ERGONOMIC INVESTIGATION OF A LOAD CARRYING TASK DURING STAIR CLIMBING

by

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ABSTRACT

ERGONOMIC INVESTIGATION OF A LOAD CARRYING TASK DURING STAIR CLIMBING

Load carrying is one of the most frequent manual material handling task we encounter in daily life. The loads are carried either manually or by use of a material handling device. Manual carrying is performed by hands, shoulder, back or head. One of the most strenuous carrying tasks is the one involves carrying during stair climbing. Water bottle carrying on shoulder is a specific type of load carrying task during stair climbing widely performed in Turkey. This type of task may be extremely exhausting and risky leading to musculoskeletal pain and disorders of, especially, low back and shoulders. The main aim of this study was to estimate the workload induced by a 19 kg water bottle carrying task during stair climbing by three ergonomic approaches: biomechanical, physiological and psychophysical. Another aim was to determine the best one among the used three carrying methods. The task is performed by 20 young and healthy male participants with these methods: Carrying on shoulder (*method 1*), by stair climbing hand trolley (*method 2*) and by a home-built track type hand trolley (*method 3*). Biomechanical approach involved estimation of shoulder and low back forces and moments by hand calculation and also by use of UM-3DSSPP and also REBA risk estimation; physiological approach involved use of heart rate recordings; and psychophysical approach involved the use of Borg RPE scale (6-20) and also VAS (0-100). The results indicate that *method 1* well-exceeds NIOSH safety limits of low back compressive force (4290±561 N for stoop and 4330±606 N for squat lifting). *Method 2* and *method 3*, on the other hand, were safe (2078±467 N and 1740±362 N, respectively). L5/S1 shear forces and shoulder moments stay within safe limits for all the three methods. Physiologically, the task is a heavy task by all three methods. Psychophysically *method 2* is the worst one and least preferred by the participants. In overall, track type hand trolley is better than other methods after considering all the approaches. In such low frequency jobs, the biomechanical criterion is the limiting factor; and thus the track type trolley should be used for such tasks.

ÖZET

MERDİVEN ÇIKARKEN YAPILAN BİR YÜK TAŞIMA İŞİNİN ERGONOMİK AÇIDAN İNCELENMESİ

Yük taşıma günlük yaşamda en sık karşılaşılan görevlerdendir ve ayrıca merdivende taşımayı gerektiren pek çok görev de mevcuttur. Yükler el ile veya bir taşıma aracı yardımıyla taşınır. El ile taşıma elde, omuzda, sırtta veya başta yapılabilir. En yorucu taşıma görevlerinden birisi da merdiven tırmanırken yapılan taşımalardır. Omuzda damacana taşıma, Türkiye'de sıkça gerçekleşen bir merdivende yük taşıma görevidir. Bu tarz malzeme elleçleme görevleri oldukça yorucu ve riskli olabilir; özellikle bel ve omuzlarda kas iskelet sistemi ağrıları ve rahatsızlıklarına sebebiyet verebilir. Bu çalışmanın ana amacı 19 kiloluk damacananın merdiven tırmanırken taşınması sırasında oluşan yükün biyomekanik, fizyolojik ve psikofiziksel açılardan belirlenmesidir. Diğer bir amaç ise kullanılan 3 taşıma yöntemi arasından en iyisinin belirlenmesidir. Görevler 20 genç ve sağlıklı erkek katılımcı ile yapılmıştır; omuzda yük taşıma (*metot 1*), merdiven çıkabilen yük aracıyla (*metot 2*) ve elde yapılan bir palet tipi yük taşıyıcıyla (*metot 3*). Biyomekanik yaklaşım omuz momentleri ve bel kuvvetlerinin manuel ve UM-3DSSP yardımıyla hesaplanması ve REBA risk belirleme araçlarını kullanmıştır. Fizyolojik yaklaşımda nabız değerleri, psikofiziksel yaklaşımda ise Borg cetveli (6-20) ve VAS (0-100) kullanılmıştır. Sonuçlara göre m*etot 1* L5/S1 sıkıştırma kuvvetleri için NIOSH güvenlik limitlerinin oldukça üzerine çıkmıştır (4290±561 N eğilme için ve 4330±606 N squat için). *Metot 2* ve *metot 3* ise güvenliydiler (sırasıyla 2078±467 N ve 1740±362 N). L5/S1 kesme kuvvetleri ve omuz momentleri tüm metodlar için güvenli sınırlardadır. Fizyolojik olarak tüm metotlar ağır iş olarak belirlenmiştir. *Metot 2* psikofiziksel açıdan en kötü ve en az tercih edilen olarak bulunmuştur. Genel olarak, palet tipi taşıma aracı tüm yaklaşımlara göre diğer metotlardan iyi olarak bulunmuştur. Bu tarz düşük frekanslı işlerde biyomekanik kriterler baskındır ve palet tipi yük aracının kullanımı uygun olacaktır.

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LIST OF SYMBOLS

D_{eh}	Distance between elbow and hand
$D_{e(com)}$	Distance between elbow and forearm center of mass
$D_{lb(com)}$	Distance between low back and center of mass of upper body, except arms
D_{lbs}	Distance between low back and shoulder
D_{se}	Distance between shoulder and elbow
$D_{s(com)}$	Distance between shoulder and upper arm center of mass
F_{es}	Force of the erector spinae muscle
F_{comp}	Compression force at L5/S1 spine
F_{shear}	Shear force at L5/S1 spine
$HL_{(y)}$ and $HL_{(z)}$	y and z components of the hand force at the hand
K	Angle between upper and lower leg behind
$M_{e(x)}$, $M_{e(y)}$, $M_{e(z)}$	Moment at the elbow joint around x, y and z axes
$M_{e(x)}$', $M_{e(y)}$', $M_{e(z)}$'	Reactive moment of the elbow moment around x, y and z
$M_{s(x)}$, $M_{s(y)}$, $M_{s(z)}$	Moments at the shoulder around x, y and z axes
$M_{s(x)}$', $M_{s(y)}$', $M_{s(z)}$'	Reactive moment of shoulder moment around x axis
$M_{lb(x)}$	Moment at the low back around x axis
$R_{e(z)}$ and $R_{e(y)}$	Reactive forces at the elbow joint
$R_{e(y)}$' and $R_{e(z)}$'	Reaction forces of the elbow reactive forces on y and z axes
$R_{s(y)}$ and $R_{s(z)}$	Reactive forces at shoulder for y and z axes
$R_{s(y)}$' and $R_{s(z)}$'	Reaction forces of the shoulder reactive forces on y and z
T	Angle between vertical line and hip-shoulder line
$W_{(fh+h)}$	Weight of the forearm and the hand section
$W_{(lb\ to\ head)}$	Weight of low back from head part of body, excepts arms
W_{ua}	Weight of the upper arm
α	Sacral cutting plane angle
β	Pelvic rotation angle
θ_e	Angle of forearm on y-z sagittal plane

θ_s	Angle of upper arm on y-z sagittal plane
δ_e	Angle of forearm on x-y transverse plane
δ_s	Angle of upper arm on x-y transverse plane
φ	Angle of L5/S1-Shoulder line on y-z plane

LIST OF ACRONYMS/ABBREVIATIONS

3DSSPP	University of Michigan 3D Static Strength Prediction Program
ANOVA	Analysis of Variance
BPDM	Body Part Discomfort Map
bpm	Beats per Minute
EMG	Electromyography
$\%HR_{max}$	Percentage of maximum heart rate
$\%HR_{inc}$	Percent increase of the resting heart rate
HR	Heart Rate
HR_1	First Heart Rate Taken During Resting on Brouha
HR_2	Second Heart Rate Taken During Resting on Brouha
HR_{inc}	Heart rate increase
HR_{max}	Maximum heart rate of the participant
HR_{rest}	Resting heart rate of the participant
HR_{task}	Heart rate measured just after the task is finished
HSD	Honestly Significant Difference
MMH	Manual Material Handling
MSDs	Musculoskeletal Disorders
NIOSH	National Institute for Occupational Safety and Health
PWC	Physical Working Capacity
RPE	Ratings of Perceived Exertion
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
US	United States
VAS	Visual Analogue Scale
VO_2	Volume of Oxygen
VO_{2max}	Maximum Oxygen volume capacity of people
WHO	World Health Organization

1. INTRODUCTION

Manual material handling tasks such as lifting, lowering, carrying, pulling, pushing and throwing are among main human activities in daily life. People are frequently performing manual material handling activities in their daily lives. These tasks are very widespread that easily include dangerous and unhealthy conditions for humans. Singh *et al.* (2011) reported that people in rural areas of Africa lifted and carried 30 kg or more weights every day on their head, shoulders, back or hand for long distances. Health Council of Netherlands (2012) also reported that almost 840,000 workers regularly lifted 25 kg or more weights and 250,000 workers lifted 40 kg or more for their works. So, manual material handling tasks are one of the main concern areas in industry in terms of musculoskeletal disorder risks. According to De Looze *et al.* (1995), MSDs and absenteeism related to these injuries were frequently occurred in jobs containing MMH tasks. Cole *et al.* (2004) also said that lifting and lowering tasks contributed greatly to risk of developing a low back pain eight times more than task which did not include such activities. Also, Hoozemans *et al.* (2004) reported from various articles that disorders like low back pain and shoulder complaints were caused from occupational risk factors like manual material handling tasks.

In the world of modernization, cities are expanding both horizontally and vertically. Many people are living at heights. Even factories and office buildings has multiple floors. Nevertheless, there are many buildings which do not have elevator systems. Thus, everyday there are thousands of load carrying tasks occurring on the stairs upwards and downwards. Unfortunately, these people are carrying loads even up to 100 kilograms of weights at one time. Chung *et al.* (2005) reported that in soft drink beverage industry, workers were carrying about 60 kg of boxes in one time through stairs. Load carrying through stairs, which is the main part of this thesis, also presents a much more complex version of manual materials handling tasks. So, there exists a wide variety of risks associated with these manual material handling tasks. These jobs may be tiring, exhausting and injury prone for human body.

2. LITERATURE REVIEW

2.1. Ergonomics and Musculoskeletal Disorders

People need to perform various physical tasks during their daily life. These tasks may be suitable with the human capabilities and attributes or they may require different characteristics that a person may not be capable of doing them. The term of "Ergonomics" is mainly about this important connection between task requirements and human capabilities. International Ergonomics Association (2016) defines ergonomics as: "Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Practitioners of ergonomics and ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people". MacLeod (2006) stated that ergonomics can be described under four basic rules: fitting tasks to person, making things user-friendly, working smarter but not harder and knowing the rules for how to optimize your work. So, ergonomics is the science of fitting the work people do and the environment people work according to the human characteristics.

Ergonomics principles are one of the most important aspects in a work environment if working conditions are wanted to be optimized. Darcor (2015) explained that ergonomics had a direct effect on productivity, quality and injury conditions. It told that ergonomic interventions improved the conditions and comfortability of work and workers tended to feel more suitable with the work they have done, efficiency and productivity increases eventually. This tells us about the importance of ergonomics on industry. It affects economic, efficiency and health issues both. But main effect and main aim of the ergonomics is about improving health and safety of humans during their work, other effects are side effects related to wellbeing of workers.

According to Darcor (2015), Musculoskeletal Disorders (MSDs) were the disorders and injuries about body parts like muscles, bones, nerves, tendons, joints, ligaments, cartilages and spinal disc. MacLeod (2006) told that MSDs were about one third of the all work related injuries and account for about ¾ of costs. Thus MSDs are main health and safety issues among work related risks for workers and also one of the main concern areas of ergonomics. Van Tulder *et al.* (1995) told that MSDs cause massive harms to both humans and society. Furthermore, these disorders were also very frequent in working population as well as general population (as cited in Van der Beek *et al.* (2000)). WHO statistics (2005) reported that every year about 268 million nonfatal workplace injuries were occurring which cause at least 3 day absenteeism from work (as cited in Kumar (2007)). Kumar (2007) also added that about 43% of injuries in US were related to sprain and strains in body; which gives us insight that a huge amount of the work related accidents are musculoskeletal injuries, similar to MacLeod. Moreover in economic terms, MacLeod (2006) also added that workers' MSD related compensation costs were about $50 billion; lost productivity and absenteeism costs were about $60 billion in US for one year. These facts tells us the whole story about MSDs in industry, they disable people from working efficiently, cause injuries and accidents, moreover they also effect economic situation of companies in terms of loss efficiency, absenteeism and injury compensations.

MSDs are related to various risk factors associated with work, environment and person. MacLeod (2006) listed these risk factors as awkward postures, static load, pressure points, repetition, excessive force, environmental factors like vibration, noise, temperature etc., organizational problems and personal issues like physical condition and diseases. Elimination or reduction of these risk factors is one of the main objectives of ergonomic evaluations. As a result, workers get the chance of working at much safer and less risky environments.

2.2. Manual Material Handling and MSDs

According to the definition of Yale University (2015), material handling was conducting activities requiring any of tasks people needed to lift, lower, push, pull, carry, throw, move, restrain or hold an object. Also Hoozemans *et al.* (1998) defined MMH as pushing, pulling, carrying, lifting or lowering objects by hand according to Snook *et al.*

(1978). As can be seen from these definitions, manual material handling consists of almost every activity related to moving and handling of objects by hand. So, MMH is very common for everybody; people conduct many MMH activities during their daily life. Furthermore, MMH tasks may be identified as a crucial part of industrial work. Hoozemans *et al.* (1998) stated that in industry automation and mechanization was growing but manual handling of the objects still remained a crucial part of the work. As a further example, according to Health Council of Netherlands (2012), as high as 800.000 of workers declared that they had to lift loads of 25 kg or more regularly during their jobs, and this number was about 12% of Netherlands working population. This statistics is only about lifting task, further numbers may be reached when other MMH tasks like pushing, pulling, carrying, holding etc. are added to these statistics.

Jansen *et al.* (2002) told that MMH tasks were obvious risk factors for developing injuries according to. Ciriello *et al.* (2010) indicated from various papers that 63-70% of all low back compensation problems were related to MMH tasks. Moreover, they also added that among all workers' compensation costs, MMH related ones were the most frequent ones with 36% frequency and the most costly ones with 35% of total costs.

Kayis and Kothiyal (1996) declared that in US, about 27% of overexertion compensations and injuries were related to pushing, pulling, lifting and carrying. They also stated that, resultant injuries containing sprain and strain in MSD system accounted for about 50% of compensation claims. Furthermore Boocock *et al.* (2006) asserted from various papers that lifting, carrying, pushing and pulling activities formed an important amount of industrial health issues. Tasks that are focused in this study are consisting of such MMH activities, too. They will be examined in more detail at the next sections.

2.2.1. Lifting-Carrying

According to Merriam-Webster (2015) definition lifting was raising an object from a lower position to a higher position. And also carrying was defined as while holding or supporting an object, moving it to another place. Cole *et al.* (2004) said that work related tasks which involved lifting or lowering carried a greater risk of developing a low back pain. Furthermore, Marras *et al.* (1995) and Chaffin and Park (1973) reported that lifting

involved tasks were eight times risky than non-lifting involved tasks in terms of developing a low back pain (as cited in Cole *et al.* (2004)). Jansen *et al.* (2002) and De Looze *et al.* (2000) also said that lifting and carrying tasks were widely analysed in literature as well as these tasks are considered unhealthy and assumed to be related for low back pain. Visser *et al.* (2014) gave an example from construction facilities, where iron bars varied from 1 kg to 50 kg, even up to 100 kg, were widely used. They stated that, in Dutch construction industry, a safe limit for lifting was thought to be 25 kg under optimal conditions and workers needed to use mechanized devices or form lifting teams in order to lift higher weights. Further, this cooperation was found to be lower the low back compression forces. Health Council of Netherlands (2012) stated according to the Netherlands Center for Occupational Diseases that workers were under increased risk of developing a low back pain if they lifted or carried a weight of more than 15 kg during 10% of a working day; and if they lifted or carried a 25 kg or more weight once in a working day. Moreover if they lifted a weight of more than 10 kg 10 times on a week for at least one year, they were under the risk of developing a work-related knee osteoarthritis or hip osteoarthritis. They also added that, if employees lifted a weight of more than 10 kg every day in a year, their risk of being absent from work for more than eight days related to a low back pain was four times higher than workers who didn't conduct such a task.

2.2.2. Pushing-Pulling

Hoozemans *et al.* (1998) defined pushing and pulling as exerting a hand force which was directed horizontally on an object or a person. Garg *et al.* (2014) talked about pushing and pulling similarly, a hand force exerted on an object horizontally, but not strictly horizontal, according to the angle there could be a vertical compound of the hand force also. Ferreira *et al.* (2004) told that people exerted some hand force on another person or object which had a dominant horizontal force generally could be determined as pushing or pulling. They also added that pushing force was directed outside the body whereas pulling hand force was directed onto the body. Pushing and pulling is also a very common manual material handling task in industry. Baril-Gingras and Lortie (1995) asserted that about 50% of manual material handling tasks in certain industries consisted of pushing and pulling tasks (as cited in Garg *et al.* 2014)) Van der Woude *et al.* (1995) listed such industries as refuse collectors, postman, truck drivers, miners and nurses. Marras *et al.* (2009) also

generalized these industries as many manufacturing industries, warehouse and distribution settlings, service, delivery and patient handling services.

Jansen *et al.* (2002) declared that despite being a very common manual material task in industry, pushing and pulling got less attention in scientific literature and there were limited work in this area. Hoozemans *et al.* (2002) stated that about 9-18% of all work related low back injuries were caused from pushing and pulling tasks. Also Knapik and Marras (2009) told that according to statistics of Bureau of Workers' Compensation Claims in Ohio, 27% of all low back pain compensation claims were related to pushing and pulling tasks. Nonetheless, Kuijer *et al.* (2007) stated that pushing and pulling tasks were more significant risk factors for shoulders rather than low back. Hoozemans *et al.* (2002) added that a significant relationship between pushing and pulling tasks and shoulder complaints was found but low back relation had a limited significance. Kuijer *et al.* (2003) said that replacing lifting jobs with pushing and pulling jobs reduced the load on the low back region but there remained a risk of developing a pain or stiffness on neck or shoulder region unless pushing and pulling tasks or objects were not optimized according to ergonomic principles. Sandfeld *et al.* (2014) also added that low back pain was not the main risk factor for pushing and pulling. But this risk existed according to working conditions. According to Kumar (2004), there were no limits that generally accepted in literature to evaluate shoulder moments. Shoulder moment capacity during a specific task could be determined by two criteria, gender and posture of arm. Chaffin *et al.* (2006) stated that there were equations that evaluate shoulder moment capabilities of average people according to gender and arm posture criteria. Kumar (2004) gave the table of average moment capabilities of men and women according to upper and lower arm angles in Table 2.1.

Kohn (1999) stated that there were no specifically determined limits for evaluation of shoulder moments; nevertheless, ratio of average shoulder moment capability of male-female to work shoulder moment requirement should be under one, otherwise this task would be hazardous for most of the workers. He also added that, for safety of most of the workers, this ratio was proposed to be below 0.5 but below 1 ratio wouldn't be a hazardous task for most of workers if frequency of the task was not quite high.

Table 2.1. Shoulder moment capability (lb) of 50th percentile male and female according to elbow and shoulder angles (Kumar, 2004).

50% Male Population				
Included Upper Arm (Shoulder) Angle (B) (º)	**Included Forearm (Elbow) Angle (B) (º)**			
	45	**90**	**135**	**180**
0	632	691	751	810
45	598	658	717	777
90	565	624	684	743
135	531	591	650	710
180	498	557	617	676
50% Female Population				
Included Upper Arm (Shoulder) Angle (B) (º)	**Included Forearm (Elbow) Angle (B) (º)**			
	45	**90**	**135**	**180**
0	332	363	395	426
45	314	346	377	408
90	297	328	359	391
135	279	310	342	373
180	262	293	324	355

2.2.3. Lifting-Carrying versus Pushing-Pulling

Lift and carry jobs as well as push and pull jobs are two common types of manual material handling tasks in industry as mentioned before. Often, these tasks are evaluated and compared in terms of ergonomics. Pushing and pulling tasks are much more favoured than lifting and carrying tasks nowadays. Schibye *et al.* (2001) reported that, in Denmark, lifting and carrying jobs were replaced by pushing and pulling jobs in order to reduce the mechanical load on workers. Schibye *et al.* (1997) stated that carried bins, bags and containers were replaced by wheeled containers to reduce physical loading during waste collection jobs (as cited in Laursen and Schibye (2002)). Straker *et al.* (1997) added that wheeled container conversion was subjectively rated as less demanding than previous lifting job.

