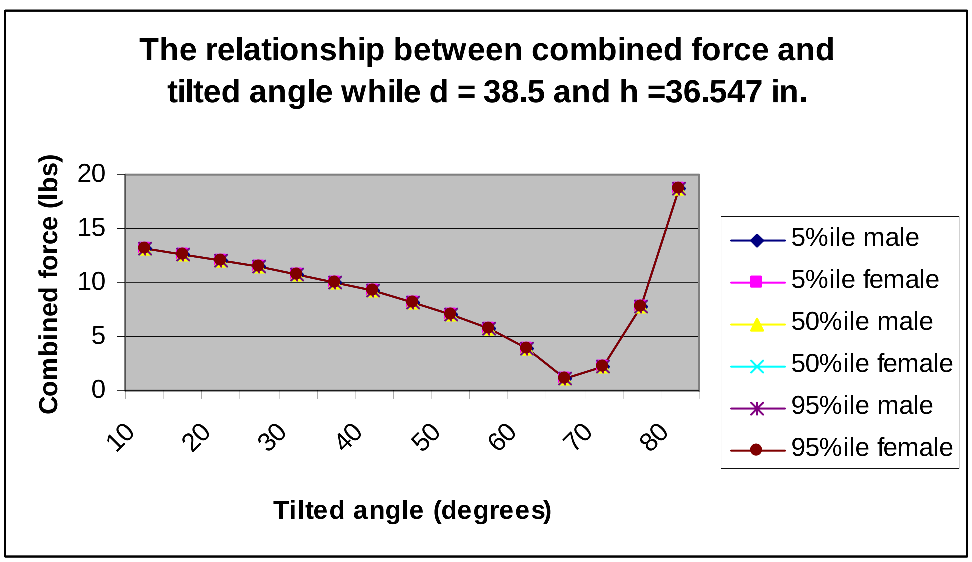


Figure 4.7 The relationship between combined force and tilted angles while d and h are fixed in the sustained phase

Table 4.11 The combined force as d and h are fixed in the sustained phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle	Approximately 42.5 degree	Approximately 38.2 degree	Approximately 47.1 degree	Approximately 42.7 degree	Approximately 51.7 degree	Approximately 47.6 degree
h**	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
d**	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in	38.5 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lb)	8.7138	9.4946	7.7525	8.675	6.6129	7.6383
Horizontal force (lb)	0.4129	0.4051	0.4225	0.4132	0.4339	0.4236
Combined force (lb)	8.7236	9.5032	7.764	8.6849	6.6271	7.6501

Note: Current luggage design (The dimension of luggage: 22”×14”×10” with a fixed handle; **: fixed variables)

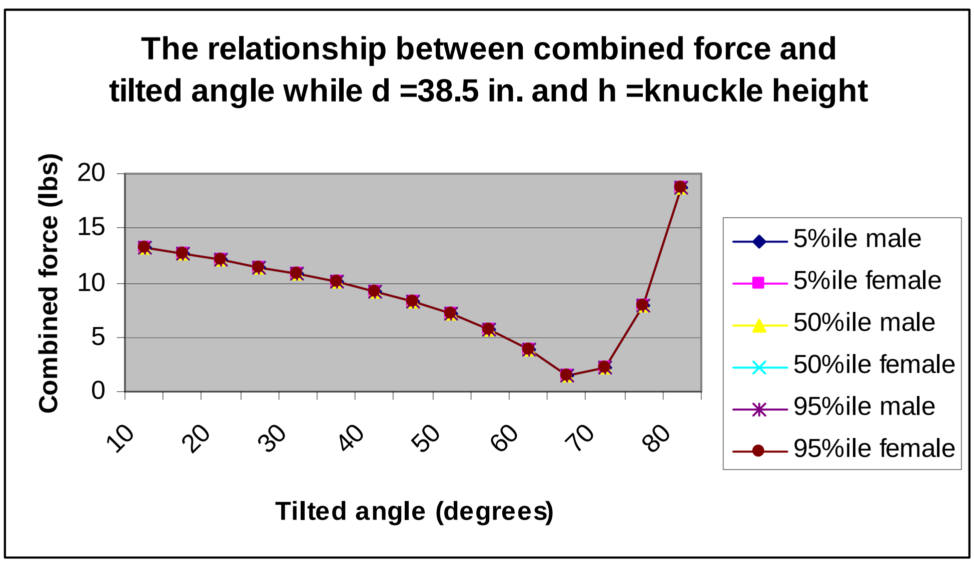


Figure 4.8 The relationship between combined force and tilted angles while d is fixed and h is maintained to user’s knuckle height in the sustained phase

Thus, the combined force was minimum at α = 42.5° for 5%ile males, 38.2° for 5%ile females, 47.1° for 50%ile males, 42.7° for 50%ile females, 51.7° for 95%ile males, and 47.6° for 95%ile females by considering optimal pulling heights.

In the analysis of case 3, the combined force ranged between 1.1791 and 1.1798 lbs (5.24 – 5.25 N) for all users with different handle height (d) while users maintained their knuckle heights as pulling heights and the optimal tilted angle (Table 4.12). The combined force was almost the same as in case 1, but was considerably lower than in case 2. Figure 4.9 showed the relationship between combined force and tilted angles when d was fixed. The combined force was least at a tilted angle of 65.56° (1.1793 lbs for 5%ile males, 1.1791 lbs for 5%ile females, 1.1796 lbs for 50%ile males, 1.1794 lbs for 50%ile females, 1.1798 lbs for 95%ile males, and 1.1796 lbs for 95%ile females).

Table 4.12 The combined force as h and α are fixed in the sustained phase

Subjects	5%ile Male	5%ile Female	50%ile Male	50%ile Female	95%ile Male	95%ile Female
Feasible Luggage tilted angle ***	Approximately 65.56 degree	Approximately 65.56 degree	Approximately 65.56 degree	Approximately 65.56 degree	Approximately 65.56 degree	Approximately 65.56 degree
h***	27.5 in	25.3 in	29.7 in	27.6 in	31.7 in	29.9 in
D	28.6 in	26.1 in	31.0 in	28.7 in	33.2 in	31.2 in
W	50 lb	50 lb	50 lb	50 lb	50 lb	50 lb
Vertical force (lb)	1.0731	1.0727	1.0733	1.0731	1.0735	1.0734
Horizontal force (lb)	0.4893	0.4893	0.4893	0.4893	0.4893	0.4893
Combined force (lb)	1.1793	1.1791	1.1796	1.1794	1.1798	1.1796

Note: Suggested luggage design (The dimension of luggage: 22”×14”×10” with an adjustable handle; ***: fixed variables)

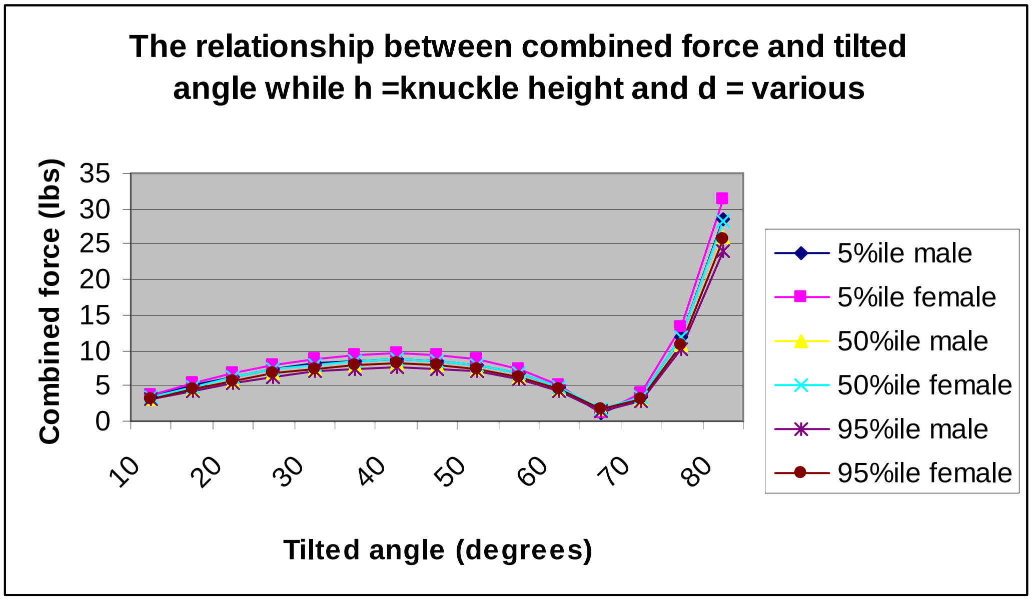


Figure 4.9 The relationship between combined force and tilted angles while h is maintained to users' knuckle height and α is fixed in the sustained phase

4.3 Statistical analysis

4.3.1 Regression and stepwise analysis for the static status

In section 4.2, we investigated the effects of tilted angles, pulling heights, and handle heights for luggage users in three conditions. However, the results from example 1 were questionable whether only the optimal angle and pulling heights were effective in an actual design study. For more realistic results, different levels of a, b, W, α , and d were considered. Level of R was fixed to 1.5 inches. In addition, levels of h were not considered because those values can be decided by a tilted angle α . In the summary, a and b values were selected from two popular commercial carry-on luggage types (22"×14"×10" and 30"×21"×11.5"). Values of d were also provided from the manual of two commercial carry-on luggage (38.5” for 5 percentile female users; 41.5” for 50 percentile male users; and 44.5” for 95 percentile male users). In addition, W was decided by Airline regulations and α ranged from 10 to 80 degree with 5 degree increments. The summary of these levels was shown in Table 4.13.

Regression analysis

To find the linear relationship between a response variable F_y and five important predictor variables (a, b, W, α, and d), a multiple linear regression was chosen. As shown in Table 4.14, the coefficient of determination (R^2) was 0.747. Thus, approximately 75% of the variation in F_y was accounted for by predictor variables.

Table 4.13 Summary of variables for pulling force prediction

Variables	a (2 levels)	b (2 levels)	W (2 levels)	α (11 levels)	D (3 levels)
Values	5 and 5.75in	11 and 15in	33 and 50lb	30-80 degree (5 increment)	38.5, 41.5, and 44.5in

Table 4.14 Summary of fit containing all predictors (the static status)

Summary of Fit	
RSquare	0.747081
RSquare Adj	0.746494
Root Mean Square Error	4.253573
Mean of Response	4.754566
Observations (or Sum Wgts)	2160

The regression equation from Table 4.15 was expressed as following.

$$F_c = 14.2337 - 0.3215\ \text{Alpha} – 1.4993\ a + 1.0114\ b – 0.1148\ d + 0.1129\ W$$

Stepwise analysis

To find most important predictor variables, a stepwise regression test was conducted because there was a large set of candidate variables. The result showed that the distance between center of mass and the bottom of luggage and the tilted angle significantly affected vertical force ($R^2 = 0.7286$). The regression equation was $F_c = 6.1065 – 0.3217\ \text{alpha} + 1.0114\ b$. Thus, users required roughly 3 lbs less of the vertical force for the increase in the tilted angle of 10 degree. However, the user should require roughly an additional 1 lb of the vertical force for increase in the distance between center of mass and the bottom of luggage of 1 inch. The summary JMP output of stepwise regression on pulling force data and graphical method are given in Table 4.16 and 4.17.

Table 4.15 Parameter estimates for all predictors (the static status)

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	14.233691	2.173039	6.55	<.0001	.
Alpha	-0.321493	0.004251	-75.63	0.0000	1.0000312
A	-1.499328	0.244061	-6.14	<.0001	1.0000104
B	1.0113677	0.045761	22.10	<.0001	1.0000104
D	-0.114768	0.037364	-3.07	0.0022	1
W	0.112876	0.010767	10.48	<.0001	1.0000104

Table 4.16 Summary of fit containing α and b as predictors

Summary of Fit	
Square	0.728638
RSquare Adj	0.728386
Root Mean Square Error	4.402865
Mean of Response	4.754566
Observations (or Sum Wgts)	2160

Table 4.17 Parameter estimates for α and b

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	6.1064693	0.653221	9.35	<.0001	.
Alpha	-0.321721	0.0044	-73.12	0.0000	1.0000104
B	1.0113756	0.047368	21.35	<.0001	1.0000104

4.3.2 Regression and stepwise analysis for the initial phase

For the initial phase, the levels of a, b, W, α, and d in Table 4.13 were considered. A level of R was fixed to 1.5 inches.

Regression analysis

To find the linear relationship between a response variable F_c, multiple linear regression analysis was conducted. As shown in Table 4.18, a higher coefficient of determination (R^2) was found (= 0.985). Thus, approximately 98.5% of the variation in F_c was account for by predictor variables. The regression equation from Table 4.19 could be expressed as following.

F_c = -2.9166 + 0.0678 Alpha – 0.2353 a + 0.1056 b – 0.0063 d + 0.7066 W

Table 4.18 Summary of fit containing all predictors (the initial phase)

Summary of Fit	
RSquare	0.985394
RSquare Adj	0.98536
Root Mean Square Error	0.753493
Mean of Response	29.30734
Observations (or Sum Wgts)	2160

Table 4.19 Parameter estimates for all predictors (the initial phase)

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	-2.916604	0.38494	-7.58	<.0001	.
Alpha	0.0677696	0.000753	89.99	0.0000	1.0000312
A	-0.235281	0.043234	-5.44	<.0001	1.0000104
B	0.105625	0.008106	13.03	<.0001	1.0000104
D	-0.006309	0.006619	-0.95	0.3406	1
W	0.7065767	0.001907	370.44	0.0000	1.0000104

Stepwise analysis

To find most important predictor variables, a stepwise regression test was also conducted. The result showed that luggage weight and tilted angles significantly affect the combined force ($R^2 = 0.984$). The regression equation was $F_c = -3.091 + 0.0678$ alpha + 0.7066 W. Thus, users required roughly an additional 0.7 lbs of the combined force for the increase in the tilted angle of 10 degree and an additional combined force of 0.7 lbs was required for increase in luggage weight of 1 lb in the initial phase. The summary JMP output of stepwise regression on pulling force data and graphical method were given in Table 4.20 and 4.21.

Table 4.20 Summary of fit containing α and W as predictors

Summary of Fit	
Square	0.984036
RSquare Adj	0.984021
Root Mean Square Error	0.787201
Mean of Response	29.30734
Observations (or Sum Wgts)	2160

Table 4.21 Parameter estimates for α and W

Term	Estimate	Std Error	T Ratio	Prob>|t|	VIF
Intercept	-3.070768	0.091661	-33.50	<.0001	.
Alpha	0.0677881	0.000787	86.17	0.0000	1.0000104
W	0.7065768	0.001993	354.58	0.0000	1.0000104

4.3.3 Regression and stepwise analysis for the sustained phase

For the sustained phase, we also considered the levels of a, b, W, α , and d in Table 4.13 considered. Level of R was fixed to 1.5 inches.

Regression analysis

From the multiple linear regression analysis, the coefficient of determination (R^2) was 0.4179. Thus, approximately 41.79% of the variation in F_c was accounted for by predictor variables in the sustained phase (Table 4.22). The regression equation from Table 4.23 could be expressed as the following.

$$F_c = 4.3467 + 0.0904 \text{ Alpha} - 0.0691 \text{ a} + 0.6386 \text{ b} - 0.1978 \text{ d} + 0.1988 \text{ W}$$

Table 4.22 Summary of fit containing all predictors (the sustained phase)

Summary of Fit	
RSquare	0.417876
RSquare Adj	0.416525
Root Mean Square Error	3.449924
Mean of Response	8.24579
Observations (or Sum Wgts)	2160

Table 4.23 Parameter estimates for all predictors (the sustained phase)

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	4.3467413	1.762476	2.47	0.0137	.
Alpha	-0.090439	0.003448	-26.23	<.0001	1.0000312
A	-0.06912	0.197949	-0.35	0.7270	1.0000104
B	0.6386144	0.037115	17.21	<.0001	1.0000104
D	-0.197764	0.030304	-6.53	<.0001	1
W	0.1988388	0.008733	22.77	<.0001	1.0000104

Stepwise analysis

According to a stepwise regression test, the result showed that tilted angles, the distance between center of mass and the bottom of luggage, and luggage weight significantly affected the combined force ($R^2 = 0.41$). The regression equation was F_c = -4.2318 – 0.09 alpha + 0.6386 b + 0.1988 W. Thus, users required roughly 0.9 lbs less of the combined force for the increase in the tilted angle of 10 degree. However, the user should required roughly an additional 6 lb of the combined force for increase in the distance between center of mass and the bottom of luggage of 1 inch and an additional combined force of 0.2 lbs was required for increase in luggage weight of 1 lb. The summary JMP output of stepwise regression on pulling force data and graphical method were given in Table 4.24 and 4.25.