2.2.4. Load Carrying through Stairs

Singh *et al.* (2011) said that people carried loads heavier than 30 kg on their head, shoulders and back; furthermore carrying such heavy loads leaded to various health problems. They also stated that asymmetrical load carrying on shoulders caused body to be loaded on one side only. Kinoshita (1985) asserted that more spinal tilt was acquired when walking with an asymmetrical load (as cited in Hong *et al.* (2011)); and according to Troussier *et al.* (1994), asymmetrical load carrying could cause a low back pain eventually (as cited in Hong *et al.* (2011)). Pascoe *et al.* (1997) reported that increased lateral spinal deviation was caused by an asymmetrical load carrying during walking. McGill *et al.* (2013) found that carrying loads in one hand (asymmetrical carrying) caused up to 82% more spinal load compared to carrying the same load by splitting it for two hand carrying. They further found that carrying a heavy load like 30 kg in one hand causes much more spine compression than carrying this amount of load for both hands; means that carrying a total load of 60 kg by splitting it into two hands. So, it can be seen that asymmetrical shoulder load carrying through stairs task is an exhaustive and risky task. Tseng and Liu (2011) asserted that high stair slope, load and walking speed led to higher physiological and psychophysical loadings. Chung and Wang (2001) stated that stair climbing and gender leads to significant differences for psychophysical and physiological criteria. Chung *et al.* (2005) analysed the effects of horizontal, upstairs and downstairs back load carrying. Stair climbing load carrying led to higher heart rate values rather than horizontal load carrying.

2.3. Manual Material Handling Devices

As mentioned in the previous section, pushing and pulling tasks are taking the place of lifting and carrying tasks whenever possible. Manual material handling devices like industrial trolleys, carts and hand trucks are the most common ways of this conversion. Kodak (1986) defined material handling devices as vehicles like wagons, carts and trolleys which were pushed or pulled without a mechanical assist, just manually (as cited in Jung *et al.* (2005)). Okunridibo and Haslegrave (1999) told that material handling devices that were transforming lifting and carrying jobs into a pushing and pulling task which operator exerts less static load, were increasingly used in industry to prevent workers from injuries

related to lifting and carrying. Moreover, Resnick and Chaffin (1995) told that industrial carts and material handling devices were taking place of potentially hazardous repetitive lifting tasks in industry. Singh *et al.* (2011) asserted that use of manual vehicles had massive advantages on moving objects from one place to another; this method was widely accepted as less stressful and more efficient than classical manual material handling tasks like lifting. Ciriello *et al.* (2010) asserted that sometimes ergonomic redesign principles suggested converting lift, carry, lower tasks into pushing and pulling tasks; also these new tasks offered new job requirements like hand forces that suitable to a high portion of male and women workers. But these vehicles had also their own characteristics and they had to be optimized in terms of ergonomics, too. Jung *et al.* (2005) reported that misuse and improper design of manual vehicles leaded to increased risk of MSD problems. They also summarized optimal usability factors of these devices as factors like wheels, handle type and height, structure, load security, floor, slope, stairs, load, motion direction, frequency, distance, speed, co-workers, posture, force requirement, efficiency and safety.

There are many types of material handling devices in industry. Wheelbarrows, carts, trolleys, hand trucks, track type trolleys, stairclimbers etc. These may be manual or electricity assisted. Mehta *et al.* (2015) said that track type stair devices which rolled on long tracks that bridged two or three stair noses got the much of the load experienced by users during lifting and carrying phase. Fredericks *et al.* (2006) asserted that track equipped stair devices eliminated the need for lifting and carrying the load, operators only needed to glide the vehicle during stairs phase, so much of the load was absorbed by tracks reducing the risk of developing a MSD. Also, track type stair devices significantly performed best among all types of emergency devices in terms of low back disorder development risk and stair climbing type ones came the second significantly, lift and carry type ones were the worst ones among them in the study of Fredericks *et al.* (2002).

2.4. Ergonomic Approaches to MMH Job Evaluation

2.4.1. Biomechanical Approach

According to Darcor (2015), ergonomists used biomechanics to determine force, strength and posture guidelines. They included factors like gender, anthropometry and

strength to evaluate muscle forces and bone-joint compression values; then these values became inputs for comparing with working population accepted limits. Ayoub and Woldstad (1999) also told that biomechanical approach was used to determine the stress upon the internal structures of the body during completing a task. They included that main goals of this approach were determining the stress on the bones, muscles and joints of the body; and also predicting the possible damage on these structures. Moreover, according to Dempsey (1998) aim of the biomechanical approach was designing tasks in order not to exceed the durability limits of the musculoskeletal system. He further added that commonly, L4/L5 or L5/S1 low back disc compression values or maximum joint torques was used as evaluation criteria in this approach. Figure 2.1. shows the places of L4/L5 and L5/S1 discs. Hoozemans *et al.* (1998) stated that if biomechanical models detected an increase in mechanical stress, it could be an early indicator of MSDs. If this stress exceeded the capacity of these structures; there was a strong risk of developing damage or a MSD. Lett and McGill (2006) summarized injury mechanisms about low back and joints in two headlines; tissue overloading and spinal segment instabilities. They explained that tissue overloading problems occurred when the load on tissues exceeds the safe suggested limits of these body parts and problematic conditions could develop afterwards. Also the second mechanism, spinal segment instabilities were a result of prior tissue damages and loss of joint stiffness.

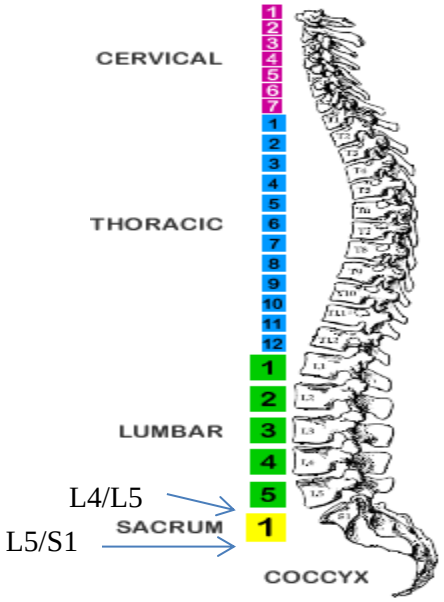


Figure 2.1. Human vertebral column.

As mentioned above, low back compression limits are one of the most important criteria for biomechanical analysis, like low back shear forces and joint moments. Ayoub and Woldstad (1999), Lett and McGill (2006) and Schibye *et al.* (2001) suggested the maximum permissible value for low back compression force at L5/S1 joint as 6400 N and 3400 N as the safe and accepted value. Jager and Luttman (1991) provided the table of suggested compression limits according to age and gender at Table 2.2 (as cited in Cole *et al.* (2004)).

Table 2.2. Suggested LB compression limits (N) related to age-gender (Cole *et al.*, 2004).

Age (Years)	**Male (N)**	**Female (N)**
20	6000	4400
30	5000	3800
40	4100	3200
50	3200	2500
≥60	2300	1800

Gallagher and Marras (2012) reported that anterior-posterior shear force limits are 1000 N if exposure to such loading per day is less than 100 in frequency; otherwise they suggest limiting shear force as 700 N. They also found the shear limit of 500 N proposed by McGill *et al.* (1998) as excessively restrictive. Kuijer *et al.* (2007) told according to the equations of Chaffin *et al.* (1999) that limits of shoulder loading moments are 61 Nm for pushing and pulling at hip level and 58 Nm for pushing at shoulder level. Moreover, when Kumar (2004) and Kuhn (1999) method is applied to a general pulling position having a upper arm angle of 45º and lower arm angle of 135º, 81 Nm of shoulder torque would be hazardous for most of the male workers conducting a pulling task as well as moments below this level will not be risky if frequencies are not considerably high.

According to Dempsey (1998), static or dynamic biomechanical models were used in estimations of reactive forces and moments at joints and also muscle forces. Then these component values were compared with the standard limit values to the acceptability of the task. He also added that these biomechanical models could consist of any combinations related to static-dynamic or 2D-3D. Ayoub and Woldstad (1999) stated that for static

modelling, University of Michigan 2D-3D Static Strength Program was the most popular software program among all. This kind of analysis showed the muscle strength and compression values of body joints. Furthermore, EMG (Electromyography) driven analysis was the second type of analysis for predicting internal muscle forces. They stated also that, an EMG analysis used EMG signals collected from muscles and predicted how these muscles respond in different situations and tasks.

Biomechanical analyses of shoulder and low back joints for manual material handling have been widely covered in literature. Laursen and Schibye (2002) found in their work analysing pushing and pulling a waste container that all of their experiment combinations led to low back compressions below 2000 N; but for pulling, some shoulder moments were as high as 100 Nm. Okunribido and Haslegrave (1999) analysed pushing of a hand trolley and found low back compression, shear and shoulder moment values well within the safe limits. Kuijer *et al.* (2003) analysed pushing and pulling of a waste collection trolley and found only some of the low back compression values as critical, reaching up to 4500 N. When they repeated with a better design, these critical values decreased a bit. Also they found much of shoulder moments as within the safe limits, only a few of them were above the limits. De Looze *et al.* (2000) investigated the shoulder values according to a pushing-pulling of various loads at different handle heights and angles. Results were well below the safe limits for shoulder moments, reaching up to only 40 Nm. Sandfeld *et al.* (2014) worked on pushing and pulling of meal carts on planes. They found shear forces well below the safe limits which were reaching up to 150 N only. They also found low back compression forces at max 1500 N. Jager *et al.* (2007) also analysed pushing and pulling of meal carts on aircraft. They reached to low back compression values which some of them were above the critical line for some positions. Schibye *et al.* (2001) included both pushing-pulling and lifting-carrying methods in their work. For pushing and pulling, a maximum of low back compression was 2000 N, shear force was 200 N and shoulder torque was 50 Nm; all of values stayed within the safe limits. For similar lifting and carrying tasks these values were 5700 N for low back, 350 N for shear force and 70 Nm for shoulder torque. They declared that these results stated low back compression was extremely critical for many workers and shoulder torque was slightly critical also. De Looze *et al.* (1995) investigated various waste collection styles like pushing and pulling containers and lifting bags. Lifting bags led to compression values

of 4500 N at maximum. Lifting a large container also led to a compression values of 6000 N. On the other hand, pushing and pulling containers resulted in a low back compression of 3500 N at maximum and mostly stayed within the safe limits. Knapik and Marras (2009) examined pushing and pulling tasks and found maximum low back compression values as 1500 N for L5/S1 and L4/L5; moreover they found maximum AP (Anterior-Posterior) shear forces as 500 N. These values were under the critical limits.

McAtamney and Corlett (1993) defined another method for evaluating biomechanical load on upper body which was named as Rapid Upper Limb Assessment, RULA in short. They said that this practical method was developed in order to investigate work related upper limb risks on workers. This method involved various body parts and postures on a pre-determined chart, and then investigator filled this chart according to the task being analysed. This was a practical method just needed a RULA chart and an investigator filling this chart. They also added that for evaluation, the worst possible position among the task was chosen and ranked according to the scorecard. It would give an insight about severity rating of this task. Hignett and McAtamney (2000) proposed another practical method, but this time different from RULA new method included entire body not only upper limbs, Rapid Entire Body Assessment, REBA in short. This method was similar to REBA mostly; it was also a practical method which required only a scorecard and an investigator to fill it. But this time it gave insights about all body exertion levels and covered much more dynamic and complex tasks like static, dynamic, rapid changing and unstable postures.

Prairie *et al.* (2016) worked on emergency stretcher carriers on ambulances. They found that 71% of the tasks exceeded the safety limit of 3.4 kN for low back compression. Mean compression value was 3.9 kN. They further constructed regression models for such tasks and found that main factors like hand load, trunk angle and weight were responsible for about 80% of variance. Arjmand *et al.* (2011) constructed a regression model for symmetrical lifting tasks and found that factors like hand load, hand distance and trunk angle were significant variables for predicting low back compression values.

2.4.2. Physiological Approach

According to Dempsey *et al.* (2008) physiological approach was one of the three main approaches that were used for designing MMH tasks. They stated that, unlike biomechanical approach, it was mostly appropriate for analysing lower loads and higher frequencies. As Ayoub and Woldstad (1999) stated, during repetitive lifting, oxygen transportation system limited a person's endurance because these activities made muscles contract and relax, muscles needed much more metabolic energy so they needed more nutrients and oxygen. If this demand couldn't be met, then muscles couldn't sustain their initial performance and fatigue occurred eventually. They asserted that, such a physical work affected physiological responses like metabolic energy cost, heart rate, oxygen consumption rate, blood pressure and blood lactate. Dempsey (1998) told that physiological approach aimed to design tasks according to the fact that physiological responses like whole body fatigue and local muscle fatigue stayed within the acceptable limits. He also added that VO_2 or kcal/min criteria were used most widely among all criteria for these responses. Darcor (2015) stated that for a repetitive and forceful manual material handling task physical working capacity (PWC) should be taken into consideration. They said that, PWC, which could be defined as metabolic expenditure capacity also, was unique for every person because it was affected by factors like age, gender, maximum heart rate, fitness and task's energy demands. They asserted that, these limits had to be considered according to general working population, if these limits were exceeded fatigue and also for most extreme cases heart failures could occur. Hoozemans *et al.* (1998) told that if local or overall fatigue was occurred during work, then musculoskeletal system could be in danger of injuries and disorders because fatigue occurrence may be seen as an early sign of overexertion on the musculoskeletal system. Astrand and Rodahl (1986) stated that absolute value for energy expenditure could be defined as completing eight hours of working day without problems of fatigue or discomfort (as cited in Hoozemans *et al.* (1998)).

Dempsey *et al.* (2008) reported that in ergonomics evaluation, energy expenditure limits were often considered in terms of VO_2, oxygen consumption rate per minute. This limiting value is 1 L/min of oxygen, in other terms 5 kcal/min of energy. They stated that evaluating these values in workplace could be difficult to assess, so pre-constructed

regression models could be used as an alternative evaluation of metabolic cost of a task. Singh *et al.* (2011) said that heart rate monitors were used commonly to determine the physical exertion levels of the body. Ekşioğlu (2014) stated from Brouha's guidelines that after the work was completed two more heart rate values had to be taken during recovery period, first one between 30-60 seconds and second one between 150-180 seconds. He also added that these values were determined as HR_1 and HR_2 values. If $HR_1 \leq 110$ bpm/min and if $HR_1 - HR_2 \geq 20$ bpm/min, then this work could be defined as an acceptable work according to heart rate recovery values. Chung *et al.* (2005) summarized workload levels according to heart rate levels of a task from the original sources of AIHA (1971), Grandjean (1988), Kroemer *et al.* (1986) and Astrand & Rodahl (1994) in Table 2.3.

Table 2.3. Workload levels according to heart rate groups (Chung *et al.*, 2005).

Workload Level	**AIHA (1971)**	**Grandjean (1988)**	**Astrand & Rodahl (1986), Kroemer et. Al. (1994)**
Light Work	75-100	<100	<90
Medium Work	100-125	100-125	90-110
Heavy Work	125-150	125-150	110-130
Very Heavy Work	150-180	150-175	130-150
Extremely Heavy Work	>180	>175	150-170

Chung and Wang (2001) used an experimental design that analysed the effect of stair climbing with a three-step mini stair while completing a task. They analysed physiological responses like VO_2 consumption and heart rate. There were a difference for both of the responses but only VO_2 consumption rate was found to be significant for stair climbing variable. Tseng and Liu (2011) analysed the effects of stair slope, climbing speed and loads on physiology. They found significant heart rate differences both for stair slopes, climbing speed and loads. As an example, handheld and backpack carried loads led to higher heart rates than unloaded climbing. Laursen *et al.* (2000) also analysed carrying different loads symmetrically or asymmetrically on uphill, horizontal and downhill surfaces. They found that uphill carrying and asymmetrical carrying led to higher oxygen uptake values than other tasks. Furthermore, Singh *et al.* (2011) compared traditional head carrying and two types of hand carts. It was found that working heart rate values were slightly higher for traditional method, traditional method was worse than others.

2.4.3. Psychophysical Approach

Ciriello *et al.* (2010) stated that psychophysical approach dealt with workers chose the best weight or force that they could work on their eight hour shift without getting very tired, strained, overheated, out of breathed and weakened. They stated that redesigning tasks according to these principles could lead to a more productive and less injury prone working environment. Ayoub and Woldstad (1999) said that psychophysics was the branch that dealt with the relationships between human's sensations and their physical stimuli on people. They stated, in terms of manual materials handling, psychophysics could be used to find the best workable weight to complete the tasks without strain or discomfort on workers. Citing Legg and Myles (1981), it was stated by them that psychophysics was suitable for determining loads that could be lifted repetitively over the shift and wouldn't lead to a metabolic, cardiovascular or subjective fatigue. Subjects in their work determined the loads that wouldn't get them overexerted or excessively fatigued according to their own perception. Also Darcor (2015) stated that psychophysics was defined as a research method that took human perceptions into consideration as well as it was applied to various manual material handling tasks like pushing, pulling, carrying, lifting and lowering. Garg *et al.* (2014) defined psychophysics as a branch of physiology that analysed the relationships between human sensations and their physical stimuli. They also added, it was shown on many studies that psychophysics was useful in determining maximum acceptable weights, forces and workloads for tasks. Moreover, psychophysical approach was shown to be reproducible and reliable in terms of maximum acceptable forces. Lett and McGill (2006) asserted that psychophysically determined forces and weights were shown to be reliable with the limits of biomechanical stress. So, psychophysically determined forces could lead to important improvements in terms of MSDs if they were successfully implemented to working environments. Furthermore, Hoozemans *et al.* (1998) asserted that if maximum acceptable weights were exceeded in working tasks, risk of developing MSDs were increased.

Shoaf *et al.* (1997) developed a regression method in order to evaluate both biomechanical and psychophysical capacity of population percentages for tasks like lifting lowering, carrying, pushing and pulling. Other evaluation methods are maximum acceptable weights and forces, defined in the article of Garg *et al.* (2014) as being

reproducible realistically simulates industrial work and predictive tools to predict back injuries. They were also negatively defined as time consuming, costly, being risky for exceeding physiological criteria at high frequency tasks and being subjective. Snook tables developed at Liberty Mutual Insurance Company are another tool for predicting suitable task values for working population in terms of psychophysical evaluation. Ergonomie Site (2015) described Snook tables as developed by controlled experiments with psychophysical evaluation and these tables were capable of showing percentage of population capable of sustaining exact force levels on the tables during tasks like lifting, carrying, pushing and pulling. Bhattacharya and McGlothin (2012) emphasized on another psychophysical method, Borg scale, as a very good method for identifying varying subjective intensity according to physical stimulus intensity. Furthermore, they reached very high correlations between heart rate and ratio scaling ratings during tasks. Borg's Ratings of Perceived Exertion (RPE) method of rated between 6-20 was shown to be highly correlated with heart rates, for medium aged people and for medium intensity work heart rate values were expected to be 10 times of the scale rating. Moreover, Bhattacharya and McGlothin (2012) talked about another method, visual analogue scales (VAS). They stated that, in most common type, VAS consisted of a 10 cm horizontal line having descriptions or verbal anchors at endpoints and it was used for measurement of perceived physical stress. It also was combined with body discomfort maps to determine perceived exhaustion levels of various body locations. Both VAS and Borg Scales were shown to be reproducible and consistent in various works in literature. These methods were both found to be highly correlated with heart rate values during work in their book. Kumar *et al.* (1999) compared VAS, Borg Scale and Body Part Discomfort Map (BPDM) in their work. They found that VAS and Borg Scale performed better than BPDM, and Borg Scale was slightly better than VAS. Grant and Zare (1999) similarly compared three psychophysical methods, VAS, Borg Scale and Likert Scale. They found that VAS performed best among them and Borg Scale was slightly behind VAS.

Okunridibo and Haslegreave (1999) used VAS in their work analysing effects of handle design on hand trolleys. They included this method for detecting strain in various body parts, hardness level of the tasks and stability of the trolleys. Chung and Wang (2001) used Borg RPE scale for determining the psychophysical effects of stair climbing, pod type and gender on load carrying and found no significant effect differences among RPE

ratings. Tseng and Liu (2011) analysed the effects of load carrying methods like empty handed, hand carrying and backpack carrying; stair slopes and climbing speed. They found significant RPE ratings for both of the variables. Singh *et al.* (2011) compared load carrying on head and two different material handling devices, found significant differences among RPE ratings. Traditional head carrying method was found to be far more heavy work than other methods. Kuijer *et al.* (2003) worked on a waste container and redesigned it. Based on the experiments, they found significant differences between old and new design in terms of 5 points likert scale, the new design was much more favourable.

2.4.4. Conflicts Between Three Approaches

Biomechanics, physiology and psychophysical approaches are three main evaluation criteria for ergonomic analysis as it was defined before. These three approaches have their own limitations and dynamics in their own systematic. So, it is not surprising that these approaches conflict in various situations. Ayoub and Woldstad (1999) stated that this conflict between three aspects of ergonomics was not surprising. They all had their own characteristics. They added that this situation led practitioners into a confusion. It was a tough selection that which criteria would be selected for a proper selection. They stated that the Kim's model (1990) that can be seen at Figure 2.2, explained this situation very well, all criteria conflicted under different situations.

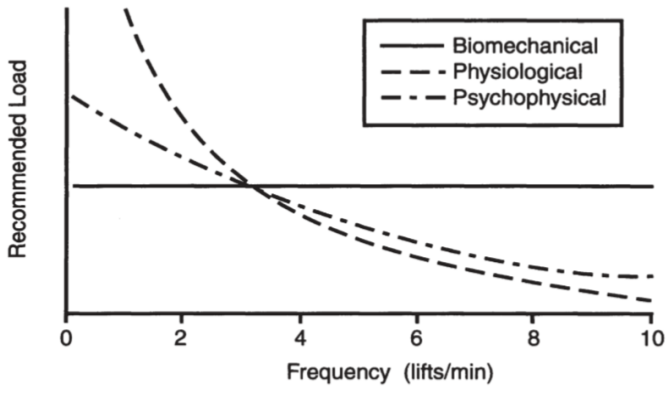


Figure 2.2. Kim's Model (1990): Conflicts between ergonomics criteria for different frequencies (cited in Ayoub and Woldstad, 1999).

According to Dempsey (1998), Kim's model showed conflicts between the three criteria exactly. He stated that physiological criterion recommended higher loads than biomechanical criterion for low frequencies, whereas biomechanical criterion recommended constant load for all frequencies and higher loads than physiological criterion for high frequencies. Simplest approach to select the proper limiting value among three conflicting criteria was suggested to be selecting the most conservative one among them. He further stated, this meant that for low frequencies biomechanical approach was the most proper one and for high frequencies physiological and psychophysical approaches were suitable ones.

Table 2.4 lists some important statements from the literature review in order to give a brief summary of literature review and point some important points that are useful for understanding the concept of this thesis. "Information obtained" section means that these information is taken from the literature review section of that article to construct the main concept of this study. This information carries the required information for the rationale behind this thesis. If the experimental phase of an article is used, experimental details and summary outcomes are listed in that table, too.

2.4.5. Summary of Findings Related to This Study

In literature, there is little work containing stair climbing load carrying tasks. Some of the articles focuses on manual carrying types like hand carrying, bag carrying, front carrying, back carrying etc.. For example, Tseng and Liu (2011) investigated the effects of hand load, stair slope and climbing speed on physiology and psychophysics of human. Higher load, stair slope and climbing speed lead to higher physiological and psychophysical stress on body. Also, Chung *et al.* (2005) investigated physiological effects of load carrying on the back for horizontal, ascending and descending stairs. Descending and ascending stairs led to significantly higher heart rate values rather than horizontal load carrying. Moreover, Chung and Wang (2001) looked into physiological and psychophysical effects of hand loads and stair climbing on humans. They found that stair climbing resulted in significantly higher physiological and psychophysical loadings on workers.

In addition, studies on the use of stair climbing trolley for load carrying are also rare in the literature. Such trolleys are analysed under emergency devices like firefighter devices or disabled person devices. As an example, Mehta *et al.* (2015) compared various stairclimbing emergency devices in terms of physiology, biomechanics and psychophysics for firefighters. They found that stairclimbing device designs resulted in significantly different effects for criteria such as maximum voluntary contraction of muscles, heart rate values and perceived exertion ratings. Also, Fredericks *et al.* (2002) compared various emergency devices including stair climber and track type stairclimbing devices in terms of biomechanics. Track type stair climbing device and stair climbers resulted in lower risk of developing low back disorder on future compared to classical emergency devices.

Table 2.4. Table of selected summary statements from literature.

STUDY	PURPOSE	EXPERIMENTAL CONDITION / OBTAINED INFORMATION	MEASURED OUTCOMES	SUMMARY STATEMENT
Kumar (2007)	Example of MSD frequencies in US workforce	Info obtained	x	43% of work related injuries are MSD's in US.
Ciriello et. al. (2010)	Example of manual material handling related injuries	Info obtained	x	Manual material handling related injuries are about 63-70% of all low back compensations, %36 of all injuries and %35 of all work related injury costs.
Cole et. al. (2004)	Defining lifting and carrying relationship with low back pain	Info obtained	x	Lifting and lowering tasks are 8 times riskier than other tasks in terms of developing a low back injury.
Health Council of Netherlands (2012)	Lifting and carrying related risk potential	Info obtained	x	Increased risk of low back pain if lift/carry >15kg weight 10% of a workday; >25kg weight once a day. If workers lift >10kg weights every day, increased risk of 8 days sick leave because of low back pain.
Hoozemans et. al. (2002)	Push-pull related disorders	Info obtained	x	About 9-18% of low back pain is related to pushing and pulling activities.
Kuijer et. al. (2007)	Push-pull shoulder disorders relation	Info obtained	x	Pushing-pulling is more related to shoulder disorders.
Kohn (1999)	Shoulder moment capabilities	Info obtained	x	If ratio of "shoulder moment during work/shoulder moment capability" is below 1 and frequency is not high, these values are considered safe.

Table 2.4. Table of selected summary statements from literature (cont.).

STUDY	PURPOSE	EXPERIMENTAL CONDITION / OBTAINED INFORMATION	MEASURED OUTCOMES	SUMMARY STATEMENT
Kumar (2004)	Shoulder moment capabilities	Info obtained	x	Shoulder moment capability of a 90-degree bended elbow task is about 81 Nm. With moderate frequencies, levels below this value are considered safe.
Schibye et. al. (2001)	Low back safety limits	Info obtained	x	6400N is maximum permissible limit for low back, 3400N is safe and acceptable limit.
Blatcharya/ McGlothin (2012)	Borg and VAS correlations with heart rate	Info obtained	x	Borg Scale and VAS are highly indicates the heart rate values of the task.
Gallagher and Marras (2012)	Literature review of shear forces at low back	Info obtained	x	Limit of shear forces is 1000N if frequency is lower than 100 times per day. Otherwise it is 700N.
Lauesen and Schibye (2002)	Pushing-pulling 2 wheel trolleys on different surfaces	7 male subjects, 3 surfaces, 3 weights	Low back and shoulder evaluation	Except for some hard conditions reaching up to 82Nm, shoulder moments are within safe limits generally. All low back compressions are below 2000N.
Okunridibo and Haslegreave (1999)	Investigating 2 wheel trolleys acc. to handles and weights	18 subjects, 9 handle orientations, 2 weights	Shoulder moments, low back shear and compression	All shoulder moments are below 65Nm. Low back shear and compression values are also well within the safe limits.
Kuijer et. al. (2003)	Redesigning a waste cart to reduce physical cost on body	9 male subjects, 2 containers	Low back compression	Generally values are between 2000-3000N band, some values reach to 4000N level for old design. New design is mostly better than the old one.

Table 2.4. Table of selected summary statements from literature (cont.).

STUDY	PURPOSE	EXPERIMENTAL CONDITION / OBTAINED INFORMATION	MEASURED OUTCOMES	SUMMARY STATEMENT
De Looze et. al. (2000)	Effect of handles and force directions	8 male subjects, 2 handles, 2 weights	Shoulder moments	All shoulder moments are below 50Nm.
Sandfeld et. al. (2014)	Determining effects pushing and pulling meal carts	17 subjects, 2 surfaces, 4 slopes, 3 handles, 2 masses	Low back shear and compression	All compression forces are below 1500N and also shear forces are below 300N levels both for pushing and pulling.
Schibye et. al. (2001)	Effects of pushing-pulling and lifting-carrying during waste collection	7 male subjects, 2 masses	LB shear and compressions, shoulder moments	All shear values are below 300N. Push-pull compression values are at most 2000N but lifting waste bags lead to 5000N of max. compressions. PP shoulder torques are maximum 50Nm and lift-carry are 25Nm.
De Looze et. al. (1995)	Effects of push-pull containers on low back	17 male subjects, 3 waste methods,	Biomechanics of low back	All shear values are below 500N. Lifting waste bags lead to compressions of 3500-4000N on low back, whereas mini containers led to the region of 2000-2500N.
Fredericks et. al. (2002)	Comparing emergency stairchairs in terms of biomechanics	8 male subjects, 6 emergency devices	Low back loads	Track type chair gets the least low back compression. Stairclimber chair is worse. But low back disorder probability of these devices are lower than hand carried ones.
McGill et. al. (2013)	Comparing weight carrying with both hands and with one hand	9 male subjects, 3 load, 2 condition	Low back loads	One hand carrying leads to higher low back compression rather than dividing the load between hands or dividing the double amount of the load between the hands.

Table 2.4. Table of selected summary statements from literature (cont.).

STUDY	PURPOSE	EXPERIMENTAL CONDITION / OBTAINED INFORMATION	MEASURED OUTCOMES	SUMMARY STATEMENT
Knapik and Marras (2009)	Determining the effects of different pushing and pulling tasks on low back	20 subjects, 2 tasks, 3 handles, 3 hand force levels	Biomechanics of low back	All of the low back compression values are below 1500N and also shear forces are about 500N region.
Prairie et. Al. (2016)	Determining low back effects of lifting activities for patient handling	58 patient handlers, 78% male, recording lifting positions	Biomechanics of low back	71% of lifting activities are above the safety limit of 3.4 kN for low back. Mean compression value is 3.9 kN for these activities. Main contributors for compression are hand load, trunk angle and weight of paramedic.
Tseng and Liu (2011)	Effects of various slopes and speeds for stair load carrying	9 male subjects, 3 carry methods, 3 slopes, 3 speeds	Physiological and psychophysical evaluation	Higher slope, higher climbing speeds and hand loads increases the physiological and psychophysical responses of the body.
Lauesen et. al. (2000)	Calculating different efforts during different walking styles	6 male subjects, 3 movements (up-horizontal-down), 3 weights	Metabolic cost	Asymmetrical uphill carrying of the loads lead to the most energy consumption among all conditions.
Kumar et. al. (1999)	Comparing 3 psychophysical techniques	20 subjects	Psychophysical techniques sensitivity and reproducibility	VAS is the best performing method among all, Borg scale performance is similar to VAS.

3. RATIONALE AND OBJECTIVES

3.1. Problem Definition

Load carrying through stairs is a very frequent activity in daily life and this activity is tiring and risky for musculoskeletal injuries. For example, Cole *et al.* (2004) and Schibye *et al.* (2001) showed that manual lifting and carrying of the weights can lead to critical low back compression values well-above NIOSH's (National Institute of Occupational Safety and Health) criterion of 3400 N. So, such tasks may lead to future MSD problems like hernia, osteoarthritis, stress fractures, and shoulder pain. These studies are rare in the literature. Therefore, it is a need to investigate such tasks, specifically stair climbing tasks, to determine the safe carrying methods.

Within the scope of this study, a specific load carrying task, water bottle carrying through stairs, which is commonly performed in Turkey is selected for investigation.

3.2. Objectives of the Study

Based on the rationale above, the objectives of this study are as follows:

(i) To estimate workload level of a load carrying task through stair climbing with three alternative methods based on biomechanical, physiological and psychophysical approaches.

(ii) To determine the best carrying method among the investigated three alternative methods namely shoulder carrying, using a stairclimbing trolley and using a track type trolley.

In accordance with the objectives of this study listed at above, following hypotheses are constructed to formally test the carrying methods:

- H1: Water bottle carrying through stair climbing task and similar ones may be exhausting and injurious.

- H2: Stair climbing hand trolleys will improve the situation of the manual load carrying in terms of physiology, biomechanics and psychophysics.
- H3: Modified track type hand trolley will further reduce the effect of gravity on carriers. Thus, it will be a better performing method for stair load carrying in terms of physiology, biomechanics and psychophysics.

4. METHODOLOGY

4.1. The Task Investigated

Ergonomic investigation of a load carrying task through stairs is the main topic of this thesis. For the purpose, water bottle carrying task was selected for the investigation. Water bottles are about 19 kg on weight and workers carry these bottles upstairs manually on their shoulders, asymmetrically, many times during a day. Load carrying was completed with three different methods. Method 1 was manually carrying a 19 kg water bottle on stairs. Other two methods consisted of different manual material handling devices; one is a stair climbing hand trolley and other one is a modified track type hand trolley.

- Method 1 involves carrying the 19 kg water bottle over one of the shoulders while climbing stairs. It can be seen on the Figure 4.1.a. Participant lifts the bottle from the ground to one of his shoulders. Then he carries the bottle over stairs. At the top of the stairs, he lowers the bottle to the ground again.
- Method 2 involves carrying the bottle with the use of a material handling device which is called as stairclimbing hand trolley. Main feature of this vehicle is its wheels which have three little wheels rotating on same structure, so they help trolley to climb stair steps one by one. It can be seen on Figure 4.1.b. Participant rolls the bottle to trolley and ties the bottle onto it. Then he pulls stairclimbing trolley through stairs. At the top, he unties it again.
- Method 3 involves also carrying the bottle with a material handling device but its mechanism is different from the first one. This vehicle has a track system, like a type of palette, apart from wheels. This track system started to operate when trolley was climbing the stairs. Tracks were long enough to touch at least one nosing and at most two nosing of each stair. So, this trolley glided over these tracks while it was climbing stairs. When it was on the flat ground, wheels took place and track mechanism didn’t operate. Figure 4.2 shows carrying the weights using track type hand trolley.

(a) (b)

Figure 4.1. Manual carrying of the load (a) and using the stairclimbing hand trolley (b).

Figure 4.2. Carrying loads using the track type hand trolley.

4.2. Participants

Experiments were conducted with a group of 20 people. These 20 people were consisted of all males because in industry such heavy carrying jobs were conducted mostly by men. These participants had an average age of 24.9 and standard deviation of 0.76. And only eligibility criterion for participating in these experiments was being free of any musculoskeletal disorders or injuries. Every participant was healthy enough for completing these carrying tasks without risk of a further injury. For experimental design, 20

participants were selected in order to have at least 0.80 power for statistical tests. Results of power analysis can be seen at Table F.1 (Appendix F).

Further experiments were conducted with 30 male participants to record videos and determine postures adopted during tasks. These participants had an age average of 24 and standard deviation of 2.23. All ethical procedures were same as above; experiments were conducted with healthy participants. Participant descriptive statistics can be seen at Table 4.1.

Table 4.1. Participant descriptive statistics for experiments.

N=20 EXPERIMENT				
	Mean	SD	Min	Max
Age (years)	24.95	0.76	23	26
Weight (kg)	77.15	12.31	58	107
Height (cm)	177.89	5.12	169	187
N=30 EXPERIMENT				
	Mean	SD	Min	Max
Age (years)	24.00	2.23	19	28
Weight (kg)	76.77	10.49	62	104
Height (cm)	178.40	4.64	169	189

4.3. Equipment

4.3.1. Polar Watch and Heart Rate Sensor

Polar watch coordinated with a heart rate sensor was used in experiments in order to determine the instantaneous heart rates before conducting a task and find the resulting heart rate just after completing the task. These heart rate values were used as an input to analyse physiological aspects of these tasks. These devices can be seen at Figure 4.3.a.

4.3.2. Chatillon Hand Dynamometer

Hand dynamometer, which can be seen at Figure 4.3.b, was used to collect required hand force data that would be used as input for biomechanical analysis of the body during

tasks. Hand dynamometer could measure the exerted hand forces on hands during pulling of the hand trucks.

(a) (b)

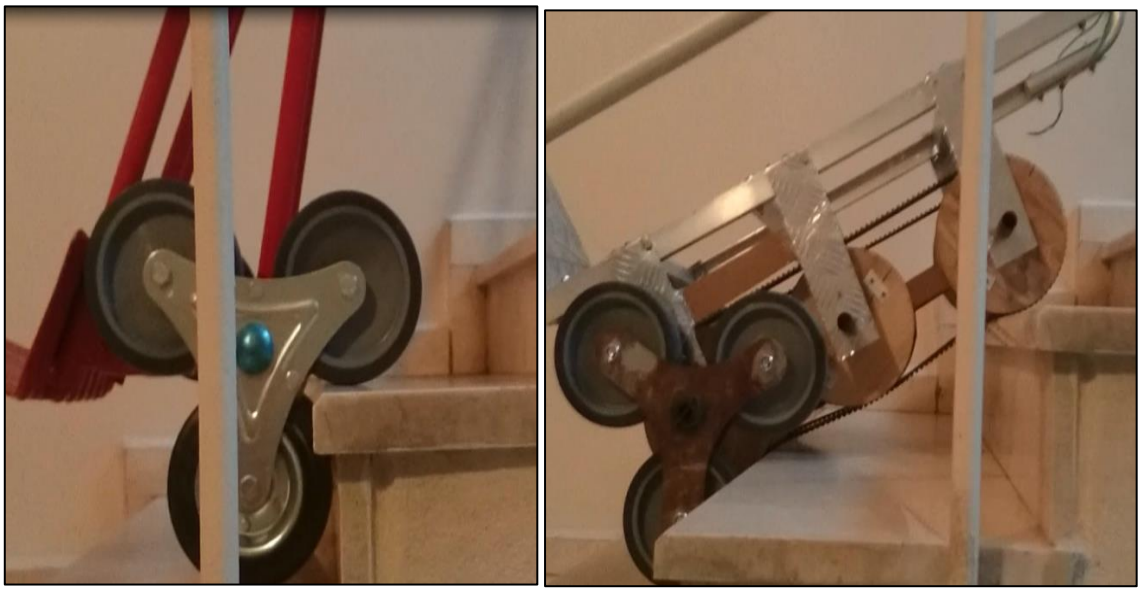
Figure 4.3. Polar watch and sensor at the left (a) and hand dynamometer at the right (b).

4.3.3. Hand Trolleys

- Trolley 1 was a commercial type stair climbing hand trolley. This trolley has two sets of triple wheels on each side. This wheeling system helps this trolley to climb over each stair step with less effort. It was about 15 kg in weight. It can be seen on Figure 4.4.a and Figure 4.5.a.
- Trolley 2 was a modified track type hand trolley. It was about 14 kg in weight. There are several kinds of this type trolleys abroad but here in this country these trolleys are rare to find. So, a similar device was constructed totally hand made in order to use in the experiments. It is based on the same concept but with some slight differences. Its tracks are neither too short nor too long. They touch at least one stair nosing each time so it results in a continuous movement. It also has stair climbing wheels at the bottom which are not operating during stair climbing section; they may help overcoming small obstacles on a horizontal road. Furthermore, this trolley has a non-optimized handle due to limitations in hand-made construction and a changeable handle could offer a better comfort, but it was good enough to meet the requirements of experiments. It can be seen on Figure 4.4.b, 4.4.c and 4.5.b.

(a) (b) (c)

Figure 4.4. Stairclimbing hand trolley at the left (a) and track type trolley at middle and right (b-c).



(a) (b)

Figure 4.5. Stairclimbing hand trolley on the left (a) and track type trolley on the right (b).