Table 4.24 Summary of fit containing α , b, and W as predictors

Summary of Fit	
RSquare	0.406334
RSquare Adj	0.405508
Root Mean Square Error	3.482342
Mean of Response	8.24579
Observations (or Sum Wgts)	2160

Table 4.25 Parameter estimates for α , b, and W

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	-4.231789	0.633343	-6.68	<.0001	.
Alpha	-0.090443	0.00348	-25.99	<.0001	1.0000208
B	0.6386145	0.037464	17.05	<.0001	1.0000104
W	0.1988388	0.008815	22.56	<.0001	1.0000104

4.4 Summary

In the previous sections, three phases for the luggage were evaluated by force which was exerted by users. Luggage design that accounts for human physical dimensions was a special challenge.

Users move the luggage by grasping the handle at the top, tilting it, and walking while pulling it. Luggage had only vertical force to be balanced in the static status. Moving luggage in the initial phase is similar to in the sustained phase except ground friction. The luggage on the sustained stage is no more affected by friction on ground. A rolling friction is introduced while luggage is moving in the sustained phase. The rolling friction is significantly lower than the friction on ground. The value of 0.01 as a rolling friction coefficient was used. Therefore, the pulling force in the sustained phase was also significantly decreased.

In section 4.2, the handle height and tilted angles had the most serious effects on luggage design (case 1 vs. case 3 and case2 vs. case 3). The wrist and arm stresses were significantly affected by the design of the trolley handle, as was the degree to which the trolley was tilted while moving forward with a load. At α =65.56°, the vertical force the user must exert is zero in static status. This angle would be the optimal solution in static status. However, the solution was not valid in the case of the existence of another force (horizontal pulling force) and frictions (ground and rolling). Based on analysis for initial and sustained phases, the third case had the least combined force. The luggage had less combined force with tilted angles between 30° and 50° in the initial phase and between 60° and 70° in the sustained phase. Over the range of 30º and 50º in the initial phase, the dimensions of d should be adjustable with a wide range of lengths (33.9 - 52 in for 5%ile males, 31.1 – 47.6 in for 5%ile females, 36.8 – 56.4 in for 50%ile males, 34.1 – 52.2 in for 50%ile females, 39.4 – 60.4 in for 95%ile males, and 37.1 – 56.8 in for 95%ile females). From the first two cases, the users' pulling heights were lower than their knuckle heights in this range although the combined force was also lower than in the optimal tilted angle (α =65.56°). Over the range of 60º and 70º in the sustained phase, the dimensions of d are varied (27.7 - 30 in for 5%ile males, 25.3 - 27.5 in for 5%ile females, 30 - 32.6 in for 50%ile males, 27.8 - 30.1 in for 50%ile females, 32.1 - 34.9 in for 95%ile males, and 30.2 - 32.8 in for 95%ile females). This result supported the importance of handle height. In addition, approximately 75% of total weight should be required to be exerted in the initial phase while 2.3% of total weight should be exerted in the sustained phase. That means that users possibly have more injury potential in the initial phase. From this point of view, it is desirable to choose a design within the range of values of the handle heights and tilted angles in initial phase. Further analysis was conducted to find the important factors for the design of luggage in section 4.3.

In section 4.3, we conducted a regression analysis and stepwise regression test to find possible predictor variables. The model contained luggage weights, pulling heights, and tilted angles. From the results, tilted angles (α), the distance between center of mass and the bottom of luggage (b), and luggage weight (W) had a significant effect on the combined force. In the sustained phase, tilted angles (α) and the distance between center of mass and the bottom of luggage (b) accounted for approximately 74% of the vertical force. In the initial phase, tilted angles (α) and luggage weight (W) had a major effect on the combined force (approximately 98.5 %). In the sustained phase, tilted angles (α), the distance between center of mass and the bottom of luggage (b), and luggage weight (W) accounted for approximately 41% of the combined force. Practically, handle height on the upright position (d) and distance between center of mass and the side of luggage (a) were not much important since those variables have a lack of relationship. However, handle height on upright position should be considered in luggage design since it was an important factor to decide the tilted angle.

CHAPTER 5 USABILITY TEST

5.1 Introduction

Usability is defined as the degree to which the system is easy to use or “user friendly” (Nielsen, 1994b). This test is an extremely important tool for evaluating the validity and reliability in a wide range of products. A usability test for two-wheeled luggage is conducted in this chapter.

Two-wheeled luggage is moved by grasping the handle, tilting it, and walking while pulling it. The motion phases are divided into three phases; initial, sustained, and ending phases. Regression models in section 4.3 showed possible predictor variables to find minimum pull force. In the initial phase, tilted angle (α) and luggage weight (W) had a major effect on the combined force. In the sustained phases, tilted angle (α), distance between the bottom of luggage and the center of mass (b), and luggage weight (W) were major factors. Tilted angle (α) is changeable by subjects’ knuckle heights and pole lengths and distance between the bottom of luggage and the center of mass (b) is changeable by using different luggage sizes. Thus, two load weights (33 lbs and 50 lbs), six pole lengths (38.5”, 41.5”, 44.5”, 45.5”, 49.5”, and 52.5”), four subject groups (5%ile female, 50%ile female, 50%ile male, and 95%ile male groups), and two luggage size (22”×14”×10” and 30”×21”×11.5”) were considered for experimental design. With those design factors, this chapter conducted usability evaluation to see users’ preference about each level of design factors for the luggage design and to recommend improvements for new design. In general, different methods and techniques used in usability evaluation have been suggested based on the companies’ or agencies’ needs. The representative methods are GOMS (Goals, Operators, Methods, and Selection) model, a heuristic evaluation, and an empirical usability test. GOMS model has been one of the few widely known theoretical concepts in human-computer interaction. Another usability tool is a heuristic evaluation, which is a variation of usability inspection where usability specialists judge whether each element of a user interface follows established usability principles. On the other hand, the empirical usability test is for assessing products by testing the interface with real users. The characteristics of usability test method were summarized in Table 5.1.

This study conducted an empirical usability test with important design factors of wheeled luggage. Some benefits such as better luggage design, less pull force, better user posture, and higher user satisfaction were expected from this usability test.

5.2 Subjects

For the usability test, eight test subjects were chosen, which was deemed a sufficient number to ensure the identification of 90% of the usability problems (Lewis, 1994; Virzi, 1992). A total of 4 male and 4 female subjects were recruited to participate in the experiments from the student population at the University of Tennessee. The ages of the subjects ranged from 27 years to 40 years, with the average of 32.75 years and standard deviation of 4.4 years. The right hand dominated for 7 subjects and the left hand dominated for 1 female subject. All subjects were healthy and divided into four user groups by their knuckle heights. Each subject group consisted of 2 persons and represented the main categories of expected users: 5%ile female, 50%ile female, 50%ile

Table 5.1 The characteristics of usability test methods

	GOMS	Heuristics	Empirical Test*
Purpose	To develop and evaluate the actual software	To judge usability problems of a user interface follows established usability principles	To assess products by testing the interface with real users
Approach	1. Goals: define the user's task and the purpose of the system 2. Operators: find an important difference between goals and users' actions 3. Methods: define a sequence of steps for accomplishing a goal 4. Selection: There are many possible ways to achieve a goal. Selection rule is used to provide a step-by-step procedure, not sequential.	1. Select appropriate guidelines 2. Tailor the guidelines to suit exact issues faced by users.	Evaluate user, task, system, and environment 1. Subjective evaluation: a questionnaire with users 2. Objective evaluation: a test with users
Essential Measurements	In general, the GOMS allows the usability evaluators to predict performance time, learn-ability, and errors.	Guidelines Checklists	Performance time Task completion Errors Learnability Memorability Satisfaction
Advantage	1. GOMS is used for an early analysis of usability, not late stages 2. GOMS has a significant advantage with regard to saving time and resources	1. HE is more cost effective than UT 2. HE uncovers as many potential usability problems as possible	1. UT is more accurate than HE 2. UT is good for an objective test (directly measure performance time, errors, etc.) 3. UT has deeper insight for problems
Disadvantage	1. GOMS does not fit with prototyping and user testing	1. HE is less accurate than UT. 2. The solution for a problem might be a new problem for other functions 3. HE has more limitation to find usability problems 4. The results from HE might be different among evaluators with different usability experience and knowledge	1. UT requires more cost and efforts 2. The results will be influenced by the behavior of test participants
Main Theories	1. (Card et al., 1983) 2. (Kieras, 1988) 3.(John & Kieras, 1996a) 4. (John & Kieras, 1996b) 5. (Kieras et al., 1995)	1. (Nielsen, 1994a) 2. (Nielsen, 1994b) 3. (Nielsen & Mack, 1994)	1. (Shackel, 1990) 2. (Virzi, 1992) 3. (Lewis, 1994)

(Note: * usability test method in this study) male, and 95%ile male groups. Table 5.2 showed the characteristics of the study groups.

5.3 Method

Two luggage prototypes (22”×14”×10” and 30”×21”×11.5”) were made with the exchangeable handle (Figure 5.1). Six different handle lengths (38.5”, 41.5”, 44.5”, 41.5”, 45.5”, 49.5” and 52.5”) were used in this study. Two different load weights (33 lbs and 50 lbs) were considered and a bundle of yellow pages (4.2 lbs per book) was used for load weights of 33 lbs and 50 lbs. The COM of the bundle of yellow pages was positioned the middle of the each luggage throughout the study and controlled by foams and straps to prevent slipping. The tilted angles of luggage for each subject were measured by an angle finder (American Science & Surplus™, Figure 5.2). For the usability test, two sets of questionnaires were prepared (Appendix C and D). Pre-questionnaires, Appendix C, consisted of demographic information of subjects and wheeled luggage experience. Questions for wheeled luggage experience were particularly important because user’s awareness of usability issues could be measured from them.

Table 5.2 Profile of test subjects

Subject	Gender	Age	Knuckle height, cm (in)	Subject category (by Knuckle height)	Mean and S.D of Knuckle height, cm (in) of each subject group
S1	Female	36	68 (26.77)	5%ie Female group	67.5/0.71 (26.57/0.28)
S2	Female	35	67 (26.38)	5%ie Female group	
S3	Female	29	70 (27.56)	50%ie Female group	71/1.41 (27.95/0.56)
S4	Female	27	72 (28.35)	50%ie Female group	
S5	Male	30	76 (29.92)	50%ie Male group	77.5/2.12 (30.51/0.83)
S6	Male	35	79 (31.10)	50%ie Male group	
S7	Male	30	84 (33.07)	95%ie Male group	82.5/2.12 (32.48/0.83)
S8	Male	40	81 (31.89)	95%ie Male group	

Figure 5.1 Two-wheeled prototypes (left: small luggage with 38.5” pole length, right: large luggage with 52.5” pole length)

Figure 5.2 Angle finder

Post-questionnaires consisted of subjective rating and open questions (Appendix D). Subjective ratings were obtained by subjects' judgments for the two-wheeled luggage in terms of usability aspects. On the other hand, the open questions covered subjects' opinions for the design of two-wheeled luggage.

5.4 Test procedure

5.4.1 Pilot test

Before committing to a main test procedure, a pilot test was performed by the author of this paper to determine whether the testing procedure needed to be modified. The pilot test is an important step in the experiment development process, in order to find out how actual users react. Despite best efforts and sound application, the quality of the outcome is not guaranteed in a main experiment. Therefore, a well-designed experimental setting through the pilot test is necessary to iron out any difficulties with procedures and test materials in the main experiment.

5.4.2 Main experiment

A number of dynamic pulling tasks were performed by subjects on an L-shaped path. Before the experiment is done, a warming-up session was given to all subjects. In the main experiment, the subjects were asked to walk forward while pulling the luggage at a self-chosen normal speed and with the upper body as symmetrical as possible over a distance of about 12 m on the normal surface (Figure 5.3). In addition, the subjects were asked that the hand should be supinated and the upper arm should be maintained as close to the upper body as subject could afford for reducing posture variations (Figure 5.4). The pole lengths were selected randomly and its tilted angles were recorded before the luggage was pulled. In addition, the walking speed was measured and recorded at the ending point of the path (Appendix B). After each pulling task was done, the subjects answered post-questionnaires for usability. Each survey questions was rated by the five-point Likert scale to quantify subjects' ratings. The independent variables, their levels for the experiments, and the scale for rating were summarized in Table 5.3 and Table 5.4, respectively.

Figure 5.3 Actual pulling task on a tiled ground surface

Figure 5.4 The hand and arm posture

Table 5.3 Independent variables and their levels for the experiments

Independent variables	Levels (levels)					
Luggage sizes	LV1 (22”×14”×10”)			LV2 (30”×21”×11.5”)		
Handle length	LV1 (38.5”)	LV2 (41.5”)	LV3 (44.5”)	LV4 (45.5”)	LV5 (49.5”)	LV6 (52.5”)
Subjects’ knuckle heights	LV1 (26.57”)	LV2 (27.95”)		LV3 (29.92”)	LV4 (32.48”)	
Load	LV1 (33lbs)			LV2 (50lbs)		

Table 5.4 Scales for rating

Scales	Rating category
1	Not important
2	Slightly important
3	Moderately important
4	Very important
5	Absolutely important

5.5 Statistical analysis

Wilcoxon rank sum tests were conducted when a factor had only two levels with an abnormal distribution while Kruskal-Wallis rank sum tests were conducted when a factor had three or more levels with an abnormal distribution. On the other hand, Tukey comparison tests were conducted when the data had a normal distribution. For the normality test, a normal fitting test and a goodness of fit test were conducted. All data were treated with assumption of equal importance of individual questions. The statistical analyses were conducted for the differences of complaint scores among body parts, pole length versus each body part (back, neck/shoulder, arm, wrist, and hand), pole length versus pulling force, pole length versus walking speed, tilted angle versus pulling force, tilted angle versus walking speed, load weights versus pulling force, and load weights versus walking speed. P values < 0.05 were considered statistically significant. All analyses were conducted using JMP (SAS© Institution Inc.).

CHAPTER 6 RESULTS

6.1 Difficulties for two-wheeled luggage use

All subjects have had an experience with two-wheeled luggage while traveling although frequency of luggage usage was comparatively different. All subjects thought that size was the most important feature of two-wheeled luggage. In addition, most subjects chose material and handle type as important features of two-wheeled luggage. Interestingly, extension of handle and comfort grip were comparatively less selected.

For the usability issues, all subjects experienced difficulties of two-wheeled luggage use due to excessive pulling force, awkward postures, trip/hit, and maneuverability. For force issue, the arm including the elbow was the most complained about body part. The shoulder and wrist followed. For trip/hit issue, the arm, wrist, and hand were dominant body parts from complaints. For maneuverability issue, the arm was the most complained about body part. The wrist was the second, the shoulder followed. The results were summarized in Table 6.1.

6.2 Risk assessment of body parts

Subjects pulled repeatedly two types of luggage with six pole lengths and two load weights. Based on the subjects' responses, the most risk-prone body part was found. The upper body parts including back, neck/shoulder, arm, wrist, and hand were focused on. Figure 6.1 represented the means of complaint scores for five body parts. The complaint scores were the numeric Y response and the five body parts were levels of the

Table 6.1 The results of pre-questionnaires

Subject	Usage (criteria of luggage selection)	Force (body parts)	Awkward posture (body parts)	Trip/hit (body parts)	Maneuvering (body parts)
#1	Sometimes (material, size, handle type, and comfort grip)	Often (low back, arm, and wrist)	Often (arm and wrist)	Often (shoulder, arm, wrist, and leg)	Sometimes (arm, wrist, and leg)
#2	Sometimes (material, size, exterior, and interior)	Sometimes (arm and wrist)	Sometimes (arm and wrist)	Sometimes (wrist and leg)	Often (shoulder, arm, and wrist)
#3	Extensively (material, size, handle type, extension of handle and comfort grip)	Sometimes (arm and wrist)	Sometimes (arm and wrist)	Sometimes (arm, wrist, and foot)	Sometimes (arm and wrist)
#4	Rarely (Size)	Rarely (arm)	Rarely (arm)	Rarely (The arm and leg)	Rarely (low back and arm)
#5	Sometimes (size, exterior, interior, handle type)	Sometimes (arm)	Sometimes (arm and hand)	Often (The arm, wrist, and hand)	Sometimes (arm, wrist, and hand)
#6	Sometimes (material, size, exterior, interior)	Often (shoulder, arm, and leg)	Often (shoulder, arm, wrist, and leg)	Often (arm, wrist, and leg)	Often (shoulder, arm, wrist, and leg)
#7	Extensively (material, size, handle type, extension of handle and comfort grip)	Often (shoulder and arm)	Sometimes (shoulder and arm)	Sometimes (The arm and hand)	Sometimes (shoulder and arm)
#8	Sometimes (material, size, exterior, and handle type)	Sometimes (shoulder and wrist)	Sometimes (shoulder and wrist)	Often (low back and arm)	Sometimes (arm)

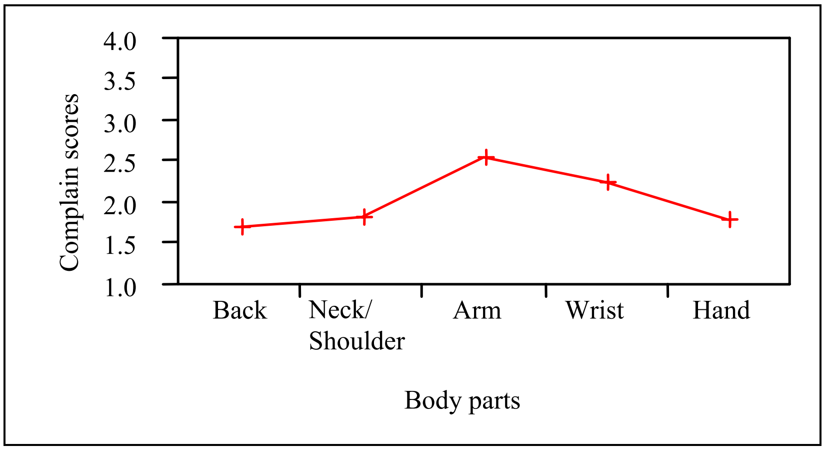


Figure 6.1 Overall Least Squares Means (LSM) of body parts

categorical X factor. The results showed that the arm was the most risk-prone body part (complaint score = 2.543). The wrist and hand (complaint score = 2.245 and 1.797, respectively) followed.