4.3.4. Software Packages

4.3.4.1. Minitab. Minitab is statistical software which can conduct various statistical operations. Minitab was used for various statistical calculations about our survey and experiment results.

4.3.4.2. SPSS. SPSS is statistical software which is similar to Minitab. In this study, statistical comparison techniques were applied to various criteria. In order to find descriptive statistics, deviation analyses, ANOVA testing and statistical comparisons, SPSS software was used.

4.3.4.3. University of Michigan's 3DSSPP. 3DSSPP software is a computer program which was developed at University of Michigan in order to analyse manual material handling tasks with biomechanical approach. People can analyse various manual material handling postures with this software and 3DSSPP can give a wide variety of outputs about these tasks such as low back compression values, various body part moments and many more. In this thesis also 3DSSPP was used to analyse material handling tasks as well as acquire low back compression values and shoulder moments.

4.3.4.4. Gpower. Gpower software was used in order to calculate power analysis of experimental designs.

4.3.5. Camera

A camera was used to record samples from each material handling method. These video recordings were analysed in order to capture the postures adopted during these tasks. Then these postures were used as an input in University of Michigan's 3DSSPP software to interpret biomechanical analyses of these tasks.

4.3.6 Survey Questionnaire

A field survey was planned on water bottle carriers in order to have an idea about effects of frequent heavy load carrying on stairs for people. A questionnaire was prepared consisting of questions related to musculoskeletal complaints of workers and their perceived strain related to their work. This survey questionnaire can be seen at Appendix A.

4.4. Experimental Design

4.4.1. Experimental Variables

Experimental variables can be seen at Table 4.2.

Table 4.2. Experimental variables.

Response Variables	Independent Variable	Levels of Independent Variable
• VAS Score (0-10) • Borg Score (6-20) • Heart Rate (bpm) • Hand Force (N) • Completion Time (sec) • Postures Adopted • Disk Compression Force (N) • Disk Shear Force (N) • Shoulder Moment (Nm)	• Load Carrying Method	• Manual load carrying on shoulders • Use of stairclimbing hand trolley • Use of track type trolley

4.4.2. Controlled Conditions

Apart from independent variable, other variables that could affect the outputs of the experiment were tried to be kept similar during the experimental process. First control

condition was the place where experiments conducted on it. All experiments were completed at the same stairway in School of Engineering building (at Boğaziçi University South Campus). These stairs had steps of 16 cm height and 32 cm depth, which led to a total of 72 steps equal to 35 meters of total distance travelled; 24 steps per floor. Stair step dimensions can be seen at Figure 4.6. Experiments took a long time for each person, approximately 2-3 hours for each, so 20 subjects randomly divided into experimental groups of 3-4 persons to use time more efficiently. Each group completed experiments on a different day. In order to eliminate environmental effects, all groups conducted experiments on similar climate conditions, meaning that indoor temperatures were similar during experiments. Two different hand trolleys were chosen to be in similar weight, so that effect of hand cart weight eliminated from evaluations. Each of three carrying method was randomly assigned to each participant. This helped us to eliminate ordering effects and results were obtained as free from such noises.

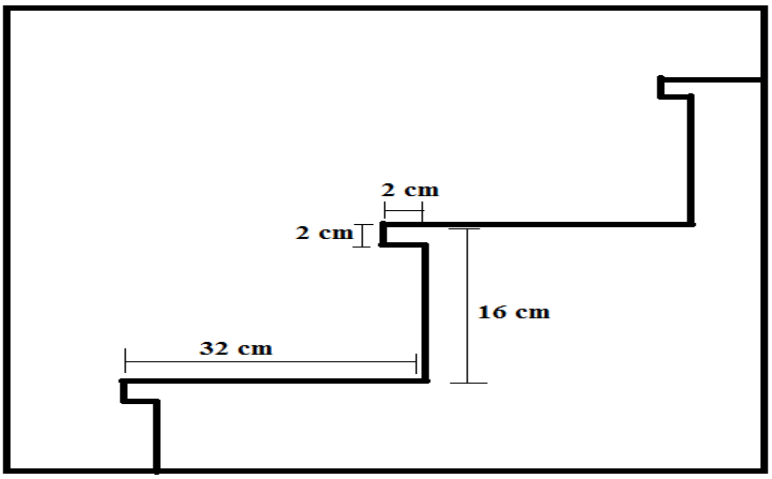


Figure 4.6. Stair step dimensions.

4.4.3. Experimental Design

In this experimental design, same subjects are used for different levels of predictor variables. This is called as “Repeated Measures Design” according to Montgomery (2012). He states that if a subject is treated with all levels of a variable, this design is repeated measures design. Equation 4.3 shows the model of repeated measures designs.

$$y_{ij} = \mu + \tau_i + \beta_j + \epsilon_{ij} \quad (4.3.)$$

y_{ij} = Response of subject j to treatment i

τ_i = Effect of the ith treatment

β_j = jth subject's parameter

ϵ_{ij} = Error term of ith treatment and jth subject

Table of experimental data can be seen at Table 4.3.

Table 4.3. Table of experimental data.

	Subjects									
Methods	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Method 1	$y_{1.1}$	$y_{1.2}$	$y_{1.3}$	$y_{1.4}$	$y_{1.5}$	$y_{1.6}$	$y_{1.7}$	$y_{1.8}$	$y_{1.9}$	$y_{1.10}$
Method 2	$y_{2.1}$	$y_{2.2}$	$y_{2.3}$	$y_{2.4}$	$y_{2.5}$	$y_{2.6}$	$y_{2.7}$	$y_{2.8}$	$y_{2.9}$	$y_{2.10}$
Method 3	$y_{3.1}$	$y_{3.2}$	$y_{3.3}$	$y_{3.4}$	$y_{3.5}$	$y_{3.6}$	$y_{3.7}$	$y_{3.8}$	$y_{3.9}$	$y_{3.10}$
	Subjects									
Methods	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Method 1	$y_{1.11}$	$y_{1.12}$	$y_{1.13}$	$y_{1.14}$	$y_{1.15}$	$y_{1.16}$	$y_{1.17}$	$y_{1.18}$	$y_{1.19}$	$y_{1.20}$
Method 2	$y_{2.11}$	$y_{2.12}$	$y_{2.13}$	$y_{2.14}$	$y_{2.15}$	$y_{2.16}$	$y_{2.17}$	$y_{2.18}$	$y_{2.19}$	$y_{2.20}$
Method 3	$y_{3.11}$	$y_{3.12}$	$y_{3.13}$	$y_{3.14}$	$y_{3.15}$	$y_{3.16}$	$y_{3.17}$	$y_{3.18}$	$y_{3.19}$	$y_{3.20}$

4.5. Experimental Procedure

4.5.1. First Experimental Phase

Purpose of first experimental phase was to collect physiological and psychophysical evaluation data regarding each of the three carrying methods.

(i) Participant sits at an area where he waits for his experiment turn.

(ii) He is provided with the consent form which includes the details of the experiment. He reads the form carefully, he becomes informed about the experiment objectives, outcomes, potential risks etc. He then signs this form meaning that he is informed

about the experiments and he knows about potential outcomes and risks. This form can be seen at Appendix B.

(iii) Participant then wears heart rate sensor on his chest to record heart rates during the experiment.

(iv) All three carrying methods are shown to the participant with details as a practice. They also go through a small training of the methods before experimental phase starts.

(v) Random ordering of methods is applied to eliminate the noise effect of ordering, so they complete the tasks according to this predetermined random order.

(vi) When it is the subject's first turn, he sits on the waiting chair. He waits until his heart rate values come to a steady resting position. This duration is about 10-15 minutes. His resting heart rate is read and recorded. Also his other information like age, height, weight is recorded. With the information of age, his maximum heart rate is calculated with the formula: $HR_{max} = 220 - Age$

(vii) When the participant's resting heart rate is reached, start command is told to the subject and eventually he starts to the task. At the same time, chronometer is started in order to measure the duration of task.

(viii) Task 1: Manual bottle carrying method starts in front of the stairs. Participant lowers his body, and then lifts the water bottle selecting the most suitable position for him between stoop, squat or semi-stoop positions; they select especially stoop lift for such a large bottle. He lifts it to the height of shoulder then places it on his shoulder. He climbs three floors with the load on his shoulder. At the top of the stairs, he lowers the bottle and places it on the ground then stands again. This task finishes at this moment. Chronometer is stopped and heart rate value is recorded eventually. After the task is ended, further data is collected according to Part 9.

Task 2: Bottle carrying with stairclimbing hand trolley again starts in front of the stairs. With the command, he rolls bottle onto the trolley. Then, he ties the bottle to the trolley with ropes to make it stable. He pulls the trolley for three floors. When he reaches at the top of the stairs, he releases the tie easily, rolls bottle to the ground again and stands. This task finishes at this point. Chronometer is stopped and heart rate value is recorded eventually. After the task is ended, further data is collected according to Part 9.

Task 3: Modified track type hand trolley operates similar as stairclimbing hand trolley. This task is the same as Task 2. After the task is ended, further data is collected according to Part 9.

(ix) After the completion of each task described in step 8, participant sits on a chair prepared before experiment. He completes all the questions prepared about the task, psychophysical and physiological evaluations are made according to these questions which can be seen at Appendix B. Furthermore, about 45 seconds and 165 seconds after the task is completed, two different heart rate values are collected and recorded, too. This is the application of Brouha guidelines.

(x) The same procedure is repeated with the next participant in the experimental order.

4.5.2. Second Experimental Phase

Purpose of second experimental phase is to collect biomechanical posture information of participants during load carrying tasks in order to complete biomechanical analysis.

(i) The participant is provided with the information form about the experiment; he reads the form and signs it. He also gives personal information of age, weight and height.

(ii) Coloured markers are placed on joint locations of participant for only one side of his body.

(iii) He conducts each task (lifting bottle with stoop and squat positions, carrying bottle with stair climbing trolley or track type trolley for about 5 seconds. Each task is recorded with a camera.

(iv) These recordings paused on proper position and selected for analysis. Approximate joint locations are determined on computer with the help of markers and position variables like elbow angle are calculated in order to use in 3DSSPP biomechanical evaluation analyses.

4.6. Job Evaluation Approaches Used

4.6.1. Biomechanical Approach

Biomechanical approach was mainly comprised of calculating L5/S1 low back compression and shear forces and also shoulder moments. Body angles collected with camera and hand force values collected with push-pull dynamometer were used as inputs to these calculations. These calculations were done for in accordance with 3D static biomechanical model for shoulder moments and 2D static biomechanical model for L5/S1 compression and shear forces.

Firstly, University of Michigan's 3DSSPP program and manual link-segment models were both used for calculating low back compression, shear forces and shoulder moments to see if they resulted similarly or not. For these analyses, three sample people from different height groups of population; short-medium-tall; were selected and these people were analysed biomechanically for three different carrying methods. Also for shoulder carrying (method 1), highest moment values were reached during standing phase, not during the initial lifting phase; so this posture was added to analysis for method 1 for medium height people in order to observe the shoulder moments. Moreover, most people preferred stoop lift posture during method 1. Also, the lifted object was a large cylindrical bottle and a squat lift may not be feasible for most people. But a squat lift might decrease the straining effects of lifting a bit more. So, this posture was added to analysis in order to compare the effects of a posture change. This analysis was also applied for method 1 and for medium height people. Figure 4.7 shows stoop and squat lift methods. Worst case postures were selected for biomechanical evaluation. For shoulder carrying, it was the scene that subject lifts bottle from ground. Pulling stage where subject pulls devices through stairs with both vertical and horizontal forces on his hand was selected as worst case posture in evaluation of other methods. After it was seen that two analyses results were similar, additional 30 participants were analysed biomechanically with 3DSSPP software only.

Outputs from the 3DSSPP evaluation were low back compression force, low back shear force and shoulder moments. These values were used to calculate the biomechanical

loadings on human body for all these methods. Body angles collected from video recordings were used as inputs of further biomechanical regression equations.

(a) (b) (c)

Figure 4.7. Standing (a), stoop lifting (b) and squat lifting (c) postures.

Furthermore, REBA evaluation method was used for comparing observational biomechanical risks of carrying tasks on workers. REBA method is a practical but efficient approach for determining risky postures in terms of biomechanical strain. REBA was applied to the most strenuous and frequent postures for three different carrying methods.

4.6.2. Psychophysical Approach

Borg scale of 6-20 was used for psychophysical evaluation related to perceived strain of carrying methods. These values were collected during the experimental phase for every subject and for all three carrying methods.

Also, VAS comprised of four different questions about tasks, which can be seen at Appendix B, was used as another psychophysical evaluation method.

These collected statistics were compared with a Repeated Measures ANOVA (Analysis of Variance) in statistical software SPSS in order to determine if there was a significant difference among them. This test was chosen because experiments were

conducted with same 20 subject set for each of the methods, meaning matched groups. This experimental structure requires Repeated Measures ANOVA while comparing these groups in order to find the mean differences among them (Idre-Ucla, 2016). P-value < 0.05 means that there is a statistically significant difference between means for different methods. Bonferroni post-hoc evaluation test was used to detect pairwise differences among methods because it was more commonly used for repeated measures ANOVA (University of Bedfordshire, 2016). Only Borg Scale values were compared with a different test, Friedman's ANOVA. Because Friedman's ANOVA is used for discrete or non-normal response data that is not suitable with Repeated Measures ANOVA test (Laerd Statistics, 2016).

4.6.3. Physiological Approach

Heart rate values related to tasks were measured and recorded just before the tasks were started and just after the tasks were completed. These values compares directly physiological strain related to carrying methods. Furthermore, Brouha's guideline was applied after the tasks which meant that further heart rates were recorded about 45 and 165 seconds later the task is completed. Also, "Percent of Maximum Heart Rate" criteria was added which was calculating the percent value of resulting task heart rate according to maximum heart rate. It was formulated as Equation 4.1.

$$\%HR_{max} = 100 \times (HR_{task}/HR_{max}) \tag{4.1}$$

Another criterion was "Percent Heart Rate Increase", which was evaluating the percent increase of resting heart rate after the task was completed. It can also be seen at Equation 4.2.

$$HR_{inc} = \Delta HR = HR_{task} - HR_{rest} \tag{4.2}$$
$$\%HR_{inc} = 100 \times (HR_{inc}/HR_{rest})$$

All of these criteria were evaluated according to same statistical comparison techniques described at the psychophysical evaluation section.

4.7. Statistical Analysis

4.7.1. Regression Analysis

Regression analysis was applied to field survey and low back compression/shear forces. For field survey, fatigue level of workers was predicted with age, number of bottles carried per day and experience variables in order to understand if there is a relationship between fatigue level and these variables. For estimating low back compression and shear forces, various body angles, height, weight and hand distance variables were used. Stepwise regression modelling was used to construct these models. Equation 4.3 shows the linear model where y is the response variable, β_0 is the constant term, x_i terms are regression variables, β_i are regression coefficients and ϵ is the error term. Level of significance was used as $p < 0.05$ for all regression models to test the null hypothesis that regression coefficients are 0 at Equation 4.4.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k + \epsilon \quad (4.3)$$

$$H_0: \beta_1 = \beta_2 = \ldots.. = \beta_k = 0 \quad (4.4)$$

$$H_1: \beta_i \neq 0 \text{ for at least one } i \ (i = 1,\ldots.,n)$$

Field (2009) lists the basic multiple regression assumptions at the list below:

- Multicollinearity: Predictor variables shouldn't correlate highly with each other at the initial model. It can be detected with pairwise correlation tables among predictor variables.
- Lineartiy: Linearity assumption is the linear relationship between independent variables and response variable. It needs to be acquired if a linear regression model needs to be constructed.
- Normally distributed error: Residuals of the final model needs to be normally and randomly distributed with a mean of 0 for a regression model. It can be tested with Anderson-Darling test of residuals. P-value < 0.05 means that residuals do not fit to a normal distribution.

- Homoscedascity: Variance of the residuals should be constant for each level of predictor variables. On residual analysis, this can be observed on standardized residual vs. fitted value graphs.
- No existing autocorrelation: Consecutive residual terms should be independent and uncorrelated. It can be tested with Durbin-Watson statistics, values between 1-3 are accepted as valid.

4.7.2. Statistical Comparison

Repeated measures design was used for the experiments of this study. Repeated measures ANOVA is applied to compare such experimental designs in order to find the mean differences between groups (Field, 2009). Hypothesis of this comparison test can be seen at Equation 4.5, where μ_k is the mean value of kth group:

$$H_0: \mu_1 = \mu_2 = \ldots = \mu_k \qquad (4.5)$$
$$H_1: \text{At least one } \mu_i \text{ is different}$$

O'Connor (2015) lists the assumptions of Repeated Measures ANOVA as "normality" and "sphericity". Normality assumption was tested with Anderson-Darling test, if normality was not violated severely, then this assumption was passed. Seltman (2015) stated that tests like ANOVA were robust to moderate violations of normality assumption; this violation wouldn't affect the results significantly. If a severe violation was occurred, then again a Friedman's ANOVA method was applied to compare the groups. Sphericity assumption was tested with Mauchy's Sphericity Test, and if there were a problem with sphericity then Greenhouse-Geiser corrected values were focused on resultant tables.

For repeated measures ANOVA, p-value < 0.05 means that there is a statistically significant difference between means of at least one variable. In order to find the pairwise differences between variables, Bonferroni post-hoc test is applied mostly for repeated measures ANOVA (University of Bedfordshire, 2016). P-value < 0.05 means that there is a significant difference between compared variables. Heart rate variables and VAS

questionnaire was evaluated with repeated measures ANOVA comparison technique if normality assumption was met.

For non-normal responses such as Borg scores, Friedman's ANOVA was used for comparison. Field (2009) states that Friedman's ANOVA is the alternative method for repeated measures ANOVA if assumptions are not met. Friedman's ANOVA tests k related groups to see if there is a statistically significant difference among them. P-value < 0.05 means a significant difference for Friedman's ANOVA. For detecting the pairwise differences, post-hoc Wilcoxon Signed Rank Test is applied to pairwise groups. In this procedure, significance level is determined with Bonferroni Correction as "p-value/# of groups" (Field, 2009).

5. RESULTS AND DISCUSSION

5.1. Survey Results

A field survey was done on water bottle carriers to gain some insights about the workload of such carrying tasks. According to the main statistical results of this survey, workers evaluated tiredness level after they finished their workday as 6.2 over 10 cm VAS on average. 41 people from a total of 100 said that they feel pain for at least one part of their body. 21% of them said that it was low back, and 20% of them had complaints on their neck, shoulder, leg, knee, feet and arms. From these 41 people, only seven of them indicated a medical examination and the results were showing various hernia and arthritis disorders. Summary statistics are shown in Table 5.1. Table 5.2 shows fatigue levels of the body parts with respect to VAS. Workers selected the body areas that they were feeling significantly tired after work and indicated the fatigue levels of them on a 10 cm VAS. Table shows the number of workers feeling discomfort on a body part with average value and spread of data. It can be seen that legs, low back, shoulders and upper arm areas are the mostly selected areas. Furthermore, Figure 5.1 shows the body areas that workers feel pain on them. Moreover, Figure 5.2 shows the VAS score boxplots.

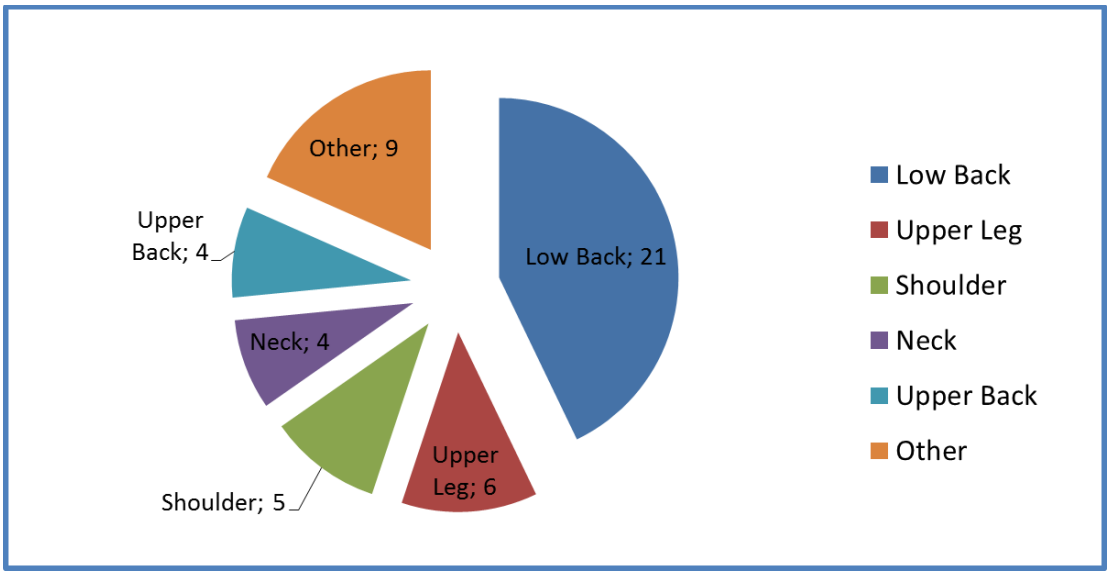


Figure 5.1. Number of complaints about body parts.