The following sections included more detailed analysis between each independent variable and body parts.

6.2.1 Load weights vs. body parts

The effects of two load weights (33 lbs and 50 lbs) on five body parts (the back, neck/shoulder, arm hand) were evaluated. Wilcoxon rank sum test rather than Tukey comparison test is useful to test for any significant differences between load weights and risk-prone body parts since the usual analysis of variance assumption of normality was not made from the raw data. Figure 6.2 represented the means of complaint scores

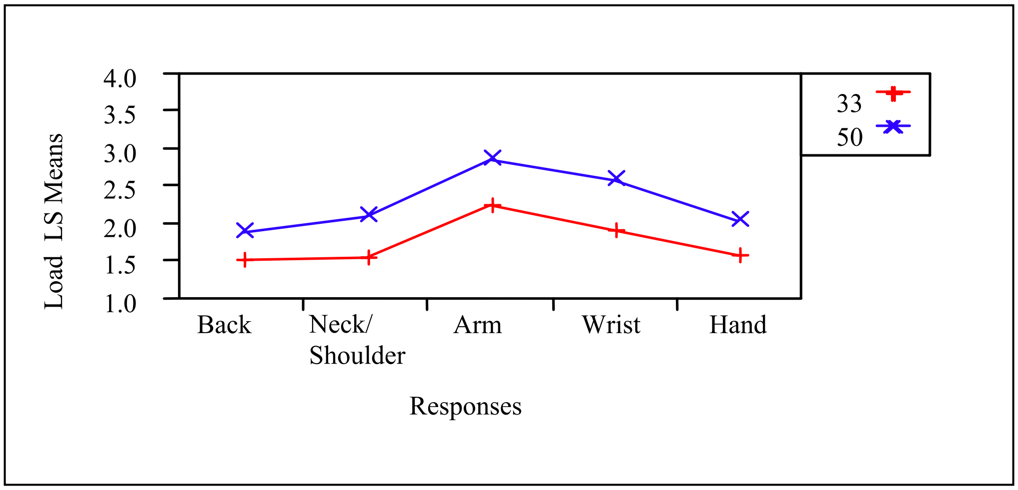


Figure 6.2 The complaint scores of body parts between load weights

between load weights for five body parts. The complaint scores were the numeric Y response and the five body parts were levels of the categorical X factor. The graph showed that the complaint scores on all body parts were increased as the load weight was increased. The arm was the most complained about body part. The difference of complaint scores on all body parts between the load weight of 33 lbs and 50 lbs were statistically significant at a 95% confidence interval. Table 6.2 showed results of Wilcoxon rank sum tests for body part complaints by load.

6.2.2 Pole lengths vs. body parts

The effects of six pole lengths (38.5", 41.5", 44.5", 45.5", 49.5", and 52.2") on five body parts (the back, neck/shoulder, arm, wrist, and hand) were evaluated. Kruskal-Wallis rank test conducted to test for any significant differences between pole lengths and risk-prone body parts since the usual analysis of variance assumption of normality was

Table 6.2 Results of Wilcoxon rank sum test for body complaints by load weights

Body part		Load		
		33 lbs N = 48	50 lbs N = 48	Z and P-value (two tailed Wilcoxon rank sum test)
Backache (8 persons)	Mean (SD) Median (interquartile range	1.510 (0.500) 1.5 (1.0, 1.5)	1.875 (0.431) 2.0 (1.5, 2.375)	Z = 4.118 P>|Z| = < 0.0001*
Neck/shoulder (8 persons)	Mean (SD) Median (interquartile range	1.552 (0.518) 1.5 (1.0, 1.875)	2.104 (0.437) 2.0 (2.0, 2.5)	Z = 5.113 P>|Z| = < 0.0001*
Arm (8 persons)	Mean (SD) Median (interquartile range	2.229 (0.574) 2.0 (2.0, 2.5)	2.854 (0.536) 2.75 (2.5, 3.5)	Z = 4.988 P>|Z| = < 0.0001*
Wrist (8 persons)	Mean (SD) Median (interquartile range	1.906 (0.502) 2.0 (1.5, 2.0)	2.583 (0.509) 2.5 (2.0, 3.0)	Z = 5.478 P>|Z| = < 0.0001*
Hand (8 persons)	Mean (SD) Median (interquartile range	1.563 (0.589) 1.5 (1.0, 2.0)	2.031 (0.510) 2.0 (1.5, 2.55)	Z = 4.089 P>|Z| = < 0.0001*

not made for the raw data. As shown in Figure 6.3, the complaint on all body parts increased as the pole length increased. The complaint scores that ranged from 38” to 45.5” were almost identical, but they clearly increased with pole lengths over 49.5”. The arm was the most complained about body part and the wrist, neck/shoulder, hand and back followed. However, based on the statistical results, the complaint scores on all body parts with the exception of the neck/shoulder and hand were significantly different by changing pole lengths at a 95% confidence interval. Table 6.3 showed results of Kruskal-Wallis rank sum tests for body part complaints by pole lengths.

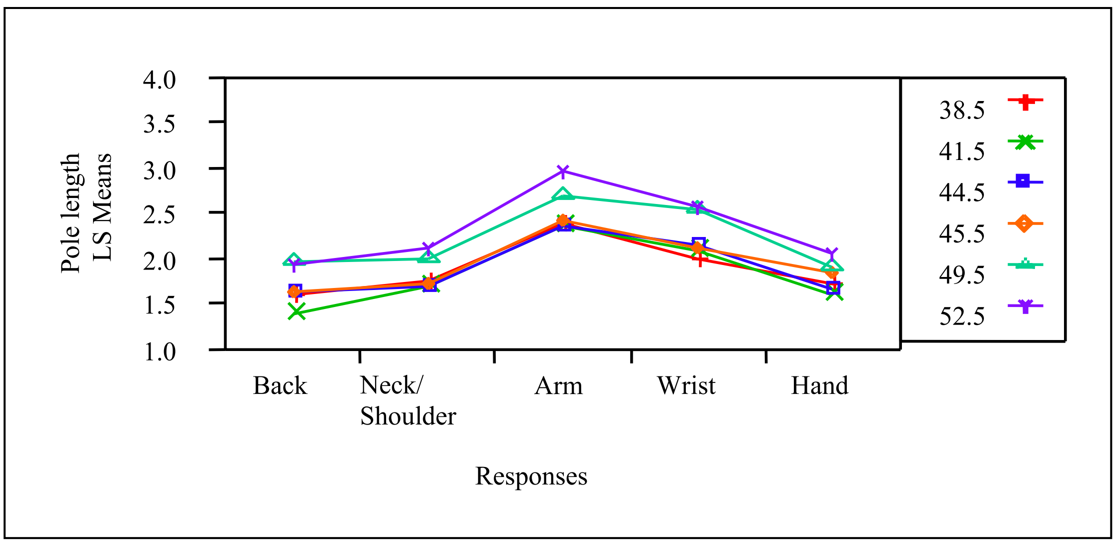


Figure 6.3 The complaint scores of body parts among pole lengths

Table 6.3 Results of Kruskal-Wallis rank sum test for body complaints by pole lengths

Body part		Pole lengths						
		38.5” N = 16	41.5” N = 16	44.5” N = 16	45.5” N = 16	49.5” N = 16	52.5” N = 16	ChiSq and P-value (one-way Kruskal-Wallis rank sum test)
Backache (8 persons)	Mean (SD) Median (interquartile range)	1.594 (0.523) 1.5 (1.0, 2.0)	1.406 (0.375) 1.5 (1.0, 1.5)	1.625 (0.428) 1.5 (1.5, 1.875)	1.625 (0.387) 1.5 (1.5, 2.0)	1.969 (0.531) 1.75 (1.5, 2.5)	1.938 (0.544) 1.5 (1.5, 2.5)	ChiSquare =13.456 P>ChiSq = 0.0195*
Neck/shou-lder (8 persons)	Mean ± SD Median (interquartile range)	1.750 (0.632) 1.75 (1.0, 2.5)	1.688 (0.574) 1.5 (1.125, 2.375)	1.688 (0.602) 1.5 (1.125, 2.0)	1.719 (0.446) 1.5 (1.5, 2.0)	2.000 (0.516) 2.0 (1.5, 2.0)	2.125 (0.428) 2.0 (1.5, 2.0)	ChiSquare =9.286 P>ChiSq = 0.0982
Arm (8 persons)	Mean ± SD Median (interquartile range	2.406 (0.712) 2.5 (1.625, 2.875)	2.375 (0.500) 2.5 (2.0, 2.5)	2.375 (0.764) 2.25 (1.625, 3.0)	2.438 (0.629) 2.5 (2.0, 2.5)	2.688 (0.544) 2.5 (2.125, 3.0)	2.969 (0.464) 3.0 (2.5, 3.5)	ChiSquare =12.321 P>ChiSq = 0.0306*
Wrist (8 persons)	Mean ± SD Median (interquartile range	2.000 (0.683) 2.0 (1.5, 2.5)	2.094 (0.612) 2.0 (1.5, 2.5)	2.156 (0.473) 2.0 (2.0, 2.5)	2.215 (0.619) 2.0 (1.5, 2.5)	2.531 (0.591) 2.5 (2.0, 3.0)	2.563 (0.479) 2.75 (2.0, 3.0)	ChiSquare =12.782 P>ChiSq = 0.0255*
Hand (8 persons)	Mean ± SD Median (interquartile range	1.719 (0.657) 1.5 (1.0, 2.375)	1.594 (0.523) 1.5 (1.0, 2.5)	1.656 (0.539) 1.5 (1.125, 2.5)	1.844 (0.569) 2.0 (1.5, 2.0)	1.906 (0.554) 1.5 (1.5, 2.375)	2.063 (0.680) 2.0 (1.5, 2.5)	ChiSquare =6.095 P>ChiSq = 0.2971

6.2.3 Subject groups vs. body parts

The effects of knuckle heights of four subject groups (67.5, 71, 77.5, and 82.5 cm) on five body parts (the back, neck/shoulder, arm, wrist, and hand) were evaluated. Kruskal-Wallis rank sum test was also conducted to test for any significant differences between knuckle heights and risk-prone body parts. The complaint score on the arm was the highest regardless of subjects' knuckle heights in all subjects groups. The wrist was the second complained about body part in all subjects groups. The hand, neck/shoulder, and back followed (Figure 6.4). From the statistical results, the complaint scores on all body parts among subject groups were significantly different at a 95% confidence interval. Table 6.4 showed the results of Kruskal-Wallis rank sum tests for body part complaints by Knuckle heights.

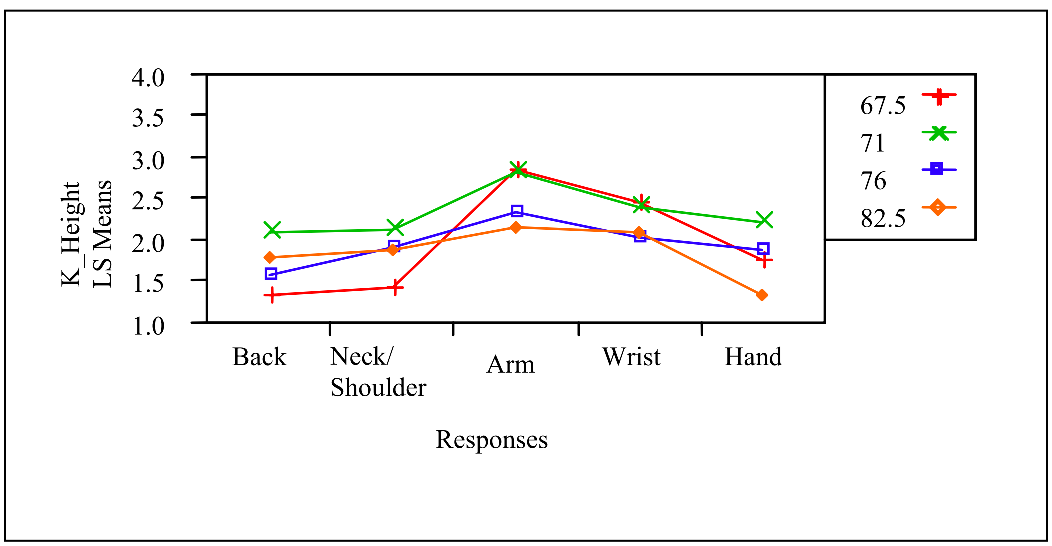


Figure 6.4 The complaint scores of body parts among knuckle heights

Table 6.4 Results of Kruskal-Wallis rank sum test for body complaints by knuckle heights

Body part		Knuckle heights				
		67.5cm (26.57 in) N = 24	71cm (27.95 in) N = 24	77.5cm (29.92 in) N = 24	82.5cm (32.48 in) N = 24	ChiSq and P-value (one-way Kruskal-Wallis rank sum test)
Backache (8 persons)	Mean (SD) Median (interquar-tile range)	1.333 (0.241) 1.5 (1.0, 1.5)	2.083 (0.620) 2.5 (1.5, 2.5)	1.563 (0.169) 1.5 (1.5, 1.5)	1.792 (0.487) 2.0 (1.5, 2.0)	ChiSquare =27.260 P>ChiSq= < 0.0001*
Neck/sh-oulder (8 persons)	Mean (SD) Median (interquar-tile range)	1.417 (0.351) 1.5 (1.0, 1.5)	2.125 (0.647) 2.5 (1.5, 2.5)	1.896 (0.361) 2.0 (1.5, 2.0)	1.875 (0.557) 2.0 (1.5, 2.5)	ChiSquare =20.401 P>ChiSq= 0.0001*
Arm (8 persons)	Mean (SD) Median (interquar-tile range	2.854 (0.699) 3.0 (2.5, 3.5)	2.813 (0.689) 3.0 (2.125, 3.5)	2.333 (0.319) 2.5 (2.0, 2.5)	2.167 (0.482) 2.25 (1.625, 2.5)	ChiSquare =19.932 P>ChiSq= 0.0002*
Wrist (8 persons)	Mean (SD) Median (interquar-tile range	2.458 (0.588) 2.5 (2.0, 3.0)	2.396 (0.691) 2.5 (2.0, 3.0)	2.042 (0.292) 2.0 (2.0, 2.0)	2.083 (0.686) 2.0 (1.5, 2.875)	ChiSquare =8.426 P>ChiSq= 0.0380*
Hand (8 persons)	Mean (SD) Median (interquar-tile range	1.771 (0.625) 1.5 (1.125, 2.5)	2.208 (0.690) 2.5 (1.5, 2.875)	1.875 (0.304) 2.0 (1.5, 2.0)	1.333 (0.319) 1.5 (1.0, 1.5)	ChiSquare =25.962 P>ChiSq= 0.0001*

6.2.4 Luggage size vs. body parts

The effects of two luggage sizes (22"×14"×10" and 30"×21"×11.5") on five body parts (the back, neck/shoulder, arm, wrist, hand) were evaluated. Wilcoxon rank sum test was conducted to test for any significant differences between luggage sizes and risk-prone body parts. The complaint score on the arm was the highest no matter what the luggage size was. The wrist was the second complained about body part. The neck/shoulder, hand, and back followed (Figure 6.5). The pattern of the graph was almost identical between luggage sizes. From the statistical results, the complaint scores on all body parts were not significantly different by luggage sizes at a 95% confidence interval. Table 6.5 showed the results of Wilcoxon rank sum tests for body part complaints by luggage size.