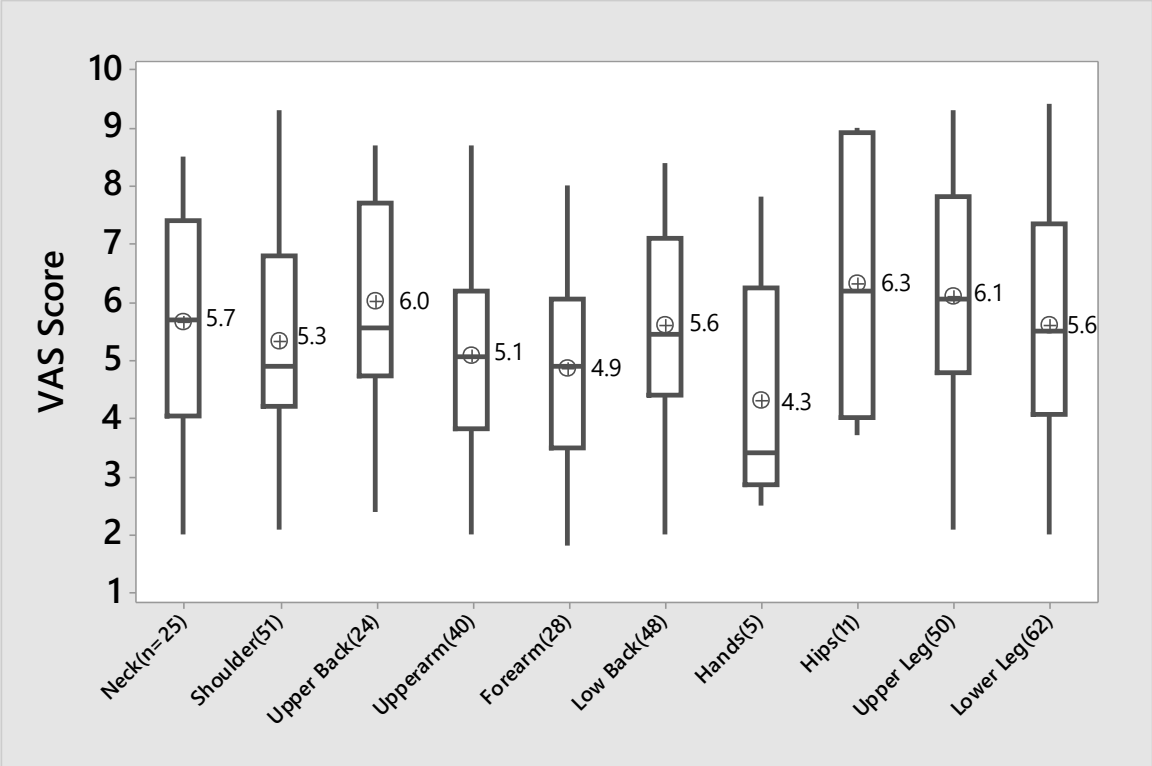


Figure 5.2. Boxplots of VAS results showing fatigue levels of body parts.

Table 5.1. Summary statistics of the survey.

	Number	Average	Std. Dev.	Minimum	Maximum
Age (years)	*	33.55	12	15	64
Experience (years)	*	7.76	*	1	30
Number of bottles carried per day	*	58.3	25.34	10	135
Number of participants feeling pain in their body	41	*	*	*	*
Number of participants consulted by a doctor	7	*	*	*	*
Number of participants diagnosed with hernia	6	*	*	*	*
Number of participants diagnosed with arthritis	1	*	*	*	*

Table 5.2. Body parts with intense fatigue statistics.

Body Part	Number of Workers Feel Fatigue	Average (on 0-10 VAS scale)	Std. Dev.	Minimum	Maximum
Neck	25	5.7	1.9	2.0	8.5
Shoulder	51	5.3	1.8	2.1	9.3
Back	24	6.0	1.8	2.4	8.7
Upper Arm	40	5.1	1.5	2.0	8.7
Lower Arm	28	4.9	1.6	1.8	8.0
Low Back	48	5.6	1.7	2.0	8.4
Hand	5	4.3	2.1	2.5	7.8
Hips	11	6.3	2.2	3.7	9.0
Upper Leg	50	6.0	1.8	2.1	9.3
Lower Leg	62	5.6	1.9	2.0	9.4

As the next step, a regression analysis was conducted on this data in order to find a small clue of a relationship between tiredness level and factors of age, experience and number of bottles carried per day. Also quadratic and interaction terms were added to initial model to detect if there existed a nonlinear relation between variables. Field (2009) lists the main regression assumptions at the list below:

- Normality of the error distribution
- Linear relationship of dependent and independent variables if linear regression is applied.
- No existing auto-correlation
- Homoscedasticity (constant variance) of the errors vs. any independent variable
- No existing multicollinearity

First of all, correlation between independent variables was calculated and it was found that there was no problem with multicollinearity. Before applying the regression, a contour plot of “age and # of bottles vs. fatigue” was constructed in order to see if a pattern

existed. Figure 5.3 shows the contour plot and it shows a sign of relationship between increasing age and # of bottles against increasing level of fatigue. Also, there seems the sign of some outlier regions against this pattern.

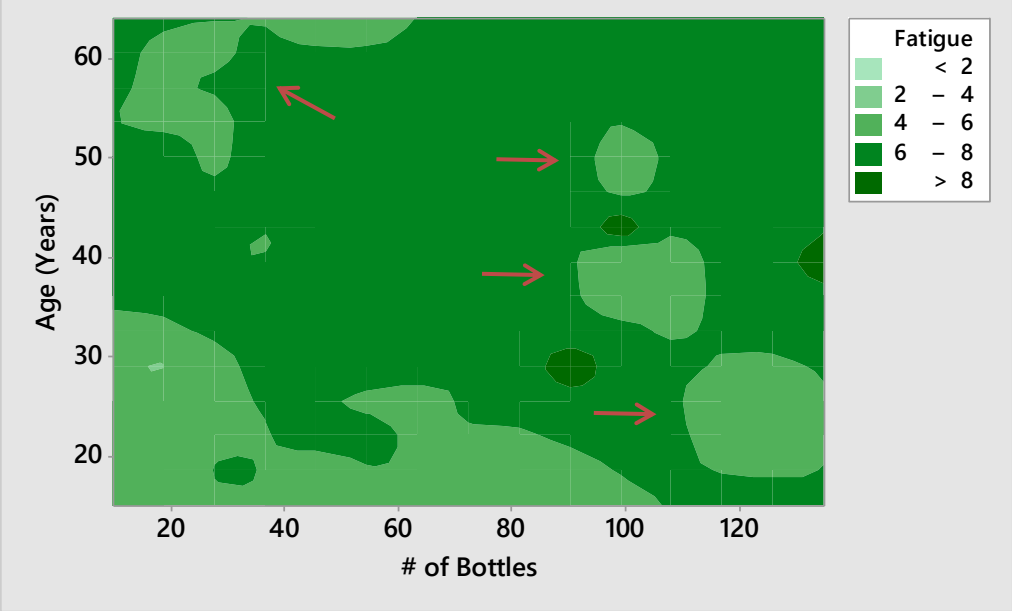


Figure 5.3. Contour plot of age and number of bottles vs. fatigue level.

Stepwise regression method was used for model selection. As mentioned before, quadratic and interaction terms were also added to initial regression model to test linearity of resultant regression. After repeating the regression for a few times in order to delete some outlier values with high deviances from the dataset, a resultant regression equation was acquired with n=95 subjects.

Normal probability plot of regression residuals at Figure 5.4. was used to test normality of residuals. Distribution of residuals seemed to be normal and insignificant Anderson-Darling value proves this. In order to test the assumption about autocorrelation, Durbin-Watson statistics was calculated and the result was 1.67 which stayed between the acceptable limits of 1 and 3. Homoscedasticity assumption also can be seen at Figure 5.4. on standardized residual vs. fitted value diagram. Residuals seem to be distributed according to equal variances assumption. Variance over time looks like unchanged.

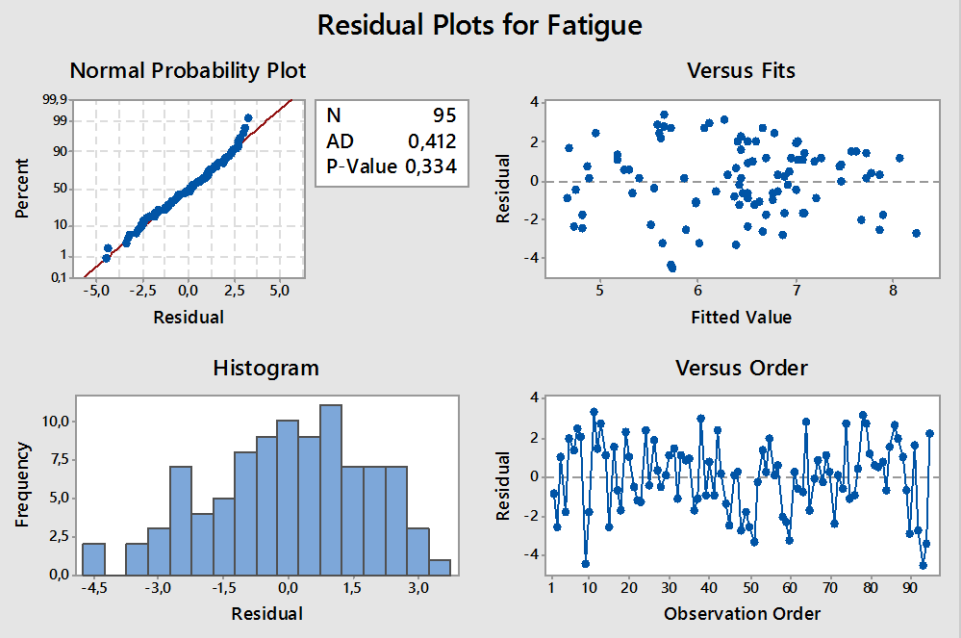


Figure 5.4. Final assumption check plots about the regression analysis

Contour plot of the last model can be seen at Figure 5.5. Also, final regression equation is shown at Equation 4.1. Furthermore, because of the fact that our response variable is bordered between 0-10, this equation can further be transformed as Equation 4.2.:

$$\text{Fatigue} = (3.397 + 0.0649 \times \text{Age} + 0.01545 \times \#\text{Bottle}) \quad (4.1)$$

$$0 \leq \text{Fatigue} \leq 10; (\text{If Fatigue} \geq 10; \text{then Fatigue} = 10) \quad (4.2)$$

Fatigue = 0 to 10 VAS score

#Bottle = 19 kg water bottle carried per day

Age = Age of the bottle carrying person (years)

R^2_{adj} value was 17.18% for this regression. Detailed information can be found in Figure C.1 (Appendix C). This value may seem a bit low but in studies involving humans there may be many factors like genetics, anthropometry, fitness level, environment, psychology that are affecting such variables and R^2 values may be low. Itaoka (2012) states that even a low R^2 value can state the effectiveness of a factor reliably. Much or less,

result of regression gives us clues about the fact that this kind of tasks may be associated with the fatigue and eventually disorders on workers.

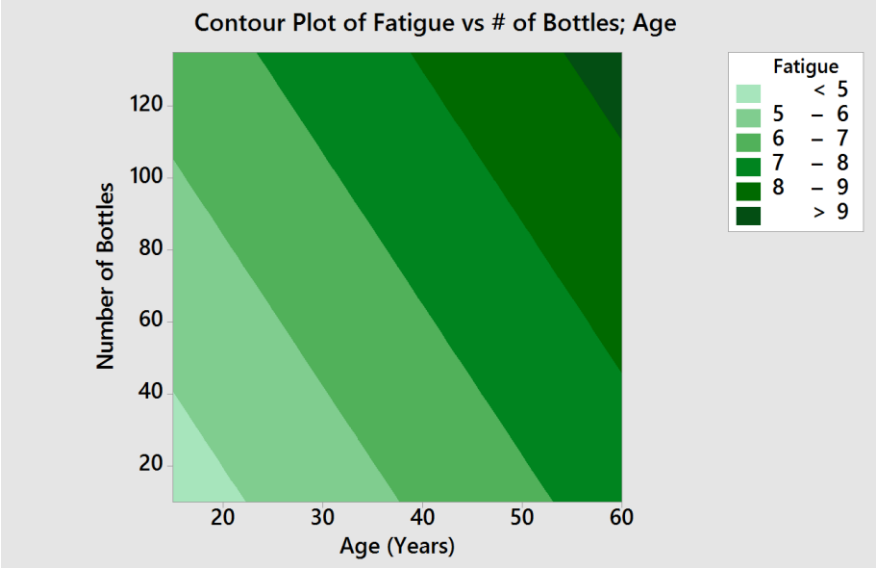


Figure 5.5. Contour plot of fatigue vs. # of bottles and age.

5.2. Biomechanical Evaluation

5.2.1. REBA Assessment

REBA evaluation was used for most frequent postures during three different carrying methods. These postures are shown in Figure 5.6.

REBA stepwise evaluation was applied for each of these postures. In every step, there is an evaluation of different body part and posture, such as trunk posture scoring, leg scoring, neck scoring etc. These points and final results are given at Table 5.3. Evaluation criteria scores are also added below the table. Evaluation worksheet can be seen at Figure D.1 (Appendix D).

According to REBA evaluation, method 1 resulted in nine points, method 2 resulted in seven and method 3 resulted in five points as a result. According to the results, it can be said that method 1 resulted in nine points from evaluation and it has a potentially high risk

of developing an MSD. It should be investigated and some changes have to be made to decrease the risk. Furthermore, the method 2 and 3 have medium risk according to developing an MSD and some changes have to be made soon, but not crucially as method 1. Method 3 got the best score among three methods; it has the lowest possibility of developing an MSD according to REBA evaluation.

Figure 5.6. Considered carrying positions during REBA evaluation.

5.2.2. Shoulder Moments and Low Back Compression/Shear

Firstly, biomechanical evaluation was done with both a basic manual link segment modelling and University of Michigan's 3DSSPP software program which was mainly operates on an advanced link segment modelling base to compare results of these methods. These analyses included resulting maximum moments on the shoulders and compression force of L5-S1 segment of the low back.

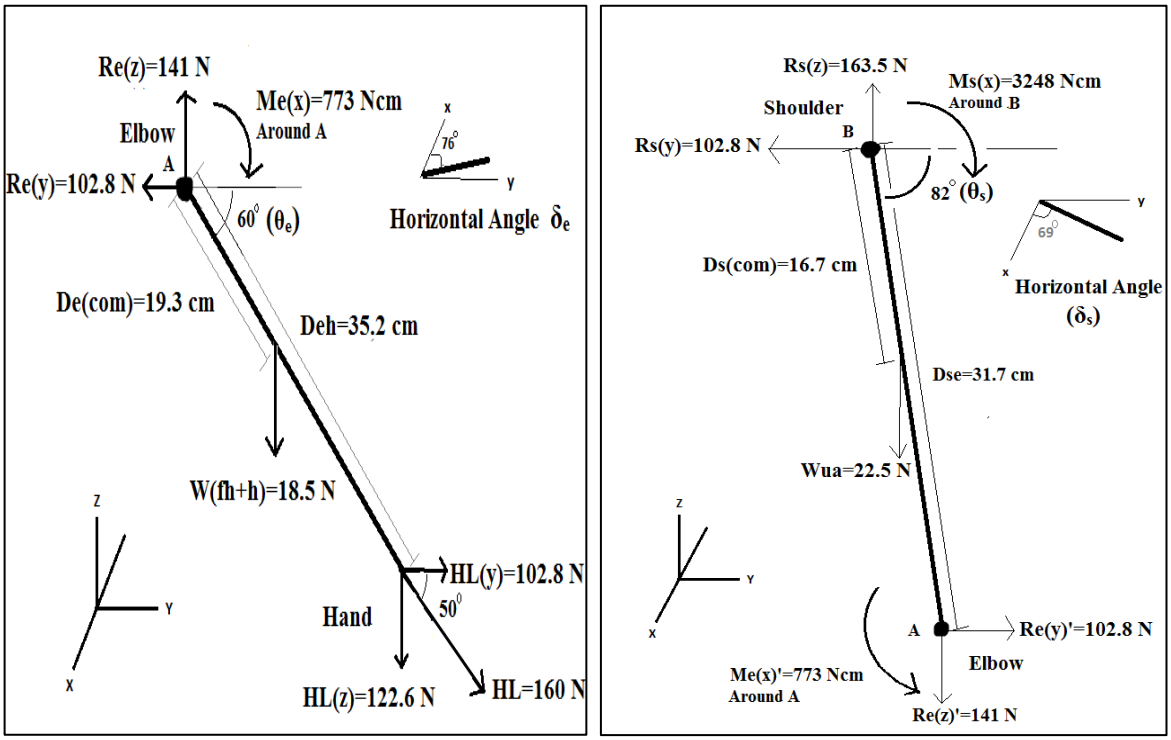
Manual link-segment modelling was applied on the anthropometrical data of 3DSSPP in order to use the same inputs. Unlike 3DSSPP, abdominal pressure was not evaluated. Erector Spinae muscle force lever from the L5/S1 disc was set as 6, 6.25 and 6.5 cm for three different samples because Chaffin *et al.* (2006) stated that erector spinae lever arm may differentiate between 5.5 and 7 in modern work and this values varies with the

Table 5.3. REBA evaluation scores and evaluation criteria.