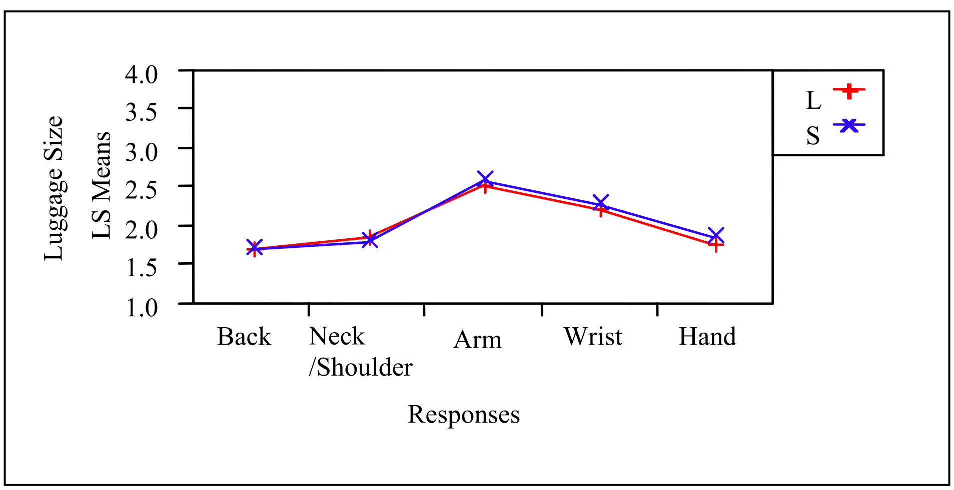


Figure 6.5 The complaint scores of body parts between luggage sizes

Table 6.5 Results of Wilcoxon rank sum test for body complaints by luggage sizes

Body part		Luggage size		
		Large N = 48	Small N = 48	Z and P-value (two tailed Wilcoxon rank sums test)
Backache (8 persons)	Mean (SD) Median (interquartile range	1.698 (0.481) 1.5 (1.5, 2.0)	1.688 (0.522) 1.5 (1.5, 2.0)	Z = - 0.241 P>|Z| = 0.8099
Neck/shoulder (8 persons)	Mean (SD) Median (interquartile range	1.854 (0.526) 2.0 (1.5, 2.375)	1.802 (0.581) 1.5 (1.5, 2.5)	Z = - 0.592 P>|Z| = 0.5538
Arm (8 persons)	Mean (SD) Median (interquartile range	2.510 (0.656) 2.5 (2.0, 3.0)	2.573 (0.619) 2.5 (2.0, 3.0)	Z = 0.575 P>|Z| = 0.5651
Wrist (8 persons)	Mean (SD) Median (interquartile range	2.208 (0.600) 2.0 (2.0, 2.5)	2.281 (0.618) 2.5 (1.625, 3.0)	Z = 0.594 P>|Z| = 0.5525
Hand (8 persons)	Mean (SD) Median (interquartile range	1.750 (0.593) 1.5 (1.5, 2.0)	1.844 (0.603) 2.0 (1.5, 2.5)	Z = 0.824 P>|Z| = 0.4100

6.3 Pulling force

6.3.1 Load weights vs. pulling force

Load had a significant effect on pulling force between load weights of 33 lbs and 50 lbs based on Wilcoxon rank sum tests. The complaint scores increased when load increased (Figure 6.6). The mean scores of pulling force for the load weights of 33 lbs and 50 lbs were 2.573 and 3.542, respectively. Their median scores were 2.5 and 3.5, respectively. The median score difference of force complaint between 30 lbs and 50 lbs was approximately 1 scale. This difference was significant at a 95% confidence interval ($p < 0.0001$) (Table 6.6).

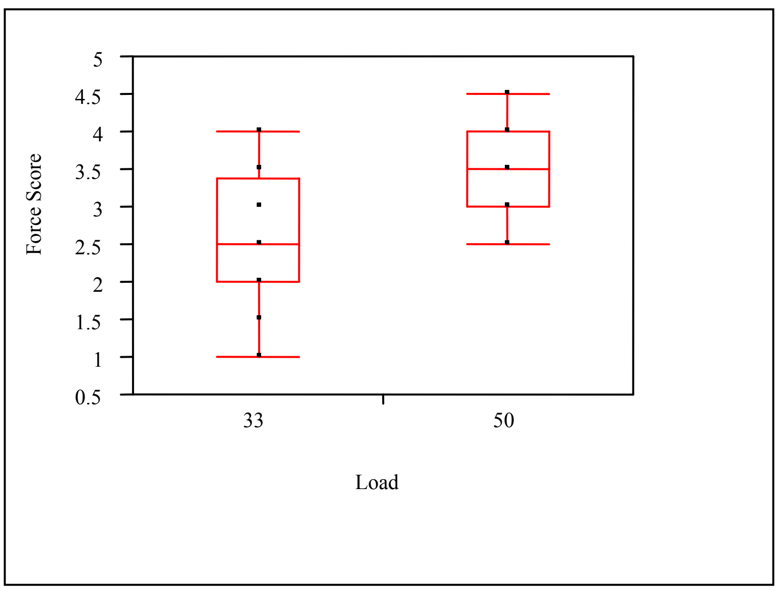


Figure 6.6 Quantile box plot of pulling force score by load weights

Table 6.6 Results of Wilcoxon rank sum test for pulling forces complaints by load weights

		Load		
		33 lbs N = 48	50 lbs N = 48	Z and P-value (two tailed Wilcoxon rank sum test)
Pulling force (8 persons)	Mean (SD) Median (interquartile range	2.573 (0.825) 2.5 (1.5, 2.5)	3.542 (0.600) 3.5 (2.95, 3.5)	Z = 5.453 P>|Z| = < 0.0001*

6.3.2 Pole lengths vs. pulling force

The effects of six pole lengths on pulling forces were evaluated. A Tukey comparison test was conducted to test for any significant differences between pole lengths and pulling force since the data was normally distributed.

Figure 6.7 showed that the mean complaint scores for pulling forces among pole lengths were the lowest at pole length of 41.5”. Table 6.7 showed the comparisons for all pairs of pole length. The table called the Tukey-Kramer LSD Threshold matrix. The matrix showed the actual absolute difference in the means minus the LSD, which is the difference that would be significant. Pairs with a positive value are significantly different. The results showed that all pairs of pole length did not affect pulling force. Table 6.8 also showed that the means of force score for six pole lengths between 38.5 inches and 52.5 inches had no significant difference each other at a 95% confidence interval ($p < 0.0769$).

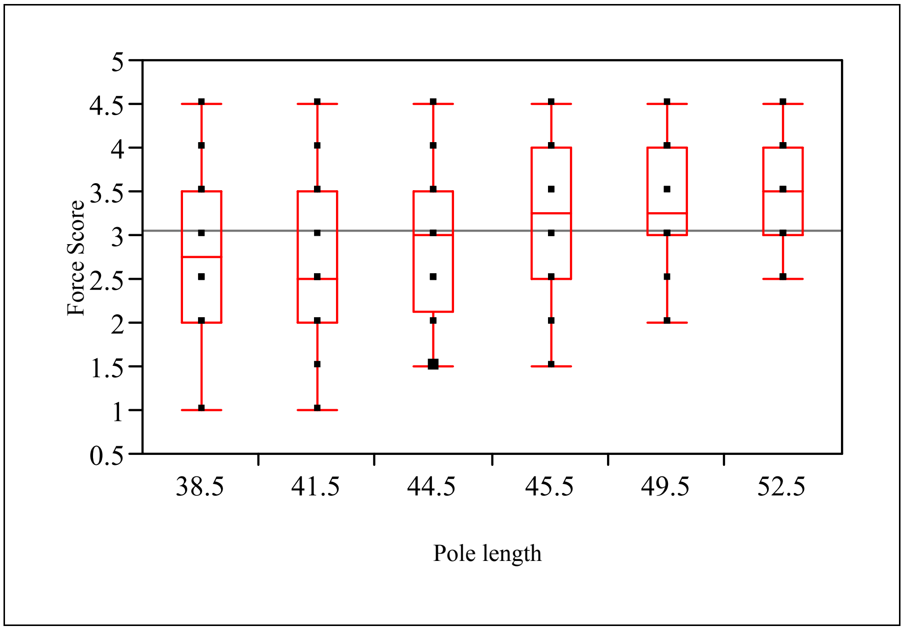


Figure 6.7 Quantile box plot of pulling force scores by pole lengths

Table 6.7 Comparisons for all pairs of pole lengths using Tukey comparison test

Abs(Dif)-LSD	52.5 (Mean = 3.469)	49.5 (Mean = 3.313)	45.5 (Mean = 3.156)	44.5 (Mean = 2.875)	38.5 (Mean = 2.844)	41.5 (Mean = 2.688)
52.5 (Mean = 3.469)	-0.86873	-0.71248	-0.55623	-0.27498	-0.24373	-0.08748
49.5 (Mean = 3.313)	-0.71248	-0.86873	-0.71248	-0.43123	-0.39998	-0.24373
45.5 (Mean = 3.156)	-0.55623	-0.71248	-0.86873	-0.58748	-0.55623	-0.39998
44.5 (Mean = 2.875)	-0.27498	-0.43123	-0.58748	-0.86873	-0.83748	-0.68123
38.5 (Mean = 2.844)	-0.24373	-0.39998	-0.55623	-0.83748	-0.86873	-0.71248
41.5 (Mean = 2.688)	-0.08748	-0.24373	-0.39998	-0.68123	-0.71248	-0.86873

(Note: Positive values show pairs of means that are significantly different.)

Table 6.8 Analysis of Variance for pole lengths

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pole length	5	7.356771	1.47135	2.0666	0.0769
Error	90	64.078125	0.71198		
C. Total	95	71.434896			

6.3.3 Subject groups vs. pulling force

The subject groups were categorized by subject's knuckle heights. Thus, in this section, the effects of four subjects' knuckle heights on pulling forces were evaluated to see the relationship between subject groups and pulling force. A Kruskal-Wallis rank sum test was conducted to test for any significant differences between subject groups and pulling force.

Force score (3.75) was the highest in 50%ile female group with knuckle height of 71 in. The second highest group (3.125) was 5%ile female group with knuckle height of 67.5 in (Figure 6.8). Comparatively, the short subjects (5%ile and 50%ile female groups) had more force complaints than the tall subjects (50%ile and 95%ile male groups). Table 6.9 showed the results of Kruskal-Wallis rank sum test for force score by subjects' knuckle height. The results showed that force score by subjects' knuckle heights was significantly different at a 95% confidence interval ($p<0.0001$).

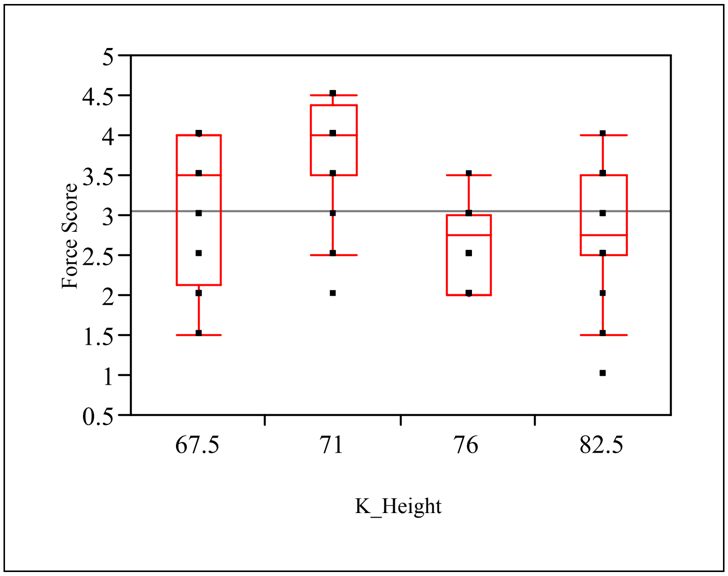


Figure 6.8 Quantile box plot of pulling force scores by subjects' knuckle heights

Table 6.9 Results of Kruskal-Wallis rank sum test for force scores by subjects' knuckle heights

		Knuckle heights				
		67.5cm (26.57 in) N = 24	71cm (27.95 in) N = 24	77.5cm (29.92 in) N = 24	82.5cm (32.48 in) N = 24	ChiSq and P-value (one-way Kruskal-Wallis rank sum test)
Pulling force (8 persons)	Mean (SD) Median (interquartile range)	3.125 (0.900) 3.5 (2.125, 4.0)	3.750 (0.737) 4.0 (3.5,4.375)	2.625 (0.472) 2.75 (2.0, 3.0)	2.729 (0.847) 2.75 (2.5, 3.5)	ChiSquare =26.259 P>ChiSq= < 0.0001*

6.3.4 Luggage size vs. pulling force

The effects of two luggage sizes on pulling forces were evaluated. A Wilcoxon rank sum test was conducted to test for any significant differences between luggage sizes and pulling force.

Figure 6.9 showed that large luggage had a slightly higher force score than small luggage (3.188 vs. 2.927) although load weight was set to equal weights (33 lbs and 50 lbs). Table 6.10 showed the results of Wilcoxon rank sum test for body part complaints by luggage size. Force score was not much different between small and large luggage ($p < 0.2199$).

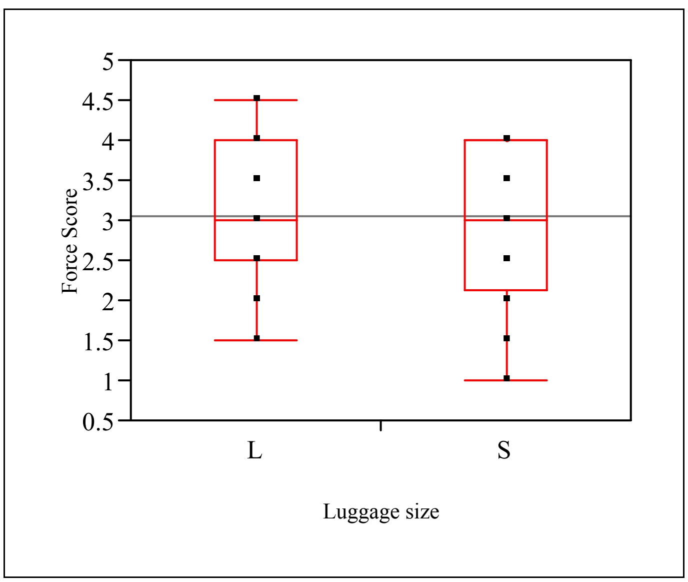


Figure 6.9 Quantile box plot of pulling force scores by luggage sizes

Table 6.10 Results of Wilcoxon rank sum test for force scores by luggage sizes

		Luggage size		
		Large N = 48	Small N = 48	Z and P-value (two tailed Wilcoxon rank sums test)
Pulling force (8 persons)	Mean (SD) Median (interquartile range	3.188 (0.823) 3.0 (2.5, 4.0)	2.927 (0.899) 3.0 (2.125, 4.0)	Z = - 1.227 P>|Z| = 0.2199

6.4 Walking time

6.4.1 Load weight vs. walking time

The effects of two load weights and walking time were evaluated. A Tukey comparison test was conducted to test for any significant differences between load weights on walking time. Figure 6.10 showed that the means of walking times were slightly higher at load weights of 50 lbs (mean of 33 lbs = 9.622 sec and mean of 50 lbs = 9.872 sec). However, the Tukey-Kramer LSD Threshold matrix showed there was no significant difference of walking time between load weights of 33 lbs and 50 lbs. The actual absolute differences in the means minus the LSDs for all pairs were negative values (Table 6.11). Table 6.12 supported that the means for two load weights were not significantly different from each other at 95 % confidence interval. (p <0.1183).

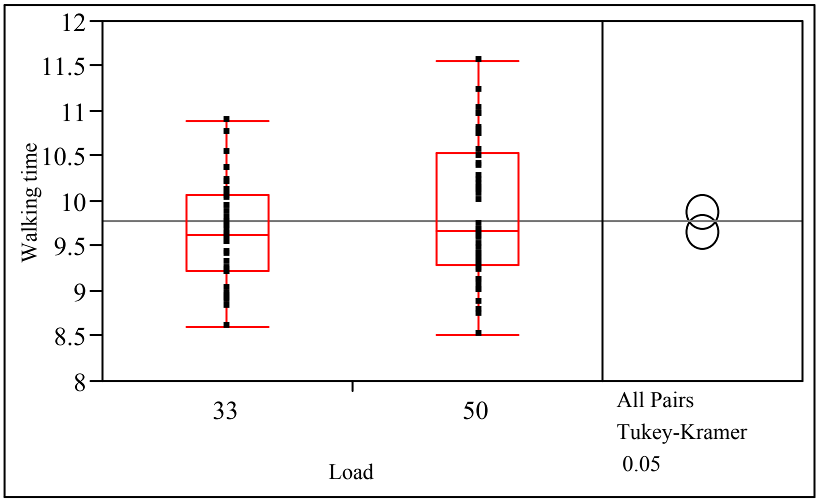


Figure 6.10 Quantile box plot of walking time by load weights

Table 6.11 Comparisons for all pairs of load weights using Tukey comparison test

Abs(Dif)-LSD	50 (Mean = 9.872)	33 (mean = 9.662)
50 (Mean =9.872)	-0.26403	-0.05440
33 (Mean = 9.662)	-0.05440	-0.26403

(Note: Positive values show pairs of means that are significantly different.)

Table 6.12 Analysis of Variance for load weights

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Load	1	1.054728	1.05473	2.4852	0.1183
Error	94	39.893912	0.42440		
C. Total	95	40.948640			

6.4.2 Pole length vs. walking time

The effects of six pole lengths and walking time were evaluated. A Tukey comparison test was conducted to test for any significant differences among pole lengths on walking time. Based on Figure 6.11, walking time was the highest at the pole length of 41.5” (the mean of walking time = 9.851 sec). The pole length of 38.5”, 45.5”, 44.5”, 52.5”, and 49.5” had the means of walking time of 9.799, 9.791, 9.729, 9.719, and 9.712 sec, respectively. Table 6.13, the Tukey-Kramer LSD Threshold matrix, showed there was no significant difference of walking time among all pairs of pole lengths. Table 6.14, ANOVA table, indicated that the means for six pole lengths were not significantly different from each other at 95 % confidence interval (p <0.9901).

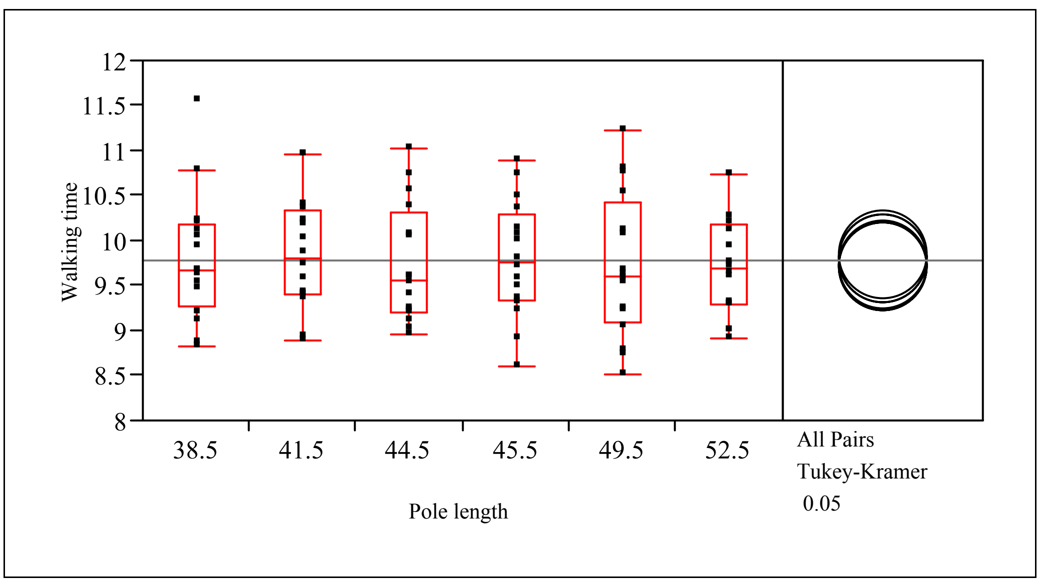


Figure 6.11 Quantile box plot of walking time by pole lengths

Table 6.13 Comparisons for all pairs of pole lengths using Tukey comparison test

Abs(Dif)-LSD	41.5 (Mean = 9.851)	38.5 (Mean = 9.799)	45.5 (Mean = 9.791)	44.5 (Mean = 9729)	52.5 (Mean = 9.719)	49.5 (Mean = 9.712)
41.5 (Mean = 9.851)	-0.69238	-0.64081	-0.63331	-0.57113	-0.56081	-0.55378
38.5 (Mean = 9.799)	-0.64081	-0.69238	-0.68488	-0.62269	-0.61238	-0.60535
45.5 (Mean = 9.791)	-0.63331	-0.68488	-0.69238	-0.63019	-0.61988	-0.61285
44.5 (Mean = 9.729)	-0.57113	-0.62269	-0.63019	-0.69238	-0.68206	-0.67503
52.5 (Mean = 9.719)	-0.56081	-0.61238	-0.61988	-0.68206	-0.69238	-0.68535
49.5 (Mean = 9.712)	-0.55378	-0.60535	-0.61285	-0.67503	-0.68535	-0.69238

(Note: Positive values show pairs of means that are significantly different.)

Table 6.14 Analysis of Variance for pole lengths

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Pole length	5	0.245754	0.049151	0.1087	0.9901
Error	90	40.702886	0.452254		
C. Total	95	40.948640			

6.4.3 Subject groups vs. walking time

The effects of four subject groups and walking time were evaluated. A Tukey comparison test was conducted to test for any significant differences between subject groups and walking time. Figure 6.12 showed that walking time was the highest at the knuckle height of 71 cm (the mean of walking time = 10.510 sec). The knuckle heights of 67.5, 82.5, and 77.5 cm had the means of walking time of 10.043, 9.263, and 9.253, respectively. Table 6.15, the Tukey-Kramer LSD Threshold matrix, walking time between the knuckle height of 71 cm and 67.5 cm, 71 cm and 82.5 cm, 71 cm and 77.5 cm, 67.5 cm and 82.5 cm, and 67.5 cm and 77.5 cm had significant differences on walking time. However, the rest of the pairs were not significantly different based on the Tukey comparison test at a 95% confidence interval. Overall results in Table 6.16 showed that the means for subjects' knuckle heights were significantly different from each other at 95 % confidence interval ($p<0.0001$).

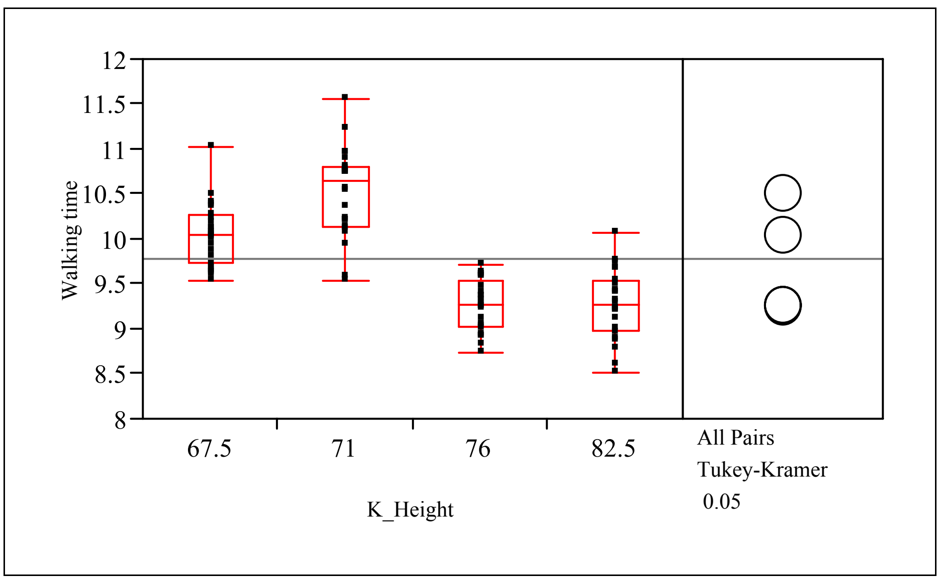


Figure 6.12 Quantile box plot of walking time by subjects' knuckle heights

Table 6.15 Comparisons for all pairs of subjects' knuckle heights using Tukey comparison test

Abs(Dif)-LSD	71 (Mean = 10.510)	67.5 (Mean = 10.043)	82.5 (Mean = 9.263)	77.5 (Mean = 9.253)
71 (Mean = 10.510)	-0.28872	0.17816	0.95816	0.96805
67.5 (Mean = 10.043)	0.17816	-0.28872	0.49128	0.50118
82.5 (Mean = 9.263)	0.95816	0.49128	-0.28872	-0.27882
77.5 (Mean = 9.253)	0.96805	0.50118	-0.27882	-0.28872

(Note: Positive values show pairs of means that are significantly different.)

Table 6.16 Analysis of Variance for subjects' knuckle heights

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
K_Height	3	27.507455	9.16915	62.7595	<.0001*
Error	92	13.441185	0.14610		
C. Total	95	40.948640			

6.4.4 Luggage size vs. walking time

The effects of two luggage sizes and walking time were evaluated. A Tukey comparison test was conducted to test for any significant differences between luggage sizes and walking time. Figure 6.13 showed that walking time with small luggage was longer than with large luggage. (the mean of walking time = 9.893 sec vs.9.641 sec). Based on the Tukey test in Table 6.17, walking time between two luggage sizes did not have significant differences on walking time. Their ANOVA table showed that the means for luggage sizes were not significantly different from each other at a 95 % confidence interval ($p < 0.0602$) in Table 6.18.

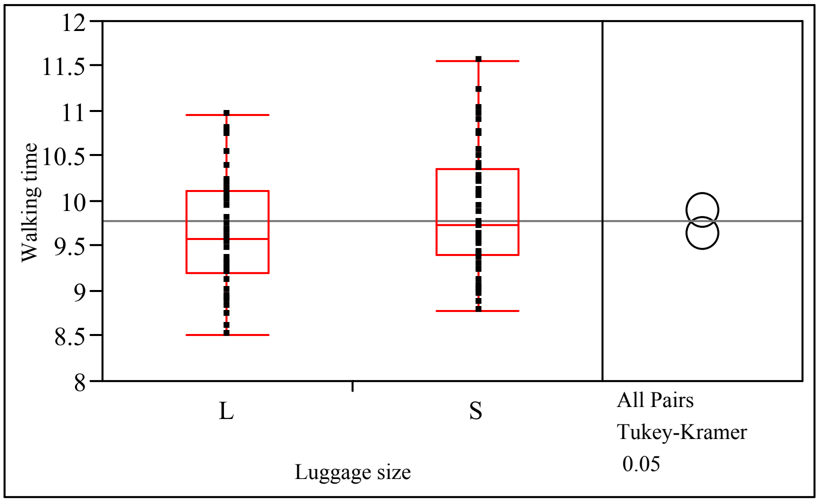


Figure 6.13 Quantile box plot of walking time by luggage sizes

Table 6.17 Comparisons for all pairs of luggage sizes using Tukey comparison test

Abs(Dif)-LSD	S (Mean = 9.893)	L (Mean = 9.641)
S (Mean = 9.893)	-0.26250	-0.01098
L (Mean =9.641)	-0.01098	-0.26250

(Note: Positive values show pairs of means that are significantly different.)

Table 6.18 Analysis of Variance for luggage sizes

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Luggage size	1	1.518180	1.51818	3.6193	0.0602
Error	94	39.430460	0.41947		
C. Total	95	40.948640			

6.5 Trip/hit

6.5.1 Load weight vs. trip/hit

The effects of two load weights on trip/hit were evaluated. A Wilcoxon rank sum test was conducted to test for any significant differences between load weights on trip/hit.

Figure 6.14 showed that the means of complaint scores of trip or hit were not much different between load weights of 33 lbs and 50 lbs in terms of median (median of 33 lbs = 1.0 and median of 50 lbs = 1.0). However, there was evidence of complaint score differences as looked at the interquartile range. In addition, according to Wilcoxon rank sum test in Table 6.19, there was significant difference between load weights of 33 lbs and 50 lbs on trip or hit at a 95% confidence interval ($p < 0.0002$).

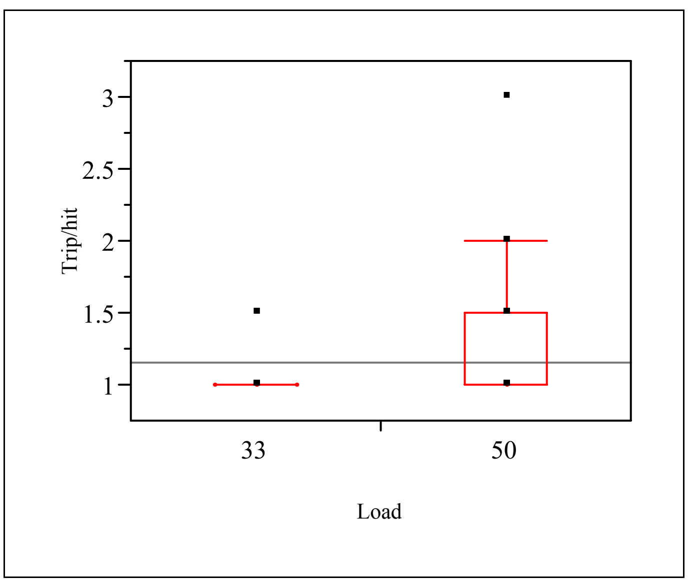


Figure 6.14 Quantile box plot of trip/hit by load weights

Table 6.19 Results of Wilcoxon rank sum test for trip/hit complaints by load weights

		Load		
		33 lbs N = 48	50 lbs N = 48	Z and P-value (two tailed Wilcoxon rank sum test)
Trip/hit (8 persons)	Mean (SD) Median (interquartile range	1.031 (0.122) 1.0 (1.0, 1.0)	1.271 (0.425) 1.0 (1.0, 1.5)	Z = 3.747 P>|Z| = 0.0002*

6.5.2 Pole lengths vs. trip/hit

The effects of six pole lengths and trip/hit were evaluated. A Kruskal-Wallis rank sum test was conducted to test for any significant differences between pole lengths and trip/hit. Based on Figure 6.15, the highest complaint score was 1.344 at the pole length of 52.5”. The pole length of 38.5”, 41.5”, 44.5”, 45.5”, and 49.5” had the means of complaint scores of 1.094, 1.125, 1.094, 1.156, and 1.094, respectively. However, the complaint scores of trip/hit were not different among pole lengths based on the median. Table 6.20 also showed that the difference of the pole lengths had no significant different on walking time based on the Kruskal-Wallis rank sum test at a 95% confidence interval ($p < 0.4762$) (Table 6.20).

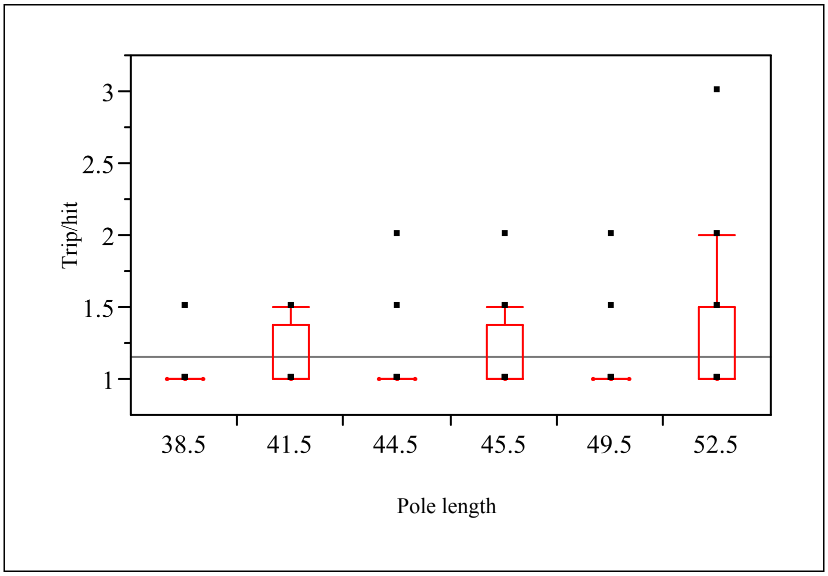


Figure 6.15 Quantile box plot of trip/hit by pole lengths

Table 6.20 Results of Kruskal- Wallis rank sum test for trip/hit complaints by pole lengths

		Pole lengths						
		38.5” N = 16	41.5” N = 16	44.5” N = 16	45.5” N = 16	49.5” N = 16	52.5” N = 16	ChiSq and P-value (one-way Kruskal-Wallis rank sum test)
Trip/hit (8 persons)	Mean (SD) Median (inter-quartile range)	1.094 (0.202) 1.0 (1.0, 2.0)	1.125 (0.224) 1.0 (1.0, 1.375)	1.094 (0.272) 1.0 (1.0, 1.0)	1.156 (0.301) 1.0 (1.0, 1.375)	1.094 (0.272) 1.0 (1.0, 1.0)	1.344 (0.569) 1.0 (1.0, 1.5)	ChiSquare = 4.528 P>ChiSq = 0.4762

6.5.3 Subject groups vs. trip/hit

The effects of four subject groups on trip/hit were evaluated. A Kruskal-Wallis rank sum test was conducted to test for any significant differences between subject groups and trip/hit. Based on Figure 6.16, the complaint score of trip/hit was obviously different at the knuckle height of 67.5 cm (the median of complaint score = 1.5). The median scores of knuckle heights of 71, 77.5, and 82.5 cm were 1.0, 1.0, and 1.0, respectively. Based on the Kruskal-Wallis rank sum test in Table 6.21, complaint scores between the knuckle height of 67.5 cm and 71 cm, the knuckle height of 67.5 cm and 77.5 cm, and the knuckle height of 67.5 cm and 82.5 cm had significant differences on trip/hit scores at a 95% confidence interval ($p < 0.0001$).