REBA Evaluation			
Evaluation Steps	**Shoulder Carrying**	**Stair Climber**	**Track Type**
1	2	1	1
2	3	2	2
3	2	3	3
4	5	4	4
5	0	2	1
6	5	6	5
7	5	2	2
8	1	2	2
9	1	1	1
10	6	2	2
11	2	0	1
12	8	6	4
13	1	1	1
Result	**9**	**7**	**5**

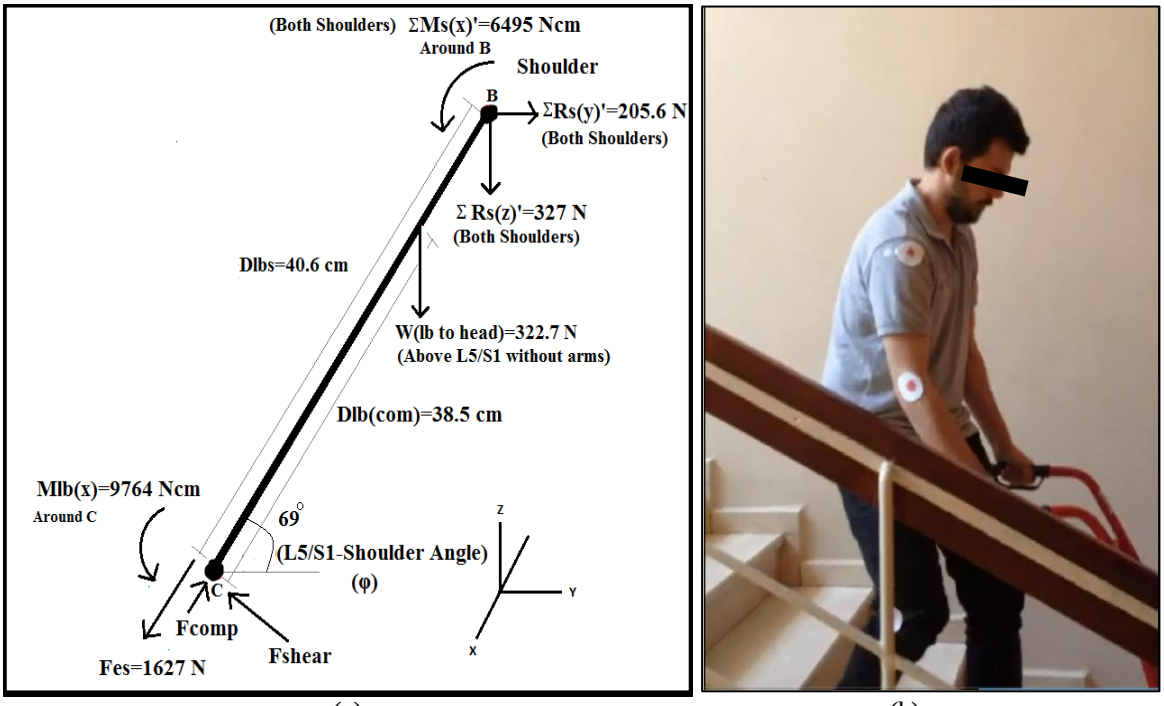
Level of MSD Risk	**Score**
Negligible Risk-No Action Required	**1**
Low Risk-Change May Be Required	**2-3**
Medium Risk-Further Investigate-Change Soon	**4-7**
High Risk-Investigate and Implement Change	**8-10**
Very High Risk-Implement Change	**11+**

personal anthropometrical data. For the evaluation of low back forces, only sagittal plane moments (around x) were calculated. For shoulder moments, a combination of x, y and z moments were calculated for a total moment around the shoulder. Figure 5.7, 5.8 and 5.9 show force diagrams regarding the example calculations for middle heighted participant 2 of stairclimber. Total list of inputs and angle definitions are listed at Tables E1-3 and Figure E1 (Appendix E).



(a) (b)

Figure 5.7. Force diagrams of forearm (a) and upper arm (b) for stairclimbing trolley.



(a) (b)

Figure 5.8. Force diagram of low back to shoulder part of the body (a) and the posture of calculations (b)

Shoulder Moment:

$$Mx: \quad F_y \times D \times \sin(\theta) \times \sin(\delta) + F_z \times D \times \cos(\theta) \times \sin(\delta) \tag{4.2}$$

$$My: \quad F_z \times D \times \cos(\theta) \times \cos(\delta) \tag{4.3}$$

$$Mz: \quad F_y \times D \times \cos(\theta) \times \cos(\delta) \tag{4.4}$$

$$M_{e(z)} = HL_{(y)} \times D_{eh} \times \cos(\theta_e) \times \cos(\delta_e) \tag{4.5.a}$$

$$M_{e(z)}=102.8 \times 35.2 \times \cos(60) \times \cos(76) = 437 \text{ Ncm} \tag{4.5.b}$$

$$M_{s(z)} = R_{e(y)}' \times D_{se} \times \cos(\theta_s) \times \cos(\delta_s) + M_{e(z)}' \tag{4.6.a}$$

$$M_{s(z)} = 102.8 \times 31.7 \times \cos(82) \times \cos(69) - 437 = 274 \text{ Ncm} \tag{4.6.b}$$

$$M_{e(y)} = \cos(\theta_e) \times \cos(\delta_e)[(D_{eh} \times HL_{(z)}) + (W_{(fh+h)} \times D_{e(com)})] \tag{4.7.a}$$

$$M_{e(y)} = \cos(60) \times \cos(76)[(35.2 \times 122.6) + (18.5 \times 19.3)] = 565 \text{ Ncm} \tag{4.7.b}$$

$$M_{s(y)} = \cos(\theta_s) \times \cos(\delta_s)[(D_{se} \times R_{e(z)}') + (D_{s(com)} \times W_{ua})] \tag{4.8.a}$$

$$M_{s(y)} = \cos(82) \times \cos(69)[(31.7 \times 141) + (22.6 \times 16.7)] - 565 = 323 \text{ Ncm} \tag{4.8.b}$$

$$M_{e(x)} = \cos(\theta_e) \times \sin(\delta_e)[(D_{eh} \times HL_{(z)}) + (W_{(fh+h)} \times D_{e(com)})] - \sin(\theta_e) \times \sin(\delta_e) \times HL_{(y)} \times D_{eh} \tag{4.9.a}$$

$$M_{e(x)} = \cos(60) \times \sin(76)[(122.6 \times 35.2) + (18.5 \times 19.3)] - \sin(60) \times \sin(76) \times 35.2 \times 102.8 = 773 \text{ Ncm} \tag{4.9.b}$$

$$M_{s(x)} = \cos(\theta_s) \times \sin(\delta_s)[(D_{se} \times R_{e(z)}') + (W_{ua} \times D_{s(com)})] - \sin(\theta_s) \times \sin(\delta_s) \times HL_{(y)} \times D_{eh} - M_{e(x)}' \tag{4.10.a}$$

$$M_{s(x)} = \cos(82) \times \sin(69)[(141 \times 31.7) + (22.5 \times 16.7)] - \sin(82) \times \sin(69) \times 31.7 \times 102.8 - 773 = 3248 \text{ Ncm} \tag{4.10.b}$$

Thus the resultant shoulder moment is:

$$M_s = [((2.74)^2) + ((3.23)^2) + ((32.48)^2)]^{0.5} = 32.75 \approx 33 \text{ Nm} \tag{4.11}$$

Low Back Compression and Shear:

$$0 = \sum M_{L5/S1} \tag{4.12}$$

$$0 = R_{s(z)}' \times D_{lbs} \times \cos(\varphi) + D_{lbs} \times \sin(\varphi) \times R_{s(y)}' + D_{lb(com)} \times W_{lbh} \times \cos(\varphi) - M_{s(x)}' \tag{4.13}$$

$$0 = 205.6 \times 40.6 \times \sin(69) + 327 \times 40.6 \times \cos(69) + 327.7 \times 36.1 \times \cos(69) - M_{lb(x)} - 6495 \tag{4.14}$$

$M_{lb(x)}$ = 10295 Ncm = F_{es}x6.25cm => F_{es} = 1647 N (4.15)

T = 19 ^{o} ; K = 160 ^{o}

$\beta = -17.5 - 0.12 \times T + 0.23 \times K + 0.0012 \times T \times K + 0.005T^2 - 0.00075 \times K^2$ (4.16)

$\beta = 3.3$; $\alpha = \beta + 40$ => $\alpha = 43.3^{o}$

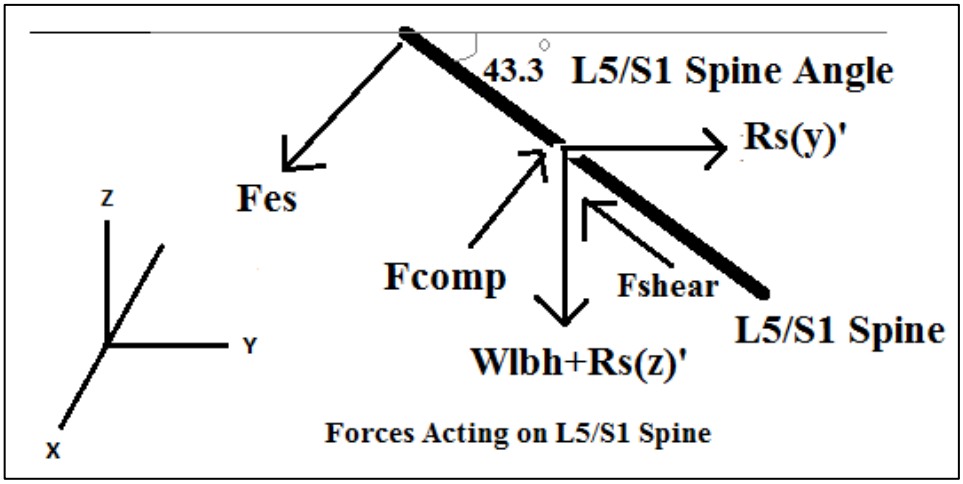


Figure 5.9. Diagram of forces acting on L5/S1 disc.

$F_{comp} = \cos\alpha \times W_{lbh} + \cos\alpha \times R_{s(z)}' + F_{es} - \sin\alpha \times R_{s(y)}'$ (4.16)

$F_{comp} = \cos(43.3) \times (327 + 327.7) + 1647 - \sin(43.3) \times 205.6 = 2120$ N (4.17)

$F_{shear} = \sin\alpha \times (W_{lbh} + R_{s(z)}') + R_{s(y)}' \times \cos\alpha$ (4.18)

$F_{shear} = \sin(43.3) \times (327 + 327.7) + 205.6 \times \cos(43.3) = 598$ N (4.19)

Results of these two same-purposed analyses, manual link-segment method and 3DSSPP software analysis, were almost same as expected before. All of these results are listed at Table 5.4. Three sample participants representing short, medium and tall population were selected for this pilot study. L5/S1 compression force, L5/S1 shear force and shoulder moments were evaluated and listed at the table. In “Sample 1-2-3” sections representing short, medium and tall subjects, these participants conducted stoop lift for method 1 and they also completed methods 2 and 3. Furthermore, for average heighted sample 2, standing posture and squat lifting evaluations were made as an extra.

To determine the joint angles, which were needed as inputs of University of Michigan’s 3DSSPP software, a second study with 30 subjects were performed. Markers

were placed at the joints of the participants. Based on the video recordings the joint angles were determined for the worst case scenarios of three methods;

- Method 1: Lifting scene of the bottle from the ground.
- Method 2: Pulling scene of the stair climbing hand trolley on the stairs when hand force is at maximum.
- Method 3: Pulling scene of the track type trolley on the stairs when hand force is at maximum.

Using the University of Michigan's 3DSSPP, L5/S1 compression and shear forces, as well as shoulder moments for the worst case scenarios of the three methods were calculated. Table 5.4 shows these results. Table 5.5. shows the biomechanical evaluation with University of Michigan's 3DSSPP results for 30 participants.

Table 5.4. Results of 3DSSPP and hand calculations.

BIOMECHANICAL ANALYSIS--3DSSPP Software									
	Method1			**Method2**			**Method3**		
	LB Com.	**LB Sh.**	**Sho. Mom.**	**LB Com.**	**LB Sh.**	**Sho. Mom.**	**LB Com.**	**LB Sh.**	**Sho. Mom.**
Sample1	3861	543	11	1534	580	37	1360	440	16
Sample2	3852	588	12	1800	600	36	1600	460	22
Sample3	4780	707	19	1980	690	51	1340	530	27
Stand S2	2000	390	48	-	-	-	-	-	-
Squat S2	3288	425	5	-	-	-	-	-	-
BIOMECHANICAL ANALYSIS--Hand Calculations									
	Method1			**Method2**			**Method3**		
	LB Com.	**LB Sh.**	**Sho. Mom.**	**LB Com.**	**LB Sh.**	**Sho. Mom.**	**LB Com.**	**LB Sh.**	**Sho. Mom.**
Sample1	3739	543	12	1694	583	34	1462	442	13
Sample2	3710	589	11	2120	598	33	1689	461	20
Sample3	4660	709	19	2109	695	47	1304	542	24
Stand S2	2236	385	50	-	-	-	-	-	-
Squat S2	3202	425	5	-	-	-	-	-	-
Low Back compression and shear forces are in N and shoulder moment is in N.m.									

Table 5.5. 3DSSPP Biomechanical evaluation results of three methods.

	Method 1: Manual Load Carrying					
	Stoop Lifting			**Squat Lifting**		
	L5/S1 Comp.	**L5/S1 Shear**	**Shoulder Mom.**	**L5/S1 Comp.**	**L5/S1 Shear**	**Shoulder Mom.**
Mean	4290.4	557.9	13.2	4329.9	411.1	27.4
Std. Dev.	561.2	60.5	9.8	606.7	69.9	10.8
	Method 2: Stair Climbing Trolley			**Method 3: Track Type Trolley**		
	L5/S1 Comp.	**L5/S1 Shear**	**Shoulder Mom.**	**L5/S1 Comp.**	**L5/S1 Shear**	**Shoulder Mom.**
Mean	2078.8	589.8	34.0	1740.0	445.7	14.9
Std. Dev.	467.1	41.8	12.8	363.8	36.4	7.4
L5/S1 compression and shear forces are in N, and shoulder moments are in N.m.						

- Method 1: Analysis of the method 1 showed that low back compression values of L5-S1 spine was generally above the NIOSH limit of 3400 N while lifting the bottle from the ground. For both squat and stoop lifting, mean value was about 4300N. Stoop lifting and squat lifting were almost equally strenuous for bottle carrying. Shear values of low back was mostly below widely accepted limit of 700 N. Stoop average was 558N and squat average was 411N. Shoulder moments were well below the conservative limit of 61 Nm while lifting phase, these values increased to 50 Nm levels at standing posture but again all of values were inside safe limits.
- Method 2: Low-back compression values of method 2 were at 2079 N in average which meant that these results were far away from the critical limits. Shear values were under the critical limit of 700 N averaging 590 N. Shoulder moments of method 2 were 34 Nm in average, again these values were under the limit of 61 Nm.
- Method 3: Method 3 low-back compression values were 1740 N in average and these were lower than any other method. Shear values of the low back were about 446 N in average, which was far from the critical limit of 700 N. Moreover, shoulder moments average was 15 N for this method.

To sum up, method 1 reached above the critical limits and also it is more than double of the method 3 values in terms of low-back compression values. Method 2 values were slightly higher than method 3 but both of them were far below the critical limit. In terms of shear forces, all methods were below the safety limits. Squat lifting was the best one with an average of 411 but there was a slight difference between it and method 3. All of the shoulder moments were well below the conservative limit; method 1 and 3 were better than method 2. So, after considering the all criteria, method 3 was the best method according to biomechanical approach and there was a potential risk for method 1 according to low-back compression values.

5.2.3. Regression Equations

In order to show the most important contributors of low back compression and shear values, and also for determining some predictive models for these tasks, regression equations were constructed by stepwise regression method. For squat and stoop lifting tasks, predictor variables of the equations were trunk angle (c), hip angle (d), knee angle (e), total of distance between low back and both hands (f), height (g) and weight (h). Furthermore for trolley pulling tasks these inputs were selected as elbow angle (a), shoulder angle (b), trunk angle (c), hip angle (d), knee angle (e), height of participant (g) and weight of participant (h). Response variables were L5/S1 compression and L5/S1 shear forces for three carrying methods. These variables can be seen on Figure 5.10. All of the input values can be seen at Figure E.2-3 (Appendix E). Hand loads were set as constant because loads didn't change in the experiments. Descriptive statistics for these variables can be seen at Table 5.6.

All dependent variables were checked with Anderson-Darling test for normality assumption of residuals. All of them were normally distributed. These graphs can be seen on Figure E.4 (Appendix E). Also there weren't any problems with homoscedasticity and auto-correlation according to" residuals vs. fitted value" and "residuals vs order" graphs. These residual plots can be seen on Figure E.5. Durbin-Watson statistics also declared that auto correlation was not a problem.

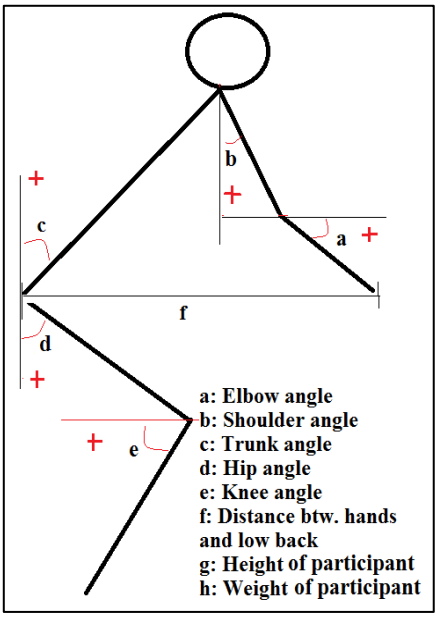


Figure 5.10. Variables used for regression equations.

For stoop lifting, hip angle was highly correlated with trunk (0.65) and knee angles (0.79), so it was deleted from the first models. There weren't any problems with collinearity for other methods so all variables were used in the initial model. Stepwise regression method was used to eliminate insignificant terms from the initial model. Table 5.7 shows the final regression equations for these methods and Table 5.8 shows the 3 highest contributors for response variable. All regression details can be seen on Figures E.6-13 (Appendix E).

5.3. Physiological Evaluation

Physiological criteria, were compared according to statistical comparison procedures explained before. Descriptive statistics information about both psychophysical and physiological evaluation variables can be seen at Table 5.12. Also, all of the variable values can be seen at Appendix F. These variables are VAS questions and Borg scale scores for psychophysical evaluation; heart rate variables for physiological evaluation and also the time variable. Normality test graphs, Sphericity test and within-subjects effect table will be included at Figure F.4, F.5, F.6 and Figure F.9 and F.10 (Appendix F); in this part statistical comparison tables will be shown.

Table 5.6. Descriptive statistics of angle and hand distance variables.

Method	Variable	Mean	SD	Minimum	Maximum
Stoop Lifting	Trunk Angle	82.37	9.92	66	104
	Hip Angle	40.60	14.27	21	82
	Knee Angle	82.03	8.52	60	95
	Hand Distance	102.03	15.16	79	147
	Height	178.40	4.64	169	189
	Weight	76.77	10.49	62	104
Squat Lifting	Trunk Angle	47.43	12.01	16	71
	Hip Angle	75.37	11.41	47	99
	Knee Angle	55.80	10.52	33	74
	Hand Distance	105.46	14.70	84	146
	Height	178.40	4.64	169	189
	Weight	76.77	10.49	62	104
Stair Climbing Trolley	Elbow Angle	58.13	6.20	45	72
	Shoulder Angle	8.77	9.78	-13	24
	Trunk Angle	23.43	10.97	4	52
	Hip Angle	31.13	10.11	14	57
	Knee Angle	90.13	13.41	53	105
	Height	178.40	4.64	169	189
	Weight	76.77	10.49	62	104
Track Type Trolley	Elbow Angle	40.73	7.73	19	55
	Shoulder Angle	17.57	11.03	-8	43
	Trunk Angle	19.10	9.36	2	38
	Hip Angle	27.57	7.74	13	44
	Knee Angle	92.40	13.64	47	105
	Height	178.40	4.64	169	189
	Weight	76.77	10.49	62	104

*All angles in degrees, hand distance in cm, participant height in cm and participant weight in kg

Table 5.7. Regression equations for response variables.

Stoop Lift	**LB Comp (N)**	**LBComp** = -6562 + 182.0 TrunkAng - 10.27 KneeAng + 19.72 HandsDist + 34.83 Weight of participant- 1.160 TrunkAng^2	R^2adj=95.4%
	LB Shear (N)	**LBShear** = -686.1 + 16.76 TrunkAng + 0.652 KneeAng - 0.2379 HandsDist + 0.382 Height of participant + 4.901 Weight of participant - 0.0887 TrunkAng^2	R^2adj=99.1%
Squat Lift	**LB Comp (N)**	**LBComp** = -6562 + 182.0 TrunkAng - 10.27 KneeAng + 19.72 HandsDist + 34.83 Weight of participant- 1.160 TrunkAng^2	R^2adj=97.7%
	LB Shear (N)	**LBShear** = 133.3 - 1.014 TrunkAng - 1.040 HipAng + 3.807 Weight of participant + 0.0468 TrunkAng^2	R^2adj=97.7%
Stair Climber Pull	**LB Comp (N)**	**LBComp** = -1135 - 23.24 ElbowAng + 24.029 ShouldAng + 68.84 TrunkAng + 6.861 HipAng+ 10.66 Height of participant + 12.432 Weight of participant - 0.4951 TrunkAng^2	R^2adj=99.3%
	LB Shear (N)	**LBShear** = 253.34 + 1.6360 TrunkAng - 0.1526 HipAng + 0.3713 KneeAng + 3.5079 Weight of participant	R^2adj=99.4%
Track Type Pull	**LB Comp (N)**	**LBComp** = -686 - 11.72 ElbowAng + 15.657 ShoulderAng + 66.88 TrunkAng - 1.019 KneeAng+ 4.09 Height of participant+ 13.046 Weight of participant- 0.637 TrunkAng^2	R^2adj=98.6%
	LB Shear (N)	**LBShear** = 131.11 + 0.0888 ElbowAng + 1.1657 TrunkAng - 0.1019 HipAng + 0.2625 KneeAng+ 3.4805 Weight of participant	R^2adj=99.7%
* All angles are in degree as unit, hand distance is in cm, height of participant in cm and weight of participant in kg.			