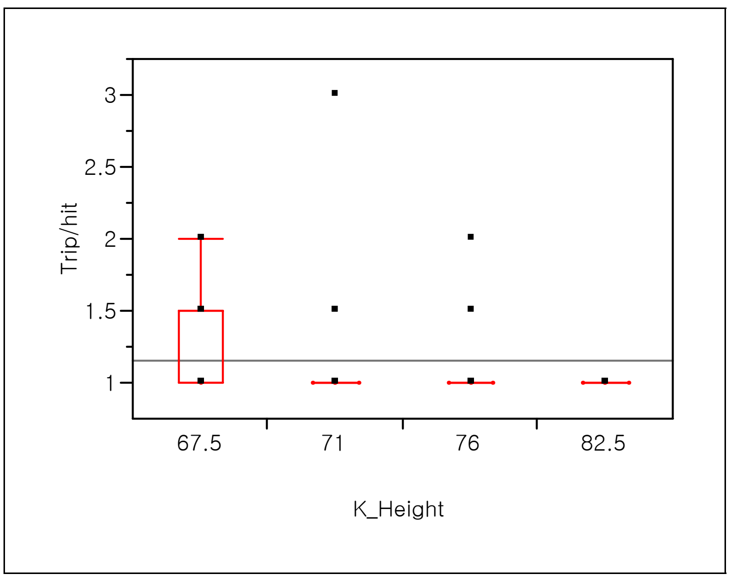


Figure 6.16 Quantile box plot of trip/hit by subjects' knuckle heights

Table 6.21 Results of Kruskal-Wallis rank sum test for trip/hit complaints by subjects' knuckle heights

		Knuckle heights				
		67.5cm (26.57 in) N = 24	71cm (27.95 in) N = 24	77.5cm (29.92 in) N = 24	82.5cm (32.48 in) N = 24	ChiSq and P-value (one-way Kruskal-Wallis rank sum test)
Trip/hit (8 persons)	Mean (SD) Median (interquartile range)	1.375 (0.369) 1.5 (1.0, 1.5)	1.146 (0.429) 1.0 (1.0, 1.0)	1.083 (0.241) 1.0 (1.0, 1.0)	1.000 (0.000) 1.0 (1.0, 1.0)	ChiSquare = 26.178 P>ChiSq = < 0.0001*

6.5.4 Luggage sizes vs. trip/hit

The effects of two luggage sizes on trip/hit were evaluated. A Wilcoxon rank sum test was conducted to test for any significant differences between luggage sizes on trip/hit. During the experiment, trip or hit were not reported from most subjects. Thus, the complaint scores were comparatively lower than in the other independent variables. Based on Figure 6.17, the medians of complaint scores for two luggage sizes were not significantly different (the median of complaint score = 1.0 sec vs.1.0). The statistical results supported this finding. Based on the Wilcoxon rank sum test in Table 6.22, the complaint scores between two luggage sizes did not have significant differences on walking time at a 95% confidence interval ($p < 0.8908$).

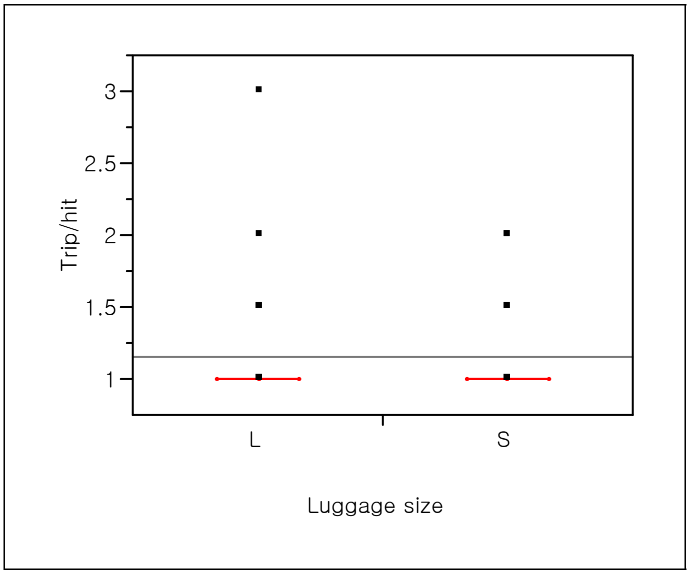


Figure 6.17 Quantile box plot of trip/hit by luggage sizes

Table 6.22 Results of Kruskal- Wallis rank sum test for trip/hit complaints by luggage sizes

		Luggage size		
		Large N = 48	Small N = 48	Z and P-value (two tailed Wilcoxon rank sum test)
Trp/hit (8 persons)	Mean (SD) Median (interquartile range	1.156 (0.360) 1.0 (1.0, 1.0)	1.146 (0.309) 1.0 (1.0, 1.0)	Z = - 0.137 P>|Z| = 0.8908

6.6 Tilted angle approximation

In this study, the relationship between tilted angle and all other dependent variables were not analyzed since the angle could be changed by person to person. Thus, this variance of person to person made it difficult for statistical analysis since huge error terms were involved. In this section, tilted angle approximation was presented by subjects' knuckle heights and pole lengths. To find the linear relationship between tilted angle and two important predictor variables (subjects' knuckle heights and pole lengths), a multiple linear regression was chosen. As seen in Table 6.23, the coefficient of determination (R^2) is 0.947. Thus, approximately 95% of the variation in tilted angle was accounted for by the predictor variables. The regression equation from Table 6.24 is expressed as following.

Tilted angle = 40.713 + 0.630 Knuckle height – 1.066 Pole length

Table 6.23 Summary of variables for tilted angle force prediction

Square	0.947103
SQuare Adj	0.945966
Root Mean Square Error	1.467749
Mean of Response	39.15365
Observations (or Sum Wgts)	96

Table 6.24 Parameter estimates for all predictors

Term	Estimate	Std Error	T Ratio	Prob>|t|
Intercept	40.713266	2.454852	16.58	<.0001
K_Height	0.6295637	0.026559	23.70	<.0001
Pole length	-1.065545	0.03208	-33.22	<.0001

CHAPTER 7 DISCUSSION

7.1 Difficulties for two-wheeled luggage use

The survey results showed that all subjects were experiencing problems with their two-wheeled luggage. Although many potential injuries existed due to a wrong selection of two-wheeled luggage, most subjects did not recognize them clearly. For instance, all subjects responded that they considered luggage size when selecting luggage. Comparatively, its handle extension and comfort grip were not a concern when they selected luggage. However, the importance of an adjustable handle and comfort grip has been emphasized as important features of carriers to reduce musculoskeletal disorders. Thus, this negligence may cause severe musculoskeletal disorders and luggage users can not be free from excessive pulling forces, awkward postures, trip/hit, and poor maneuverability without much attention to luggage selection.

In the usability test, interestingly, the subjects did not answer low back as the most complained about body part. Instead of this body part, most subjects complained the arm, wrist, and hand when they carried two-wheeled luggage. The reasons can be found out from comparatively less load weights and different motion dynamics of human body. More detailed descriptions will be presented in the next section.

7.2 Risk assessment of body parts

Many authors have suggested pushing and pulling as occupational risk factors for low back pain (de Looze et al., 2000; Frymoyer et al., 1980; Garg & Moore, 1992;

Hoozemans et al., 2004; Hoozemans et al., 2002; Kuiper et al., 1999; Lee et al., 1991; Lee et al., 1989; Snook et al., 1978). In epidemiology studies, many epidemiological studies found that the handling aids still had various injury types such as strains, sprains, bruises, cuts, etc. and 9 % to 18 % of the low back injuries were associated with pushing and pulling (Garg & Moore, 1992; Lee et al., 1991; Snook et al., 1978). de Looze et al. (2000) reported handle height clearly affected the direction of force exertion, which influences the shoulder and low back. However, a different result was concluded in this study. Based on the user's responses, the most risk-prone body part was the arm among the back, neck/shoulder, arm, wrist, and hand. The wrist and hand followed. This finding was totally understandable because the pulling was done with one hand rather than two hands. Force is transmitted from one hand to the body and its internal structures when opposing external forces are applied against the surface of the body. Therefore, the different body motion mechanism of two-wheeled luggage than four-wheeled carts resulted in more force on the arm and wrist. Surprisingly, the backache was ranked as the forth risk-prone body part. This finding was explained based on the previous studies. Based on Resnick and Chaffin (1995), subjects produced excessive spinal compression forces when the load reached 450 kg. They concluded that cart loads should be kept under 250 kg to avoid high back forces. The range between 33 lbs and 50 lbs were relatively small amounts of load and resulted in less force on the back. However, the load weight was the most influential factor on the arm complaints. Pole length and subjects' knuckle height were also important to reduce potential injuries on the arm, shoulder, and wrist as two-wheeled luggage design factors. Therefore, user's knuckle height should be considered as pole lengths are determined. Finally, luggage size did not affect body parts.

7.3 Pulling force

In this study, pulling force has been investigated in terms of load weights, pole lengths, subject groups, and luggage size. Load had a significant effect on pulling force. The heavier the load, the more pulling force was required. This result was consistent with reports from Al-Eisawi et al (1999a; 1999b). In their study, they reported that the minimum push/pull forces were linearly proportional to cart weight. In addition, they also said that higher force was applied as cart load increased. Their studies were conducted for four-wheeled carts, but this study for two-wheeled luggage was also reported the same result.

On pole length and pulling force, de Looze et al. (2000) concluded that the effects of the force level and handle height were also significant in pulling. Mechanical models in this study showed that different handle lengths were suggested to each subject group. Based on the results from the mechanical models, 41.5" for 5%ile females, 45.5" for 5%ile males and 50%ile females, 49.5" for 50%ile males and 95%ile females, and 52.5" for 95%ile males were suggested. However, all subject groups selected the pole lengths between 38.5" and 49.5" as a preferred pole length after a usability test was conducted. The results were unexpected especially in 95%ile male groups. In terms of minimum pulling force criteria, the user group should select pole lengths of 52.5". However, 95%ile male group selected 38.5" for small and large luggage. The reason was found in statistical analysis. Pulling force was not significantly different between pole lengths from 38.5" to 52.5". This finding was understandable because the pulling force differed by only 0.01 lbs in this range based on the mechanical model in Chapter 4. This small amount of load weight could be ignorable if better usability was guaranteed from the users' viewpoint. Thus, the theoretical results are not always guaranteed to provide optimal solutions. For this reason, the importance of usability test should be emphasized. In addition, there was evidence of a significant increase of pulling force under 38.5" and over 49.5". The range of pole lengths from 38.5" to 49.5" formed at the range of tilted angle from 30° to 50° by users' knuckle heights. Figure 4.6 showed that the pulling force was smallest at the tilted angle from 30° to 50° and increased beyond the range of those tilted angle. This result was also supported by the study of Chengalur et al. (2004). They reported the preferred handle height should be less than 127 cm (50 in.) in their study. Therefore, pole length should be recommended at minimum 38.5" and maximum 49.5".

The result of subjects' knuckle heights on pulling force showed that the short subjects (5%ile and 50%ile female groups) had larger force complaints than the tall subjects (50%ile and 95%ile male groups). However, Van der Beek et al. (2000) reported that male workers exerted significantly higher average forces than females. Gender differences in exerted forces were not caused by differences in anthropometry and maximum capacity. Thus, the result in study could indicate the difference of genders rather than subjects' heights.

The study of luggage size on pulling force has not been published yet. Only maneuverability and vision related study was published by Chengalur et al. (2004) and Das and Wimpee (2002). They concluded that bigger dimension made it more difficult to maneuver in a standard aisle. In this study, large luggage has a higher force score, but the difference between large and small luggage was not significantly different.

7.4 Walking time

For the relationship between load weights and walking time, the walking time took longer as pulling of heavy loads. The average velocities reached from 1.25 $m \times s^{-1}$ with 33 lbs and 1.22 $m \times s^{-1}$ with 50 lbs. This result was consistence with that of Resnick and Chaffin (1995). They reported that the slower movement speeds were required for pushing of heavy loads, especially over short distances. The peak velocities reached ranged only from 0.2 $m \times s^{-1}$ to 1.1 $m \times s^{-1}$ (MTM standard 1.80.$m \times s^{-1}$) for long distances. Thus, the peak velocities for pulling were lower than MTM, but comparatively higher than pushing. However, there was no significant different of walking speed between load weights of 33 lbs and 50 lbs.

The relationship between pole lengths and walking speed has not been published yet. In this study, the average velocities were the highest with the pole length of 49.5" (1.23 $m \times s^{-1}$). The worst pole length was 41.5" (1.22 $m \times s^{-1}$). The statistical results showed that the pole length did not influence walking speed.

The relationships between subject groups and walking speed and between luggage sizes and walking speed have also not been published. The results showed that the means for subject groups were significantly different while the means for luggage sizes were not different at 95 % confidence interval. However, this result was arguable in terms of a gender difference since the small subject groups consisted of females and the tall subject groups consisted of males. Thus, further work is required to find the relationship between different gender and walking time by considering more subject groups (5%ile male and 95%ile female groups)

However, the conclusion of this study indicated that the subject knuckle height significantly affected walking speed while load weights, pole lengths, and luggage size did not affect walking speed.

7.5 Trip/hit

Pushing and pulling were accompanied by an increased risk of accidents due to slipping or tripping. In this study, the complaint scores of trip/hit have been recorded after subjects pulled luggage with a turning operation on the curved path. The result showed that load significantly influenced on the complaint score of trip or hit. The heavier the load, the more complaint scores for trip/hit were reported. That means that the heavier load should require more force on hand and wrist and reflect the force to the complaint score. Between pole length and trip/hit, no relationship was found by changing pole lengths. However, subject groups affect trip/hit. In addition, the effects of luggage size on trip/hit were not found. This result was opposite to the result of Chengalur et al. (2004). In their study, they emphasized bigger dimensions it made more difficult to maneuver in a standard aisle. However, their study had a big flaw due to the negligence of load weights and center of mass (COM). The higher load weights and the displacement of the COM should affect on maneuverability. This study revealed that the large luggage size did not have negative effects on maneuverability if the same load weights are used and the COM is displaced in the direction of wheel axis.

7.6 Tilted angle

The relationship between tilted angle and two important predictor variables (subjects' knuckle heights and pole lengths) showed clearly that they were linearly related. The coefficient of determination (R^2) was 0.947. From the linear relationship, knuckle height was positively related while pole length was negatively related. For the increase in the knuckle height of 1 cm, the tilted angle could be changed roughly 0.63° higher from the ground. However, for increase in pole length of 1.066 inch, the tilted angle could be changed 1.066º less from the ground.

CHAPTER 8 CONCLUSION

In this chapter, section 8.1 summarizes the research conducted in this dissertation. Section 8.2 discusses research contributions and section 8.3 discusses possible extensions to this research as future work.

8.1 Research summary

This study ergonomically investigated two-wheeled luggage design through mechanical models and a usability test. The mechanical model indicated that load, tilted angle, and center of mass (COM) are the most important factors to decide pulling force. Based on this finding, two load conditions, four different subject groups, and two different luggage types were considered for a usability test.

The following conclusion can be drawn from this study.

1. A heavier luggage loads are increased, the complaint scores on all body parts increased;
2. Pole lengths have significant effects on the back, arm, and wrist.
3. As pole lengths are above 49.5”, the complaint scores on all body parts increased;
4. The arm is the most complained by all subject groups when carrying two-wheeled luggage.
5. As load weights are increased, more pulling forces are required;
6. As pole lengths are below 38.5” and above 52.5”, the pulling force increased;
7. The short subject groups feel a higher pulling force than the tall subject group while carrying two-wheeled luggage;

8. Subject groups affected walking speed;
9. Luggage size does not influence body parts, pulling force, walking speed, and trip/hit;
10. Load weights and subjects' knuckle heights significantly affect trip/hit;
11. Tilted angle is significantly related to subjects' knuckle heights and pole lengths.

From the findings, most upper body parts were affected by load weights, pole lengths, and subjects' knuckle heights. In addition, pole lengths between 38.5" and 49.5" were recommended in terms of usability although the mechanical models indicated the optimal pole lengths ranged between 38.5" and 52.5". It was found that there was a gap between theoretical and practical measurements. However, the pole lengths between 38.5" and 49.5" had an advantage since they satisfied both theoretical and practical results. With reference to the mechanical models, the difference of pulling force was only 0.01 lb in the range of pole lengths between 38.5" and 52.5". It was found that the difference of 0.01 lbs could be affordable to luggage users since the better usability of luggage was guaranteed. For this reason, pole should be adjustable within the range from 38.5" to 49.5" to maintain the tilted angle between 30º and 50º during the trip. Of course, pole length and the tilted angle should be determined by subjects' knuckle heights. Thus, load weights, pole length, and subjects' knuckle heights are primarily considered when luggage is designed.

8.2 Research Contributions

Due to business expansion or globalization, the use of two-wheeled luggage has been increased. The use of two-wheeled luggage reduces lifting and carrying activities. However, the luggage in the market has been revealed negative results in its application due to its poor design and misusage. For this reason, research on two-wheeled luggage has significant impact on travelers' health and safety. Especially, some design factors play an important role in pulling force and travelers' body postures.

As pointed out in Chapter 2, most studies have focused on industrial two- and four-wheeled carts. Comparatively, the pulling task with two-wheeled luggage has been considered as a light work and not been attracted to researchers. However, the study of two-wheeled luggage has a merit as much as that of industrial carts because the pulling task of two-wheeled luggage has different dynamics of human body. This type of material handling device is pulled with one hand, not two hands. Furthermore, the study of two-wheeled luggage has can be extended to waste containers, laundry containers, and any similar carriers. For those reasons, the design of an efficient and effective two-wheeled luggage should be considered as an important issue from human factors perspectives.

Contributions from this research are related to both the field of manufacturing engineering and human factors. The work provides critical design factors for two-wheeled carriers and a guideline of usability tests to manufacturers and human factor engineers for further research. This benefit has a broader impact on luggage design because it allows designers to probe the luggage design to gain a better understanding of how the luggage should be designed depending on different user groups.

In addition, this research has another advantage over previous studies since critical design factors are considered by mechanical models and a usability test. In our living environment, as mentioned earlier, theoretical results are not always consistent with practical results. This fact is clearly revealed through mechanical models and a usability test in this study. For instance, tall subjects (95%ile male group) select a pole length of 38.5” in the usability test although the pulling force should be a minimum at the pole length of 52.5” in the mechanical models. Therefore, it is very difficult to say that theoretical results are always optimal in the real world. This dissertation can be appreciated for initiating and providing the first stage of two-wheeled luggage study with consideration of mechanical models and a usability test. From this point of view, this study has an advantage over other studies since luggage design and its usability can be improved simultaneously.

8.3 Future work

In this study, some important factors such as ground surface, wheel maintenance, and wheel size were not considered because of the limitation of the mechanical model. Sticky and carpeted floors, poor wheel bearing system, and small wheel size increased the forces required to move the aid, while rough surfaces and bumps or steps not only increased the force, but made it difficult to move at all. For the mechanical models in the future study, 3-D models for two-wheeled luggage including biomechanical models are suggested to explain the effects of the missing factors on pulling force. In addition, as mentioned earlier, gender differences issue should be considered with a more systematical manner in the future study. To achieve more realistic results, the mechanical models in this study should be validated based on kinematical and biomechanical analysis with different tasks. An ideal case (walking on the flat and tiled surface) was selected as the task in this study, but the future study should be conducted with more difficult tasks such as running on flat or curved surface and pulling the luggage on the hills or steps. Although survey questionnaires are developed for this study, the questionnaires should be continually improved and refined their structures and presentations for the future study. Finally, this study will be extended to waste containers, laundry containers, and any similar carriers in the future study.

REFERENCES

REFERENCES

Al-Eisawi, K. W., Kerk, C. J., Congleton, J. J., Amendola, A. A., Jenkins, O. C., & Gaines, W. (1999a). Factors affecting minimum push and pull forces of manual carts. *Appl Ergon, 30*(3), 235-245.

Al-Eisawi, K. W., Kerk, C. J., Congleton, J. J., Amendola, A. A., Jenkins, O. C., & Gaines, W. (1999b). The effect of handle height and cart load on the initial hand forces in cart pushing and pulling. *Ergonomics, 42*(8), 1099-1113.

Anderson, J. E. (1983). *Grant's Atlas of Anatomy* (8th Ed. ed.). Baltimore, MA 21202: Williams & Winkins.

Armstrong, T. J., Buckle, P., & Fine, L. J. e. a. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scand J Work Envirn Health., 19*, 73-84.

Arvidsson, I., Akesson, I., & Hansson, G. A. (2003). Wrist movements among females in a repetitive, non-forceful work. *Appl Ergon, 34*(4), 309-316.

Baril-Gingras, G., & Lortie, M. (1995). The handling of objects other than boxes: univariate analysis of handling techniques in a large transport company. *Ergonomics, 38*, 905-925.

Batmanabane, M., & Malathi, S. (1985). Movements at the carpometacarpal and metacapophalangeal joints of the hand and thier effect on the dimensions of the articular ends of the metacarpal bones. *Anat. Rec., 213*, 102-110.

Bernard, B. P. (1997). *Musculoskeletal Disorders (MSDs) and Workplace Factors: A critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back.* Washington, DC: US Dept of Health and Human Services, National Institute of Occupational Safety and Health.

Burdorf, A., & Sorock, G. (1997). Positive and negative evidence of risk factors for back disorders. *Scand J Work Environ Health, 23*(4), 243-256.

Bureau of Labor Statistics. (2003). *US Dept of Labor, Bereau of Labor Statistics*.

Calais-Germain, B. (1993). *Anatomy of Movement* (English language edition ed.). Seattle, WA 98139: Eastland Press.

Card, S. K., Moran, T. P., & Newell, A. (1983). *The psychology of human-computer interaction*. Hillsdale, N.J.: L. Erlbaum Associates.

Chaffin, D. B. (1979). Manual materials handling: the cause of over-exertion injury and illness in industry. *J Environ Pathol Toxicol, 2*(5), 31-66.

Chaffin, D. B. (1987). Manual materials handling and the biomechanical basis for prevention of low-back pain in industry--an overview. *Am Ind Hyg Assoc J, 48*(12), 989-996.

Chengalur, S. N., Rodgers, S. H., & Bernard, T. E. (2004). *Kodak's ergonomic design for people at work* (2nd ed.). Hoboken, N.J.: Wiley.

Ciriello, V. M., MCGorry, R. W., & Martin, S. E. (2001). Maximum acceptable horizontal and vertical forces of dynamic pushing on high and low coefficient of friction floors. *International Journal of Industrial Ergonomics, 27*, 1-8.

Crumpton-Young, L. L., & Killough, M. K. e. a. (2000). Quantitative analysis of cumulative trauma risk factors and risk factor interactions. *J Occup Environ Med., 42*(1013-1020).

Das, B., & Wimpee, J. (2002). Ergonomics evaluation and redesign of a hospital meal cart. *Appl Ergon, 33*(4), 309-318.

de Looze, M. P., Stassen, A. R., Markslag, A. M. T., Borst, M. T., Wooning, M. M., & Toussaint, H. M. (1995). Mechanical loading on the low back in three methods of refuse collecting. *Ergonomics, 38*, 1993-2006.

de Looze, M. P., van Greuningen, K., Rebel, J., Kingma, I., & Kuijer, P. P. (2000). Force direction and physical load in dynamic pushing and pulling. *Ergonomics, 43*(3), 377-390.

Estryn-Behar, M., Kaminski, M., Peigne, E., Maillard, M. F., Pelletier, A., Berthier, C., et al. (1990). Strenuous working conditions and musculo-skeletal disorders among female hospital workers. *Int Arch Occup Environ Health, 62*(1), 47-57.

Feuerstein, M., Miller, V. L., Burrell, L. M., & Berger, R. (1998). Occupational upper extremity disorders in the federal workforce: prevalnce, health care expenditures, and patterns of work disability. *J Occup Environ Med., 40*, 546-555.

Friedrich, M., Kranzl, A., Heiller, I., Kirtley, C., & Cermak, T. (2000). Spinal posture during stooped walking under vertical space constraints. *Spine, 25*(9), 1118-1125.

Frymoyer, J. W., Pope, M. H., Costanza, M. C., Rosen, J. C., Goggin, J. E., & Wilder, D. G. (1980). Epidemiologic studies of low-back pain. *Spine, 5*(5), 419-423.

Garcin, M., Cravic, J. Y., Vandewalle, H., & Monod, H. (1996). Physiological strains while pushing or hauling. *Eur J Appl Physiol Occup Physiol, 72*(5-6), 478-482.

Garg, A., & Beller, D. (1990). Onehanded dynamic pulling strength with special reference to speed, handle height and angle of pulling. *International Journal of Industrial Ergonomics, 6*, 231-240.

Garg, A., & Moore, J. S. (1992). Epidemiology of low-back pain in industry. *Occup Med, 7*(4), 593-608.

Hales, T. R., & Bernard, B. P. (1996). Epidemiology of work-related musculoskeletal disorders. *Orthop Clin North Am, 27*, 679-709.

Harkness, E. F., Macfarlane, G. J., Nahit, E., Silman, A. J., & McBeth, J. (2004). Mechanical injury and psychosocial factors in the work place predict the onset of widespread body pain: a two-year prospective study among cohorts of newly employed workers. *Arthritis Rheum, 50*(5), 1655-1664.

Harkness, E. F., Macfarlane, G. J., Nahit, E. S., Silman, A. J., & McBeth, J. (2003). Mechanical and psychosocial factors predict new onset shoulder pain: a prospective cohort study of newly employed workers. *Occup Environ Med, 60*(11), 850-857.

Haslam, R. A., Boocock, M., Lemon, P., & Thorpe, S. (2002). Maximum acceptable loads for pushing and pulling on floor surfaces with good and reduced resistance to slipping. *Safety Science, 40*, 625-637.

Hoozemans, M. J., Kuijer, P. P., Kingma, I., van Dieen, J. H., de Vries, W. H., van der Woude, L. H., et al. (2004). Mechanical loading of the low back and shoulders during pushing and pulling activities. *Ergonomics, 47*(1), 1-18.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van der Woude, L. H., & van Dijk, F. J. (2002). Pushing and pulling in association with low back and shoulder complaints. *Occup Environ Med, 59*(10), 696-702.

Hoozemans, M. J., van der Beek, A. J., Frings-Dresen, M. H., van Dijk, F. J., & van der Woude, L. H. (1998). Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. *Ergonomics, 41*(6), 757-781.

Jansen, J. P., Hoozemans, M. J., van der Beek, A. J., & Frings-Dresen, M. H. (2002). Evaluation of ergonomic adjustments of catering carts to reduce external pushing forces. *Appl Ergon, 33*(2), 117-127.

John, B. E., & Kieras, D. E. (1996a). The GOMS Family of User Interface Analysis Techniques: Comparison and Contrast. *ACM transactions on computer-human interaction, 3*(4), 320-351.

John, B. E., & Kieras, D. E. (1996b). Using GOMS for user interface design and Evaluation: Which Technique? *ACM transactions on computer-human interaction, 3*(4), 287-319.

Kieras, D. E. (1988). Towards a practical GOMS model methodoloy for user interface design. In *Handbook of human-computer interaction* (pp. xxxiii, 1167). Amsterdam ; New York
New York, N.Y., U.S.A.: North-Holland ;
Sole distributors for the U.S.A. and Canada Elsevier Science Pub. Co.

Kieras, D. E., Wood, S. W., Abotel, K., & Hornof, A. (1995). *Glen: A Computer-Based Tool for Rapid GOMS Model Usability Evaluation of User Interface Designs.* Paper presented at the Paper presented at the Proceedings of the 8th annual ACM symposium on User interface and software technology, Pittsburgh, Pennsylvania, United States.

Kingma, I., Kuijer, P. P., Hoozemans, M. J., van Dieen, J. H., van der Beek, A., & Fring-Dresen, M. H. (2003). Effect of design of two-wheeled containers on mechanical loading. *International Journal of Industrial Ergonomics, 31*, 73-86.

Kuijer, P. P., Hoozemans, M. J., Kingma, I., Van Dieen, J. H., De Vries, W. H., Veeger, D. J., et al. (2003). Effect of a redesigned two-wheeled container for refuse collecting on mechanical loading of low back and shoulders. *Ergonomics, 46*(6), 543-560.

Kuiper, J. I., Burdorf, A., Verbeek, J. H. A. M., Frings-Dresen, M. H. W., van der Beek, A. J., & Viikari-Juntura, E. R. A. (1999). Epidemiologic evidence on manual materials handling as risk factors for back disorders. A systematic review. *International Journal of Industrial Ergonomics, 24*, 389-404.

Kumar, S., Narayan, Y., & Bacchus, C. (1995). Symmetric and asymmetric two-handed pull-push strength of young adults. *Hum Factors, 37*(4), 854-865.

Latko, W. A., Armstrong, T. J., & Franzblau, A. e. a. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorers. *Am J Ind Med, 36*, 248-259.

Laursen, B., & Schibye, B. (2002). The effect of different surfaces on biomechanical loading of shoulder and lumbar spine during pushing and pulling of two-wheeled containers. *Appl Ergon, 33*(2), 167-174.

Lee, K. S., Chaffin, D. B., Herrin, G. D., & Waikar, A. M. (1991). Effect of handle height on lower-back loading in cart pushing and pulling. *Appl Ergon, 22*(2), 117-123.

Lee, K. S., Chaffin, D. B., Waikar, A. M., & Chung, M. K. (1989). Lower back muscle forces in pushing and pulling. *Ergonomics, 32*(12), 1551-1563.

Lewis, J. R. (1994). Sample sizes for usability studies: additional considerations. *Hum Factors, 36*(2), 368-378.

Macfarlane, g. J., Hunt, I. M., & Silan, A. J. (2000). Role of mechanical and psychosocial factors in the onset of forearm pain: prospective population based study. *BMJ, 321*, 676-679.

Macfarlane, G. J., Thomas, E., Papageorgiou, A. C., Croft, P. R., Jayson, M. I., & Silman, A. J. (1997). Employment and physical work activities as predictors of future low back pain. *Spine, 22*(10), 1143-1149.

Mack, K., Haslegrave, C. M., & Gray, M. I. (1995). Usability of manual handling aids for transporting materials. *Appl Ergon, 26*(5), 353-364.

Manning, D. P. (1983). Deaths and injuries caused by slipping, tripping and falling. *Ergonomics, 26*(1), 3-9.

Manning, D. P., Mitchell, R. G., & Blanchfield, L. P. (1984). Body movements and events contributing to accidental and nonaccidental back injuries. *Spine, 9*(7), 734-739.

Marras, W. S. (2000). Occupational low back disorder causation and control. *Ergonomics, 43*(7), 880-902.

Molteni, G., & De Vito, G. (2001). [Diseases caused by repetitive trauma of the upper limbs: epidemiology, diagnosis, prevention. Epidemiological aspects]. *G Ital Med Lav Ergon, 23*(2), 110-115.

Neal, C. (1997). The assessment of knowledge and application of proper body mechanics in the workplace. *Orthop Nurs, 16*(1), 66-67, 69.

Nielsen, J. (1994a). Heuristic evaluation. In *Usability inspection methods* (pp. 25-62): John Wiley \& Sons, Inc.

Nielsen, J. (1994b). *Usability engineering* ([Updated] ed.). San Francisco, Calif.: Morgan Kaufmann Publishers.

Nielsen, J. (1994b). *Usability engineering* ([Updated] ed.). San Francisco, Calif.: Morgan Kaufmann Publishers.

Nielsen, J., & Mack, R. (1994). *Usability Inspection Methods*. New York, NY: John Wiley and Sons.

Okunribido, O. O., & Haslegrave, C. M. (1999). Effect of handle design for cylinder trolleys. *Appl Ergon, 30*(5), 407-419.

Pope, M. H. (1989). Risk indicators in low back pain. *Ann Med, 21*(5), 387-392.

Ranney, D. (1993). Work-related chronic injuries of the forearm and hand: their specific diagnosis and management. *Ergonomics, 36*, 871-880.

Resnick, M. L., & Chaffin, D. B. (1995). An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. *Appl Ergon, 26*(3), 173-178.

Sanders, M. S., & McCormick, E. J. (1993). *Human Factors In Engineering and Design* (English language edition ed.). Seattle, WA 98139: Eastland Press.

Schibye, B., Sogaard, K., Martinsen, D., & Klausen, K. (2001). Mechanical load on the low back and shoulders during pushing and pulling of two-wheeled waste containers compared with lifting and carrying of bags and bins. *Clin Biomech (Bristol, Avon), 16*(7), 549-559.

Schoenmarklin, R. W., Marras, W. S., & Leurgans, S. E. (1994). Industrial wrist motions and incidence of hand/wrist cumulative trauma disorders. *Ergonomics, 37*, 1449-1459.

Schultz, R. J., Stroave, A., & Krishnamurthy, S. (1987). Metacarpophalangeal joint motion and the role of the collateral ligaments. *International orthopaedics, 11*, 149-155.

Serway, R. A., & Faughn, J. S. (2003). *College Physics*: Brooks Cole; 6th Edition.

Shackel, B. (1990). Human factors and usability. In *Human-computer interaction* (pp. 27-41): Prentice Hall Press.

Silverstein, B. A., Fine, L. J., & Armstrong, T. J. (1986). Hand wrist cumulative trauma disorders in industry. *Br J Ind Med., 43*, 779-784.

Smedley, J., Inskip, H., Trevelyan, F., Buckle, P., Cooper, C., & Coggon, D. (2003). Risk factors for incident neck and shoulder pain in hospital nurses. *Occup Environ Med, 60*(11), 864-869.