Table 5.8. Three highest contributed variables for the regression equations.

	Stoop Lift		**Squat Lift**	
	Variable	**Contribution**	**Variable**	**Contribution**
L5/S1 Comp.	Weight	43%	TrunkAng.	35%
	HandDist.	37%	Weight	27%
	KneeAng.	6%	HandDist.	24%
L5/S1 Shear	Weight	66%	TrunkAng.	64%
	TrunkAng.	24%	Weight	27%
	Height	5&	HipAng.	5%
	StairClimber Pull		**TrackType Pull**	
	Variable	**Contribution**	**Variable**	**Contribution**
L5/S1 Comp.	TrunkAng.	82%	TrunkAng.	80%
	Weight	8%	Weight	10%
	ShoulderAng.	4%	Height	4%
L5/S1 Shear	Weight	76%	Weight	87%
	TrunkAng.	21%	HipAng.	6%
	HipAng.	2%	KneeAng.	4%

5.3.1. Heart Rate Values

Heart rate averages for three methods were 153 bpm, 147 bpm and 145 bpm. Statistical difference was found between method 1 and 3 heart rate values at the end of the carrying task which can be seen at Table 5.9. Difference between methods 1 and 2 was also at the border of being significant. As stated in Table 2.3 of the Chung *et al.* (2005) paper, shown before, these heart rate values correspond to similar groups. Either method 1 HR value is at Very Heavy Workload group's lower end, others are at Heavy Workload group's upper end or HR1 is at Extremely Heavy Workload group's lower end others are at Very Heavy Workload group's upper end. Furthermore, like HR variable, there was also a statistically significant difference between methods 1 and 3 in terms of % Heart Rate Increase and % Maximum Heart Rate values. Mean percentage of maximum heart rate values were %78.3, %76.4 and %74.5. These values show us that there is not a practically large difference between these methods in terms of heart rates. All of these results can be seen at Tables 5.9., 5.10. and 5.11.

Table 5.9. Comparison test results for heart rate values.

Pairwise Comparisons						
HR Factors					**95% Confidence Interval for Difference[b]**	
I	**J**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
1	2	6,100	2,346	,053	-,059	12,259
	3	7,500*	1,658	,001	3,147	11,853
2	1	-6,100	2,346	,053	-12,259	,059
	3	1,400	1,912	1,000	-3,619	6,419
3	1	-7,500*	1,658	,001	-11,853	-3,147
	2	-1,400	1,912	1,000	-6,419	3,619
Based on estimated marginal means *. The mean difference is significant at the ,05 level. b. Adjustment for multiple comparisons: Bonferroni.						

Table 5.10. Comparison test results for % heart rate increase.

Pairwise Comparisons						
HRInc Factors					**95% Confidence Interval for Difference[b]**	
I	**J**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
1	2	9,000	3,587	,064	-,415	18,415
	3	11,150*	2,510	,001	4,560	17,740
2	1	-9,000	3,587	,064	-18,415	,415
	3	2,150	2,887	1,000	-5,428	9,728
3	1	-11,150*	2,510	,001	-17,740	-4,560
	2	-2,150	2,887	1,000	-9,728	5,428
Based on estimated marginal means *. The mean difference is significant at the ,05 level. b. Adjustment for multiple comparisons: Bonferroni.						

5.3.2. Brouha Guideline

According to Brouha guideline (1967), further two heart rate values are recorded about 45 seconds and 165 seconds after the task has ended. Table 5.13 shows unacceptable

values for each of the Brouha criteria as signed. First criteria is being ≤ 110 beats per minute (bpm) at first recording and second criteria is recovering heart rate ≥ 20 bpm between two recordings. Table 5.14 shows the subjects that violates at least one of the criteria. Some values that are considerably low are also accepted for criteria two. It can be seen that most of the subjects violated at least one criteria for each method according to Brouha guideline. So the job, in overall, is not acceptable to majority of the participants, in terms of physiological cost.

After considering all of the assessment done above, it can be asserted that there is not an important practical difference between these methods regarding physiology. There is a slight, and statistically significant, difference for heart rate values especially between methods 1 and 3, but these values are very near in practical terms and also Brouha results state this similarity because most of subjects violated the rules of Brouha. It should also be considered that tempo of method 1 is naturally higher than others; this fact may have an effect on this slight heart rate difference. To sum up, as stated by all of the evaluations, these three methods are similar in terms of physiological strain.

Table 5.11. Comparison test results for % of maximum heart rate.

Pairwise Comparisons						
HRMax Factors					**95% Confidence Interval for Difference[b]**	
I	**J**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
1	2	1,900	1,304	,484	-1,522	5,322
	3	3,850*	,834	,001	1,660	6,040
2	1	-1,900	1,304	,484	-5,322	1,522
	3	1,950	1,406	,544	-1,740	5,640
3	1	-3,850*	,834	,001	-6,040	-1,660
	2	-1,950	1,406	,544	-5,640	1,740
Based on estimated marginal means *. The mean difference is significant at the ,05 level. b. Adjustment for multiple comparisons: Bonferroni.						

Table 5.12. Descriptive statistics for physiological and psychophysical variables

Evaluation	Methods	N	Minimum	Maximum	Median	Mean	Std. Deviation	Std. Error	95% Confidence Interval	
									Lower	Upper
Psychophysical Question 1 (0-100 Scale)*	Psycho1M1	20	14	83	56.5	52.40	19.48	4.36	43.28	61.52
	Psycho1M2	20	20	93	69.5	64.95	18.16	4.06	56.45	73.45
	Psycho1M3	20	30	83	52	52.65	14.18	3.17	46.01	59.29
Psychophysical Question 2 (0-100 Scale)	Psycho2M1	20	1	83	32	38.70	22.84	5.11	28.01	49.39
	Psycho2M2	20	0	47	11	14.50	12.23	2.74	8.78	20.22
	Psycho2M3	20	15	71	37	38.35	17.06	3.82	30.36	46.34
Psychophysical Question 3 (0-100 Scale)	Psycho3M1	20	0	55	16	19.80	17.19	3.84	11.75	27.85
	Psycho3M2	20	0	62	24.5	26.70	19.08	4.27	17.77	35.63
	Psycho3M3	20	4	81	48	47.25	20.97	4.69	37.44	57.06
Psychophysical Question 4 (0-100 Scale)	Psycho4M1	20	13	97	51	49.50	23.65	5.29	38.43	60.57
	Psyhco4M2	20	0	53	21	23.70	15.63	3.49	16.39	31.01
	Psycho4M3	20	19	87	52	51.20	16.89	3.78	43.30	59.10
Heart Rate (Beats per minute)	HRM1	20	138	168	151.5	152.85	8.27	1.85	148.98	156.72
	HRM2	20	115	163	151	146.75	13.19	2.95	140.57	152.92
	HRM3	20	127	160	148	145.35	9.26	2.07	141.01	149.69
Heart Rate Increase (Percent)	HRIncPctM1	20	88	150	122.5	117.85	18.72	4.19	109.09	126.61
	HRIncPctM2	20	67	142	113	108.85	20.26	4.53	99.37	118.33
	HRIncPctM3	20	82	128	108.5	106.70	14.77	3.30	99.79	113.61
Percentage of Maximum Heart Rate (Percent)	HRMaxPctM1	20	71	86	77.5	78.35	4.43	0.99	76.28	80.42
	HRMaxPctM2	20	59	92	78	76.45	7.68	1.72	72.86	80.04
	HRMaxPctM3	20	65	82	76	74.50	4.78	1.07	72.26	76.74
Borg Scores (6-20 Scale)	BorgM1	20	9	16	13.5	13.40	1.76	0.39	12.58	14.22
	BorgM2	20	10	19	15	15.15	1.98	0.44	14.22	16.08
	BorgM3	20	12	17	13	13.45	1.19	0.27	12.89	14.01
Time (Seconds)	TimeM1	20	56	90	72	73.05	9.25	2.07	68.72	77.38
	TimeM2	20	195	378	248.5	253.60	39.47	8.83	235.13	272.07
	TimeM3	20	215	328	236.5	245.95	28.30	6.33	232.71	259.19

*For the questions, refer to Appendix B.

Table 5.13. Heart rate results for all subjects according to Brouha procedures.

		Subjects									
Time period*	**Methods**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
30-60 sec	M1	141	132	75	90	143	112	95	113	109	103
	M2	130	106	85	89	132	115	96	111	104	97
	M3	130	105	83	80	133	112	90	108	94	110
150-180 sec	M1	101	82	68	74	111	75	67	68	84	72
	M2	112	81	70	75	106	90	84	91	92	72
	M3	99	75	80	75	116	94	79	80	82	76
		Subjects									
Time period*	**Methods**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
30-60 sec	M1	122	121	147	133	113	120	128	115	115	92
	M2	145	117	134	142	114	139	122	126	114	107
	M3	136	110	125	130	122	136	120	111	111	98
150-180 sec	M1	91	98	98	89	95	98	101	80	75	76
	M2	102	95	108	110	99	116	105	86	98	87
	M3	103	91	98	106	103	110	96	80	84	62
* After completion of the task											

Table 5.14. Table of subjects that violate at least one criterion of Brouha.

		Subjects																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Methods	1																				
	2																				
	3																				

5.4. Psychophysical Evaluation

All psychophysical criteria were also compared among the methods with statistical comparison techniques defined before. Normality test graphs, Sphericity test and within-subjects effect table are listed at Figure F.1, F.2, F.3 and Figure F.8 and F.10 (Appendix F). In this section, Repeated Measures ANOVA and Friedman's ANOVA comparison results will be listed only.

5.4.1. Borg Criteria

First criteria were Borg Scale of 6-20 which aimed to determine perceptual strain of workers during carrying tasks. Averages of three methods were 13.4 (somewhat hard), 15.1 (heavy) and 13.4 (somewhat hard), respectively for method1, method2 and method3. According to comparison test in Table 5.15, left table shows that there is at least one significantly different method among three. Later, Wilcoxon Signed Ranks test was applied to see the different one. According to Bonferroni Correction, significance level was equal to 0.0167 for this post hoc test. It was found that method 1 and method 3 were significantly lower than method 2 as well as there weren't any significant difference between 1 and 3. As stated by Borg Scale results, Method 2 was perceptually much more strenuous than others.

Table 5.15. Comparison test results for Borg scale.

Ranks	
	Mean Rank
BorgM1	1,78
BorgM2	2,68
BorgM3	1,55
Test Statistics[a]	
N	20
Chi-Square	15,972
df	2
Asymp. Sig.	,000
a. Friedman Test	

Test Statistics[a]			
	BorgM2 - BorgM1	**BorgM3 - BorgM1**	**BorgM3 - BorgM2**
Z	-2,918[b]	-,174[b]	-3,115[c]
Asymp. Sig. (2-tailed)	,004	,862	,002
a. Wilcoxon Signed Ranks Test			
b. Based on negative ranks.			
c. Based on positive ranks.			

5.4.2. VAS Criteria

VAS Question 1: Another four criteria were regarding VAS questionnaires. First of the questions was "Define the effort you exerted during the task between 0-100; 100 being very high". Average scores of this question were 52.4, 64.9 and 52.6 in turn. As claimed by the test results in Table 5.16, there were no significant difference between methods 1 and 3

but method 2 was significantly higher than the others. It can be concluded that people felt extra exhausted after completing the task 2 relative to other tasks.

Table 5.16. Comparison test results for psychophysical question one.

Pairwise Comparisons						
Psycho1 Factors					95% Confidence Interval for Difference[b]	
I	J	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
1	2	-12,550*	3,533	,006	-21,824	-3,276
	3	-,250	3,215	1,000	-8,690	8,190
2	1	12,550*	3,533	,006	3,276	21,824
	3	12,300*	3,076	,002	4,224	20,376
3	1	,250	3,215	1,000	-8,190	8,690
	2	-12,300*	3,076	,002	-20,376	-4,224
Based on estimated marginal means *. The mean difference is significant at the ,05 level. b. Adjustment for multiple comparisons: Bonferroni.						

VAS Question 2: Second question was “Assume that, you are doing this upstairs load carrying task many times during an eight-hour workday. What would be your preference level for this method on a 0-100 scale, 100 means most definitely would prefer?” 3 methods got average scores of 38.7, 14.5, and 38.3 in order. Normality assumption was violated severely, so Friedman’s test was applied for this variable. In Table 5.17, left table shows that there is at least one significantly different method. So, pairwise comparisons were applied with Wilcoxon Signed Ranks Test. Again post hoc significance level was 0.167. Method 2 was preferred with a significantly lower rate than other two methods. There weren’t any significant difference between methods 1 and 3. It could be asserted that workers tend to prefer using methods 1 and 3 rather than 2 for a whole working day.

VAS Question 3: The next question of psychophysical evaluation was “Think about an eight-hour workday which you have to carry weights of heavier than 20 kg. What would be your preference rate over a scale of 0-100, 100 means most definitely would prefer?” Average preference rates were 19.8, 26.7 and 47.2 this time. As stated by the comparison test results in Table 5.18, there weren’t any significant difference between preferences of

method 1 and 2 but method 3 had a significantly higher preference ratio than others. This results leads to a fact that method 3 is much more preferable than other methods while carrying loads heavier than 20 kg according to workers' perceptions.

Table 5.17. Pairwise test results of psychophysical question two (Friedman's Test).

Ranks	
	Mean Rank
Psycho2M1	2,20
Psycho2M2	1,18
Psyhco2M3	2,63

Test Statistics[a]	
N	20
Chi-Square	22,506
df	2
Asymp. Sig.	,000

a. Friedman Test

Test Statistics[a]			
	Psyc2M2 - Psyc2M1	Psyc2M3 - Psyc2M1	Psyc2M3 - Psyc2M2
Z	-3,251[b]	-,728[c]	-3,825[c]
Asymp. Sig. (2-tailed)	,001	,466	,000

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.
c. Based on negative ranks.

Table 5.18. Comparison test results for psychophysical question three.

Pairwise Comparisons						
Psycho3 Factors					**95% Confidence Interval for Difference[b]**	
I	**J**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**Lower Bound**	**Upper Bound**
1	2	-6,900	5,234	,609	-20,640	6,840
	3	-27,450*	4,151	,000	-38,348	-16,552
2	1	6,900	5,234	,609	-6,840	20,640
	3	-20,550*	3,832	,000	-30,608	-10,492
3	1	27,450*	4,151	,000	16,552	38,348
	2	20,550*	3,832	,000	10,492	30,608

Based on estimated marginal means
*. The mean difference is significant at the ,05 level.
b. Adjustment for multiple comparisons: Bonferroni.

VAS Question 4: Last question of the evaluation was "Make an assessment about the ease of use for the method while conducting the task on a 0-100 scale, 100 being very

good" Average values for these methods were 49.5, 23.7 and 51.2 in order. As can be seen at Table 5.19, there was no significant difference between methods 1 and 3; whereas these two methods were significantly higher than method 2 as a result. According to this fact, it can be asserted that workers evaluated usability of method 2 as the worst among all three methods.

As a result, it may be said that method 2 performs as the worst one among all in terms of psychophysics both for Borg and VAS criteria. Method 1 and 3 are almost same for psychophysics; only difference is higher preference rate of method 3 for heavier loads scenario.

Table 5.19. Comparison test results for psychophysical question four.

Pairwise Comparisons						
Psycho4 Factors		**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**95% Confidence Interval for Difference[b]**	
I	**J**				**Lower Bound**	**Upper Bound**
1	2	25,800*	6,246	,002	9,404	42,196
	3	-1,700	6,219	1,000	-18,025	14,625
2	1	-25,800*	6,246	,002	-42,196	-9,404
	3	-27,500*	4,172	,000	-38,453	-16,547
3	1	1,700	6,219	1,000	-14,625	18,025
	2	27,500*	4,172	,000	16,547	38,453

Based on estimated marginal means
*. The mean difference is significant at the ,05 level.
b. Adjustment for multiple comparisons: Bonferroni.

5.5. Discussion

Three load carrying methods are evaluated according to three ergonomics approaches; biomechanical, physiologic and psychophysical. The obtained results are summarized in Table 5.21.

(i) For the case of Method 1:

- Biomechanically, REBA evaluation method suggests that this method is a risky one and needs to be changed soon. Also, low back compression forces are above the critical limits during lifting phase, both for stoop and squat type lifting methods. This may lead to a hazardous situation if such forces are encountered regularly by causing cumulative micro-traumas on low back. On the other hand, there is not a problem with low back shear forces and shoulder moments during application of this method because these values stay within the safe zone.
- According to the physiological evaluation, method 1 may be regarded as a "heavy" or "very heavy" task as heart rate of subjects reaches up to 150 bpm during work. Furthermore, most of the subjects couldn't provide the required criteria for Brouha guideline which is an insight of physiologically exhausting task.
- Psychophysically, method 1 was not the worst one among three methods. People said that, if the load was higher, then they wouldn't prefer this method.

As a result, it can be concluded that there are some risk evidence for method 1. Especially, low back compression values have the potential of reaching up to risky levels. Also, physiologically this task can be considered as very heavy and exhausting. This method may lead to potential health problems. Hypothesis one can be accepted partially.

(ii) For the case of Method 2:

- For REBA evaluation, method 2 gets a better score than method 1. It also needs some changes but not as critical as method 1. Furthermore, there is an important difference between low back compression scores. Method 2 obtains much lower low back compression scores than method 1 and these are within safe limits. On the other hand, shear forces are similar. Only continuous shoulder moments are higher than method 1. But these values are within safe limits also.
- Physiologically, method 2 values are almost same as method 1. It can, also, be considered as "heavy" or "very heavy" work according to physiological criteria.
- Psychophysically, method 2 is clearly the worst one among all the three methods. People need to exert high static forces during pulling this vehicle through stair

climbing task. So, it can be asserted that people do not prefer the continuous static forces required by method 2. It makes them feel tired after the task.

As a result, biomechanically method 2 is a better method than method 1; it improves the risky situation related to method 1. Nonetheless, it needs high static forces during the task and people find this method as less preferable and more exhaustive. Therefore, hypothesis two can be partially accepted.

(iii) For the case of Method 3

- REBA evaluation score of the method 3 is better than other methods. It has also some improvement areas but these improvements are less critical than others. Moreover, in terms of low back compression values and low back shear forces method 3 is the best among all. Continuous shoulder moments are as same as method 1 and they are well below the safe limits. Also, they are lower than method 2 values.
- According to physiological evaluation, there isn't any big difference between 3 methods. There is a slight difference in heart rate values, method 1 is higher, but this difference is not practically meaningful. Because, method 3 can also be considered as "heavy" or "very heavy" work according to its heart rate levels. Furthermore, most of the subjects violated Brouha criteria for both of the three methods, too.
- Psychophysically, method 3 and method 1 are almost the same. There is only a slight difference which people prefer method 3 for heavier loads. Moreover, it is better than method 2 in all areas.

In summary, method 3 seems to be performing better than other methods. All methods were physiologically exhaustive and rated as "heavy" tasks. Between method 1 and 2, there is not a clear distinction. Actually, method 2 is better in terms of biomechanics and method 1 is better in psychophysics. It may look like a dilemma but Kim's model in Figure 2.5 explains such situations in his graph and leads evaluators for better statements. This graph shows us the correct way of analysing tasks under such contradictions. Under different job characteristics, different criteria act as constraint. As an example, for high frequencies like four lifts per minute, dominant constraints are physiological and psychophysical criteria. On the other hand, for low frequency tasks, biomechanics is the

dominant criteria for determining a safe load limit. With the help of this information, it can be asserted that for low frequency jobs method 2 can be preferred rather than method 1. Furthermore, method 3 can be preferred independent from criteria because it performs better than the two other methods for almost all criteria. All methods are exhaustive according to physiological criteria but this case may become the leading constraint for high frequency jobs, too. It is not a big problem for low frequency tasks. If load carrying on stair tasks are done with interruptions and low frequencies, physiological exhaustion will not be such a problem at all.