Snook, S. H., Campanelli, R. A., & Hart, J. W. (1978). A study of three preventive approaches to low back injury. *J Occup Med, 20*(7), 478-481.

Springhouse Corporation. (2001). *Atlas of human anatomy*. Springhouse, Pa.: Springhouse.

Steindler, A. (1955). *Kinesiology of the human body*: Charles Thomas Publisher.

Stock, S. R. (1991). Workplace ergonomic factors and the developmentr of musculoskeletal disorders of the neck and upper limbs:a meta-analysis. *Am J Ind Med*(87-107).

Suherman, S., & Plaut, R. H. (1997). Effect of human response time on rocking instability of a two-wheeled suitcase. *Journal of Sound and Vibration, 207*(5), 617-625.

Thelen, D. G., Ashton-Miller, J. A., & Schultz, A. B. (1996). Lumbar muscle activities in rapid three-dimensional pulling tasks. *Spine, 21*(5), 605-613.

US Dept of Labor, O. S. a. H. A. (2000). *Ergonomics Program; Final Rule: 29 CFR Part 1910*: US Dept of Labor, Occupational Safety and Health Administration. Federal Register.

van der Beek, A. J., Frings-Dresen, M. H., van Dijk, F. J. H., Kemper, H. C. G., & Meijman, T. F. (1993). Loading and unloading by lorry drivers and musculoskeletal complaints. *International Journal of Industrial Ergonomics, 12*, 13-23.

van der Beek, A. J., Kluver, B. D., Frings-Dresen, M. H., & Hoozemans, M. J. (2000). Gender differences in exerted forces and physiological load during pushing and pulling of wheeled cages by postal workers. *Ergonomics, 43*(2), 269-281.

Virzi, R. A. (1992). Refining the test phase of usability evaluation: how many subjects is enough? *Hum. Factors, 34*(4), 457-468.

Wassermann, R. J., Howard, R., Markee, B., Payne, W., Ondrovic, L., Lee, W., et al. (1997). Optimization of the MGH repair using an algorithm for tenorrhaphy evaluation. *Plast Reconstr Surg, 99*(6), 1688-1694.

Winkel, J., & Mathiassen, S. E. (1994). Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. *Ergonomics, 37*, 979-988.

Youm, Y., Mcmurty, R. Y., A.E., F., & T.E., G. (1978). Kinematics of the wrist. *Journal of bone and joint surgery, 60*(A), 424-431.

APPENDIX

Appendix A Consent form

The University of Tennessee
Department of Industrial and Information Engineering

Title of Project: Design Assessment of a Wheeled Luggage Based on Mechanical Models and Usability Test

Principal Investigator: Jun-Seok Lee (865-974-9814, jlee20@utk.edu)
Other Investigators: Dongjoon Kong, Ph.D. (865-974-3079, dkong@utk.edu)
Robert Ford, Ph.D. (865-974-7567, cford@utk.edu)

1. INTRODUCTION:

The purpose of this study is to ergonomically investigate for selecting optimal luggage design through mechanical models for pulling force estimation and a usability test. This study suggests a luggage design criteria by comparing the various configurations of a wheeled carry-on luggage. This thesis addressed the following research objectives: (1) to examine the pulling force in motion phases of luggage through a mechanical model analysis, (2) to validate a mechanical model for pulling force through experimental studies of a pulling task, (3) to measure the hand and wrist tendon force through an experiment, (4) to investigate the users' preference through a usability test, and (5) to provide guidelines of an optimal luggage criteria with a comparison of various luggage types. Eight healthy, active males and females, of ages ranging from 20 to 40 years will be recruited from the student population at the University of Tennessee. The subjects are divided into four groups: five-percentile female group (2 persons), fifty-percentile female group (2 persons), fifty-percentile male group (2 persons), and ninety-five percentile male group (2 persons) according to their heights. Four different types of luggage and two different load weights (33 lbs and 50 lbs) will be used. Each participant will perform 48 luggage-pulling trials in about 2.5 hours. During the experiment, the participation's hand and shoulder posture will be recorded with three video recorders. For the usability test, a set of well-prepared survey questionnaire, which consists of 30 questions, will be answered by each participant. These sessions will not exceed 0.5 hour.

2. PROCEDURES TO BE FOLLOWED:

The participant agrees to the following procedures in order to participate in this study. Participants will be provided a brief description of the goals and procedures of the experiment before the experiment starts. Each applicant who agrees to participate will be measured his/her body dimensions including heights, weights, and knuckle heights. Then he/she completes a set of experiments and a set of survey for the usability test. In the experiments, pulling force will be measured while participants will walk about 0.1 mile with wheeled luggage on the carpeted and non-carpeted ground surfaces under various conditions of design features of wheeled luggage. In addition, a glove mapping system which has 12 sensors will be used for evaluate finger and phalange force contributions. Four different types of luggage and two different load weights (33 lbs and 50 lbs) will be used. Each participant will perform 32 luggage-pulling trials and the participants' hand and shoulder posture will be recorded with three video recorders. For the usability test, a set of well-prepared survey questionnaire, which consists of 30 questions, will be answered by each participant..

3. RISKS ASSOCIATED WITH PARTICIPATION:

The medical and/or emotional risks involved in this study are minimal. Slight fatigue due to a long walk and trip by carpet or luggage may be resulted. The fatigue can be reduced with a short break, approximately 3-5 minutes, between trials. If fatigue persists over time or any participant refuse to participate, the study will be terminated for the participant. For the trip issue, the experimental setup will be performed by a qualified technician or the principal investigator and warnings are verbally informed in the event that abnormal working condition will be involved.

4. BENEFITS ASOCIATED WITH PARTICIPATION:

From this study, we have some benefits economically and ergonomically.
For me,
1. Understand design factors to develop more comfortable luggage design
For other researchers,
2. Provide study guidelines for two-wheeled carriers.
For luggage users,
3. Minimize the force and provide better hand posture required to perform tasks.
4. Maximize the safety, health, and well-being of all luggage users.
For luggage industry,
5. Continually improve the quality and reliability of products.
6. Minimize insurance and hospitalization cost by improving safety.
7. Provide important design factors for luggage industry.
For airline industry,
8. Recommend baggage allowance including size and weight for airline industry.

5. ALTERNATIVES TO PARTICIPATION:

There are no alternative procedures incorporated into this study.

6. CONFIDENTIALITY:

My participation in this study is confidential. Identification and records of all participants will be known only to the investigators and strictly kept confidential in locked filing cabinets in Human Factors Lab and will be destroyed after data analysis. In the event of any publication of this study, no personal identifiable information will be disclosed.

7. COMPENSATION AND TREATMENT FOR INJURY:

I understand that I am not waiving any legal rights or releasing the University of Tennessee or its agents from liability for negligence. I understand that, in the event of physical injury resulting from research procedures, the University of Tennessee does not have funds budgeted for compensation either for lost wages or for medical treatment. Therefore, the University of Tennessee does not provide for treatment or reimbursement for such injuries".

8. QUESTIONS:

I have an opportunity to ask any questions that I may have regarding this study and am confident that they will be answered to my satisfaction. Questions regarding the nature of the research should be directed to Dr. Dongjoon Kong (865-974-3079).

9. PAYMENT FOR PARTICIPATION:

There is no compensation, monetary or otherwise, for participating in this study.

10. COSTS OF PARTICIPATION:

No additional costs to the subject result from participation in the research.

11. PREMATURE TERMINATION:

The medical and/or emotional risks involved in this study are minimal. However, the subject's participation may be terminated by the investigator if fatigue persists over time during the study period or any participant refuse to participate.

12. VOLUNTARY PARTICIPATION:

I understand that my participation in this study is voluntary. I am 18 years of age or older and have no physical problem in handling the wheeled luggage. I may decline to participate without penalty. If I decide to participate, I may withdraw from the study at anytime without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed, your data will be returned to you or destroyed.

13. CONSENT OF SUBJECT:

I have read or have had read to me the description of the research study as outlined above. The investigator or his/her representative has explained the study to me and has answered all of the questions I have at this time. I have been told of the potential risks, discomforts, side effects and adverse reactions as well as the possible benefits (if any) of the study. In addition, I have received a copy of this form.

Participant's name (print) ___________________________________

Participant's signature ___________________________________ Date _____________

I, the undersigned, have defined and explained the studies involved to the above participant.

____

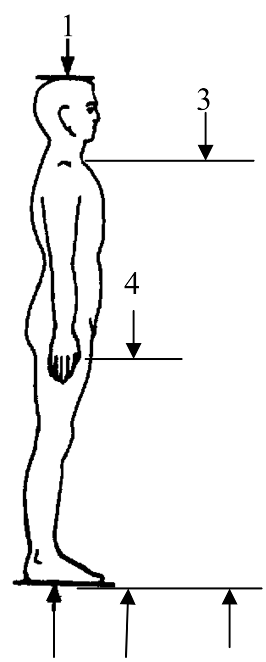
Principal Investigator Date

Appendix B Anthropometric and luggage Information

NAME: ___________________________________

The height and weight will be measured in indoor clothing without shoes.

No	Dimension	ft. in.	lbs.
1	**Height**		
2	**Weight**		
3	**Shoulder height**		
4	**Knuckle height**		



Appendix C Pre-Questionnaire

Thank you for considering being a volunteer for our usability test. Please read the following questions and reply by filling in the correct answer, circling the correct answer, or making an *X* (or color in) the answer that best applies. Thank you again for your participation in this usability test.

DEMOGRAPHIC INFORMATION

1. Name: ____

2. Gender: M F

3. Age: __________

4. Right or Left Handed: R L

WHEELED LUGGAGE EXPERIENCE

5. What is your experience with two-wheeled luggage while traveling?
   [ ] Used extensively [ ] Often used [ ] Sometimes used
   [ ] Rarely used [ ] Never used

6. In general what features do you think the most important when you select two-wheeled luggage? (Check all that apply)
   [ ] Material [ ] Size [ ] Exterior [ ] Interior [ ] Handle type
   [ ] Expansion of handle [ ] Comport grip [ ] Larger wheel
   [ ] Others __________

7. Have you ever been experienced any difficulties (i.e. excessive pulling force, awkward posture, trip/hit, maneuverability, etc.) while you carried two-wheeled luggage?
   [ ] Always [ ] Often [ ] Sometimes [ ] Rarely [ ] Never

If you answered “Never”, please “Stop here”. Otherwise, move on the next questions below.

8. Have you ever experienced excessive pulling force while carrying two-wheeled luggage?
[ ] Always [ ] Often [ ] Sometimes [ ] Rarely [ ] Never

9. What body parts were uncomfortable by excessive pulling force? (check all that apply)
[ ] Low back [ ] Shoulder [ ] Arm [ ] Wrist
[ ] Hand [ ] Leg [ ] Foot [ ] Others ___________

10. Have you ever experienced awkward posture while carrying two-wheeled luggage?
[ ] Always [ ] Often [ ] Sometimes [ ] Rarely [ ] Never

11. What body parts were uncomfortable by awkward posture? (check all that apply)
[ ] Low back [ ] Shoulder [ ] Arm [ ] Wrist
[ ] Hand [ ] Leg [ ] Foot [ ] Others ___________

12. Have you ever experienced tripping or hitting by two-wheeled luggage while traveling?
[ ] Always [ ] Often [ ] Sometimes [ ] Rarely [ ] Never

13. What body parts were uncomfortable by trip or hit? (check all that apply)
[ ] Low back [ ] Shoulder [ ] Arm [ ] Wrist
[ ] Hand [ ] Leg [ ] Foot [ ] Others ___________

14. Have you ever had a difficulty for maneuvering (controlling) two-wheel luggage while traveling?
[ ] Always [ ] Often [ ] Sometimes [ ] Rarely [ ] Never

15. What body parts were uncomfortable while maneuvering two-wheeled luggage? (check all that apply)
[ ] Low back [ ] Shoulder [ ] Arm [ ] Wrist
[ ] Hand [ ] Leg [ ] Foot [ ] Others ___________

Appendix D Post-Questionnaire (33lbs/50lbs)

Thank you for considering being a volunteer for our usability test. Please read the following questions and reply by filling in the correct answer, circling the correct answer, or making an *X* (or color in) the answer that best applies. Thank you again for your participation in this usability test.

Name: ____

USABILITY ISSUE (SMALL LUGGAGE WITH 38.5" POLE LENGTH)

1. Backache occurred in any motion phases when I carried two-wheeled luggage.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

2. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

3. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

4. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

5. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

6. I think the luggage could be made more usable.
   [ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

7. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

8. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (SMALL LUGGAGE WITH 41.5" POLE LENGTH)

9. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

10. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

11. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

12. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

13. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

14. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

15. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

16. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (SMALL LUGGAGE WITH 44.5" POLE LENGTH)

17. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

18. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

19. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

20. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

21. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

22. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

23. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

24. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (SMALL LUGGAGE WITH 45.5" POLE LENGTH)

25. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

26. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

27. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

28. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

29. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

30. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

31. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

32. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (SMALL LUGGAGE WITH 49.5" POLE LENGTH)

33. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

34. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

35. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

36. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

37. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

38. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

39. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

40. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (SMALL LUGGAGE WITH 52.5" POLE LENGTH)

41. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

42. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

43. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

44. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

45. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

46. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

47. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

48. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

LUGGGE SELECTION (SMALL LUGGAGE)

49. The adjustable handle should be designed by considering human heights to minimize pulling force.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

50. Which handle length of the small luggage was the most comfortable in terms of pulling force?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

51. Which handle length of the small luggage was the most stable for you?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

52. Which handle length of the small luggage was the most steerable for you?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

53. Which handle length of the small luggage was the safest from hitting/tripping?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

54. Which load was required less effort while the small luggage was being carried?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

55. Fewer loads helped to decrease pulling force.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

USABILITY ISSUE (LARGE LUGGAGE WITH 38.5” POLE LENGTH)

56. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

57. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

58. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

59. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

60. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

61. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

62. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

63. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (LARGE LUGGAGE WITH 41.5” POLE LENGTH)

64. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

65. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

66. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

67. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

68. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

69. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

70. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

71. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (LARGE LUGGAGE WITH 44.5" POLE LENGTH)

72. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

73. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

74. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

75. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

76. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

77. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

78. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

79. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (LARGE LUGGAGE WITH 45.5" POLE LENGTH)

80. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

81. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

82. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

83. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

84. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

85. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

86. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

87. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (LARGE LUGGAGE WITH 49.5" POLE LENGTH)

88. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

89. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

90. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

91. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

92. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

93. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

94. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

95. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

USABILITY ISSUE (LARGE LUGGAGE WITH 52.5" POLE LENGTH)

96. Backache occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

97. Neck and shoulder pain occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

98. Arm pain was occurred in any motion phases when I carried two-wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

99. Wrist pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

100. Hand pain was occurred in any motion phases when I carried the wheeled luggage.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

101. I think the luggage could be made more usable.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

102. Whenever I made a mistake (i.e., slipping, tripping, hitting, etc.) using the luggage, I recovered easily and quickly.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

103. Overall rating of effort (4-very heavy and 0-very light).
[ ] 4 [ ] 3 [ ] 2 [ ] 1 [ ] 0

LUGGGE SELECTION (LARGE LUGGAGE)

104. The adjustable handle should be designed by considering human heights to minimize pulling force.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

105. Which handle length of the large luggage was the most comfortable for you?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

106. Which handle length of the large luggage was the most stable for you?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

107. Which handle length of the large luggage was the most steerable for you?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] 45.5” [ ] 48.5” [ ] 51.5”
[ ] No difference

108. Which handle length of the large luggage was the safest from hitting/tripping?
[ ] 38.5” [ ] 41.5” [ ] 44.5” [ ] No difference

109. Fewer loads helped to decrease pulling force.
[ ] Absolutely [ ] Very much [ ] Moderately [ ] Slightly [ ] Never

USABILITY ISSUE (GENERAL)

110. Do you have any other comments, criticisms or suggestions relating to the usability (ease of use) of the current luggage?

Comments:

____

Criticisms/Negative aspects:

____

Suggestions:

____

111. List the most positive aspect(s) of the current luggage.

____

VITA

Jun-Seok Lee was born in Kwangju, Korea, on April 12, 1969, and he had lived in Kwangju until he was 28. In 1987, he graduated from Suk-San High School and entered the Chosun University, Kwangju, Korea. He received a Bachelor of Science degree in Industrial Engineering from Chosun University in 1992. He began his Masters program in Industrial Engineering at the University of Tennessee, Knoxville in 1998, and continued his PhD program specializing in Human Factors in the Industrial and Information engineering department at UT in 2001. He completed his work toward a Ph.D. degree in 2006. He has been conducting research within the industrial ergonomics, human computer interaction, automobile ergonomics, and usability fields for the past 8 years, and is very familiar with testing protocol. Jun-Seok has also participated in many classes involving ergonomics, statistics, and computer labs, as well as assisting in some of the industrial engineering classes.