Of course, this selection may be considered according to practical life constraints besides theoretical evaluations. Such devices offer less in terms of mobility and it is a disadvantage in practical life and industry. Also, Table 5.20 shows the descriptive statistics of task completion times.

Table 5.20. Descriptive statistics of time variable of tasks.

					95% Confidence Interval for Mean			
Methods	**N**	**Mean**	**Std. Dev.**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Min.**	**Max.**
1	20	73.05	9.25	2.07	68.72	77.38	56.00	90.00
2	20	253.60	39.47	8.83	235.13	272.07	195.00	378.00
3	20	245.95	28.30	6.33	232.71	259.19	215.00	328.00
Total	60	190.87	88.63	11.44	167.97	213.76	56.00	378.00
Time (Seconds)								

Time required to complete these methods are on average 73, 253 and 245 seconds in order. It can be seen that method 1 is faster and more practical than others. In work life, this may be seen as an advantage for frequent and time-constrained jobs. In real life, optimal solution would be on a trade-off point between practical optimal and theoretical optimal. This thesis aims to give insights for theoretical sides of such trade-off analyses. Making this trade-off analysis is not in the scope of this study.

Table 5.21. Summary table of the results.

		Shoulder Carry	Stair Climber	Track Type Trolley
Biomechanics	REBA Evaluation	Get 9 points equals to High Risk score; needs critical investigation and changes	Get 7 points equals to Medium Risk; needs changes less critical than shoulder carrying.	Get 5 points equals to Medium Risk. It also needs changes but least critical among all.
	L5/S1 Compression	It leads to average force about 4300N which is above the safety limits. Worst one among all.	Average force about 2000N, below the safety limits.	1750N compression force in average, below the safety limits and the best one of all.
	L5/S1 Shear	470N average, below the safety limits.	600N average, below the safety limits.	450N average, below the safety limits.
	Shoulder Moment	About 20Nm in average, below the safety limits.	About 34 Nm in average, below the safety limits.	15Nm in average, below the safety limits.
	Summary	Method 1 has potential risks associated with high low back compression values. REBA evaluation says that it is riskier than others. All methods are below the safety limits according to shoulder moments and low back shear forces		
Physiology	Heart Rate	152.8 bpm in average.	146.7 bpm in average.	145.3 bpm in average. Significantly lower than method 1.
	%Max Heart Rate	%78.3 in average.	%76.4 in average	%74.5 in average. Significantly lower than method 1.
	Heart Rate Increase %	117.8% in average.	108.8% in average.	106.7% in average. Significantly lower than method 1.
	Brouha	14 participants violated at least 1 criteria of guideline.	15 participants violated at least 1 criteria of guideline.	13 participants violated at least 1 criteria of guideline.
	Summary	Method 3 is statistically lower than method 1.This statistical difference doesn't relate to an important practical difference. Heart rate values are very near, also maximum heart rate% regions are similar. Most of the subjects for both methods violated Brouha criteria. There is not an important difference.		

Table 5.22. Summary table of the results (cont.).

Psychophysics	Borg Scale (6-20)	13.4 average Borg score	15.1 average Borg score, significantly higher than others. People feel more exhausted	13.4 average Borg score
	Psychophysical Question 1 (0-100)	52.4 average perceived effort	64.9 average perceived effort, people feel significantly higher effort during this method	52.6 average perceived effort
	Psychophysical Question 2 (0-100)	38.7 preference score	14.5 preference score significantly lower than others.	38.3 average preference score
	Psychophysical Question 3 (0-100)	19.8 preference score for heavier weights	26.7 preference score for heavier weights	47.2 preference score for heavier weights, significantly higher than other methods
	Psychophysical Question 4 (0-100)	49.5 usability score for this method	23.7 usability score for this method, significantly lower than other methods.	51.2 usability score
	Summary	Method 2 is the worst one according to feelings of people in terms of psychophysics. There is not a big difference between methods 1 and 3, only for heavier weights people prefer method 3 rather than method 1. Other criteria are similar for both.		

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

In this study, the workload of water bottle carrying task during stair climbing, which is widely encountered in Turkey, was chosen for ergonomic evaluation. The task, in its usual performance, involves carrying a 19 kg water bottle on shoulder while climbing a stair. After determining the workers´ complaints through a survey, alternative methods of carrying were tested to find a safer method. That is, besides shoulder carrying, a stairclimbing trolley and a home-built track type trolley were tested by a sample of participants. The workloads are determined for all the three methods of carrying in terms of biomechanical, physiological and psychophysical approaches. The following conclusions are reached based on the statistical analysis:

(i) The field survey indicates some evidence of relationship between bottle carrying through stairs and MSD risks. 41% of workers stated that they had physical pain and 21% of them stated that they had low back pain.

(ii) The induced average L5/S1 compression force during shoulder carrying of the water bottle is above the NIOSH safety limits for both squat and stoop lifting techniques. On the other hand, the mean compressive forces for the other two methods, use of stairclimbing hand trolley and track type trolley, are well below this critical limit; track type trolley inducing the lowest one.

(iii) Average L5/S1 shear forces are found below the safety limits for all the three methods. The highest shear force is induced by the stairclimbing trolley.

(iv) Average shoulder torque values induced by the carrying methods are also below the safety limits for all the methods.

(v) In terms of induced physiological stress, all of the carrying methods are considered as heavy tasks with respect to Brouha Guideline and heart rate values. All the three methods induced similar heart rate values but the track type trolley is statistically lower than the others. For all the three methods, most of the participants violated at least one of the Brouha criteria; that, the task can be considered physiologically exhaustive regardless of any of the methods.

(vi) In terms of psychophysical stress, the average Borg score of stairclimbing hand trolley is statistically higher than the other two methods, which means that participants consider this method of carrying more fatiguing.

(vii) According to the second psychophysical scale, the visual analogue scale, carrying by the use of stairclimbing hand trolley is the least preferable and usable among the three methods. In addition, track type hand trolley has a statistically higher preference score for carrying heavier weights than 19 kg.

(viii) The average task completion time of shoulder carrying is almost three times less than the other two methods.

(ix) For such low frequency tasks, Kim's model in Figure 2.2 suggests that biomechanical criterion is the limiting factor rather than physiological or psychophysical criteria. With respect to this, track type trolley is better than the other two methods in terms of low back safety.

It is found that manual load carrying on stairs possess serious risk potential of developing musculoskeletal disorders on long term. Especially, according to low back biomechanics, such tasks lead to high force exertions and increase the potential risk of developing a low back disorder. Manual material handling devices offer less force requirements and reduce the force loadings on human body. It is found that these devices improve the situation regarding manual load carrying. Therefore, they reduce the risks associated with such manual carrying tasks. In practical life, such devices may not be preferred to use but trade-off decisions should focus on human health in general. If these devices become more mobile and light, their usability in industry can increase over time.

6.2. Recommendations for Future Research

- In this study, track type trolley is constructed by hand, so it may not be as efficient as professionally manufactured one. Using an improved track type trolley, especially with a more ergonomic handles, may lead to even better results in a further research.
- Gender difference is not included in this study and this may be a research topic in future.
- Manual carrying style of the load is chosen as shoulder carrying in this study but there may be several different carrying styles like back carrying, front carrying, hand carrying and even head carrying. Weight of the load can be a variable in a different study.
- Carrying distance may be changed and rather than an ascending task, a descending task or a combination of both may be applied.
- In calculation of low back and shoulder forces and moments, the study used a static biomechanical model. The future studies may consider a dynamic modeling approach instead of static.

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APPENDIX A: SURVEY OF LOAD CARRYING

A.1. Occupational Strain Survey

Occupational Strain Survey

- What is your age?
- How long have you been working at this job?
- How many hours do you work per day?
- How many water bottles do you carry per day approximately?
- Do you carry two water bottles at the same time?
- Were you consulted by a doctor because of a Musculoskeletal Disorder last year? If so, which area of your body was the problem?
- Are there any areas in your body that is aching, paining or restricting your movements?
- After your work finishes on a day, how do you evaluate it in terms of exhaustion?

Little Exhaustive ——— Very Exhaustive

- After you finish your work, at which areas of your body do you feel discomfort? Choose and rate the exhaustion level of that area below.

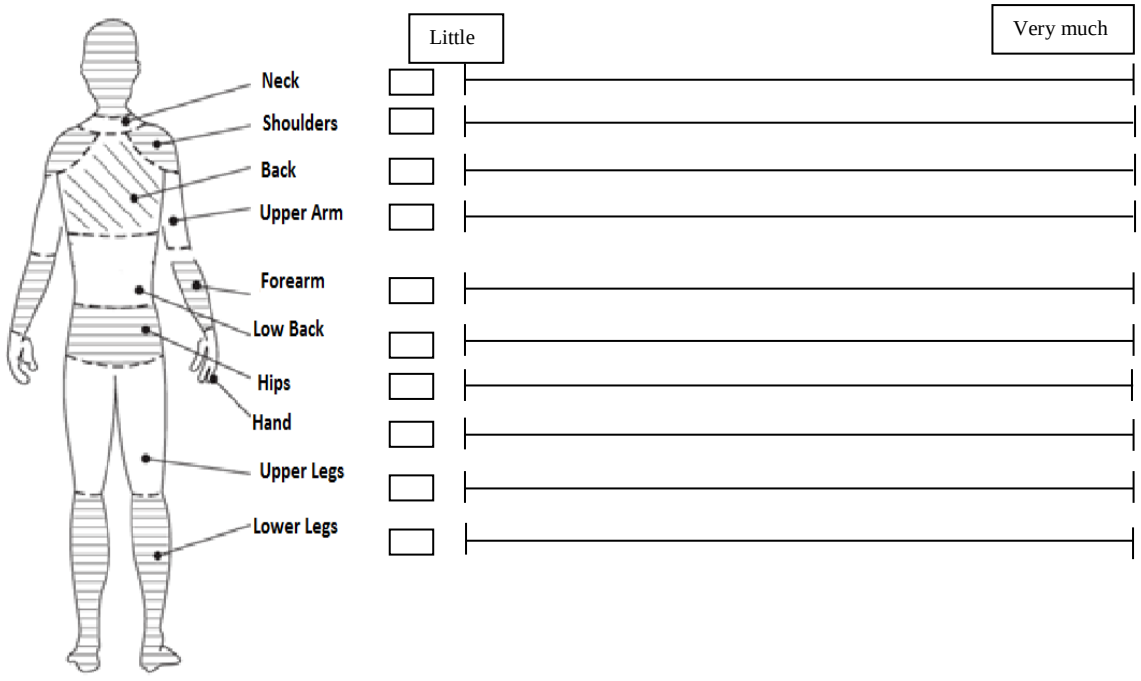
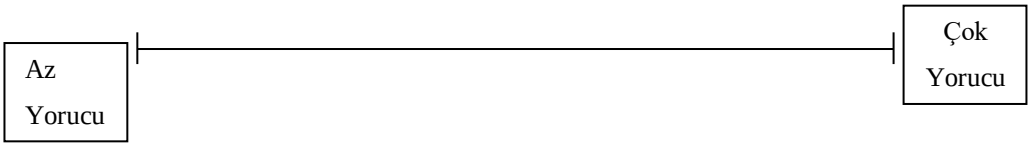


Figure A.1. Occupational strain survey form.

A.2. Occupational Strain Survey in Turkish

Mesleki Yıpranma Anketi

- Yaşınız:
- Kaç yıldır bu mesleği yapıyorsunuz?:
- Günde kaç saat çalışıyorsunuz?:
- Günde yaklaşık olarak kaç tane damacana taşıyorsunuz?:
- 2 damacanayı aynı anda taşır mısınız?:
- Son yıllarda hiç kas-iskelet hastalığı sebebiyle doktora gittiniz mi? Hangi bölgenizde rahatsızlık vardı?:
- Vücudunuzda ağrıyan, acı veren, hareketinizi kısıtlayan bir bölge var mı?:
- Gün sonunda mesainiz bittikten sonra işiniz size ne kadar yorucu geliyor?:



- Mesainiz bittiğinde vücudunuzun hangi bölgelerinde ağrı ve acı hissediyorsunuz? Vücudunuzdaki yorgunluk düzeyini nasıl notlandırırsınız?:

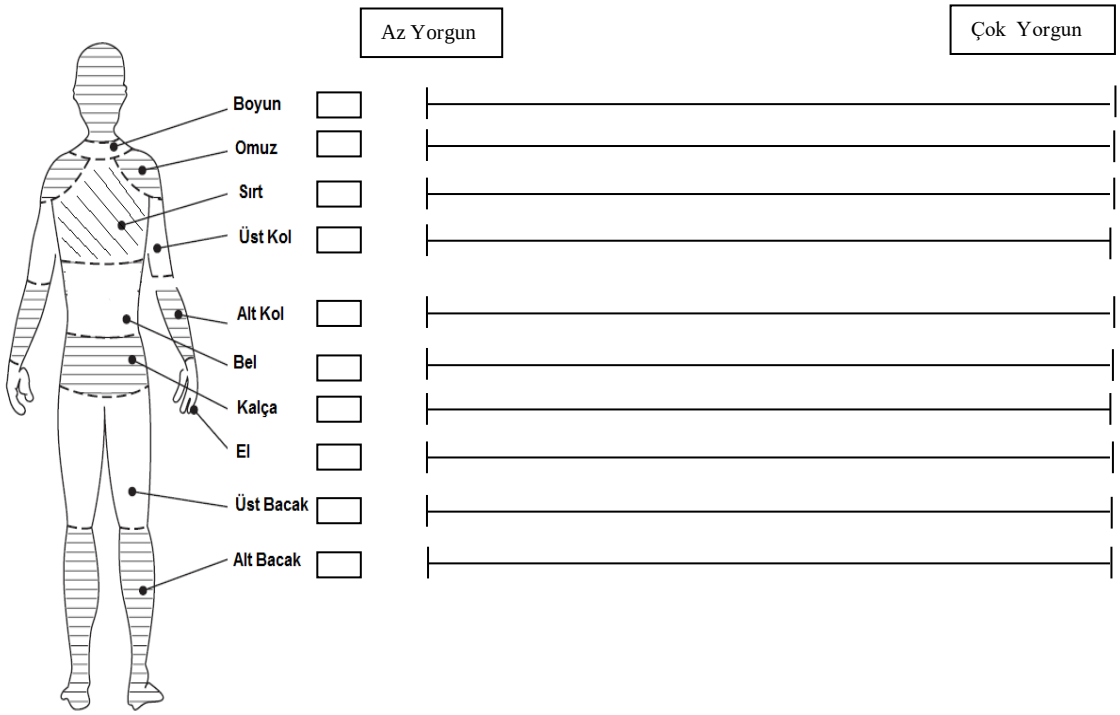


Figure A.2. Occupational strain survey form in Turkish.

APPENDIX B: CONSENT FORM, PARTICIPANT INFORMATION FORM, VAS AND BORG SCALE

B.1. Consent Form for Experiment Participants

Project Director: Doç. Dr. Mahmut Ekşioğlu

Project Title: Ergonomic Investigation of a Load Carrying Task during Stair Climbing

Project Subject: In modern times, countless of load carrying tasks through stairs have been happening every day. The scene that people carrying loads up to 100 kg on stairs is a very common event that can be seen frequently. This kind of tasks may be exhausting, tiring and injurious. Main purpose of ergonomics has been always organizing job and tasks in harmony with humans. Because of this reason, load carrying task through stairs; which are encountered frequently in daily life as well as have the potential of reaching beyond human capabilities and hurting them; are the main subject of this study. Within this study, load carrying on stairs will be done with three different methods; manual carrying of the loads, using a stair climbing hand trolley and also using a modified track type hand trolley. It is planned to carry 19 kg's of water bottles for three floors in experiments because these loads will not be risky for subjects in short term and also water bottle carrying is a frequently encountered task in market. Measurements taken in the experiments may be shared with subjects after the study. Equipment that will be used in experiments does not possess a potential health risk. Experimental studies will be taken at the stairs of Engineering Building and at Boğaziçi University Ergonomics lab with the permission of *Institutional Review Board for Research with Human Subjects*.

Approval: We are inviting you to the experiments regarding the effects of load carrying during stair ascend. Inside the scope of this study, three different carrying methods will be conducted and biomechanical, physiological and psychophysical effects of these methods

Figure B.1. Consent form for experiment participants.

will be analysed to detect if there is a difference between them or not. In case you accept to participate in this study, you will be included to the experiments that will be conducted at the stairs of Boğaziçi University for at most four hours. Data that will be collected from you may be used for various studies in future. Your name will not appear in these studies or reports.

The decision for participating in this study is totally up to you. You can forfeit whenever you want without a reason. We do not demand any charge from you and also you will not be paid at the end of study.

There is not a possible health risk regarding these experiments. Measurement devices are totally safe for human health.

Before signing this form, please call and ask Assoc. Prof. Mahmut Ekşioğlu about the questions you wonder about. You can refer to local ethics committees about your rights, too.

Please inform us if your address or phone number changes.

……

I have understood everything you tell me and written above. I have taken a copy of this form with me. I accept to participate in this study.

Participant Name-Surname and Signature Date

If exist, Name-Surname and signature of participant's parent Date

Figure B.1. Consent form for experiment participants (cont.)

KATILIMCI BİLGİ ve ONAM FORMU

Proje yürütücüsü: Doç. Dr. Mahmut Ekşioğlu

Proje başlığı: Merdivende Yük Taşıma Görevlerinin Ergonomik Açıdan Araştırılması

Proje konusu: Günümüzde her gün merdivenler üzerinde sayısız yük taşıma işi gerçekleşmektedir. İnsanların merdivenlerde ağırlığı 100 kilograma varan yükleri çıkarıp indirdiklerini görmek sıklıkla rastlanan manzaralardandır. Bunlar Bu tip işler insanların doğası açısından oldukça yorucu, tehlikeli ve tüketici boyutlara ulaşabilir. Ergonominin ana amacı her zaman için yapılan iş ve görevlerin insan doğasına uygun olacak şekilde düzenlemesini sağlamak olmuştur. Bu sebeple her gün rastlanılan ve insan doğasının dışına çıkıp çalışanlara zarar verme potansiyeli olan merdivende yük taşınması işlemlerinin ergonomik açıdan incelenmesi ve iyileştirme alternatiflerinin araştırılması bu projenin ana konusu olmuştur. Proje dahilinde 3 farklı, merdivende yük taşıma işlemi gerçekleşecektir; yükü aletsiz taşıma, yükü piyasada da bulunan merdiven çıkabilen bir el arabası yardımı ile taşıma ve son olarak piyasadaki modelin modifiye edilmiş başka bir konsepti ile yükü taşıma. Bu taşımalarda hem denekleri zorlamamak hem de piyasada sık kullanılan bir aktivite üzerinden çalışmış olmak amacıyla örnek görev olarak 20 litrelik damacanaların merdivende 3 kat taşınması planlanmıştır. Alınan ölçüler çalışma sonunda kişi isterse kendisi ile de paylaşılacaktır. Çalışmada kullanılacak ölçme aletleri herhangi bir sağlık riski taşımamaktadır. Deneysel çalışmalar *Boğaziçi Üniversitesi "İnsan Araştırmaları Kurumsal Değerlendirme Kurulu*" onayı ile Boğaziçi Üniversitesi Ergonomi Laboratuvarı´nda ve Mühendislik Binası merdivenlerinde yapılacaktır.

Onay: Merdivende yük taşımanın insan vücudu üzerine olan etkilerini araştırdığımız çalışmamıza katılmaya sizi davet ediyoruz. Çalışmamız kapsamında 3 farklı metod ile yük taşıma görevleri gerçekleştirilecek ve bu metodların fizyolojik, antropometrik ve psikofiziksel etkilerinin farklılık gösterip göstermediği araştırılacaktır. Araştırmaya katılmayı kabul ettiğiniz takdirde en fazla 4 saat boyunca Boğaziçi Üniversitesi Mühendislik Binası merdivenlerinde yapılacak olan yük taşıma çalışmalarında yer

Figure B.2. Consent form for experiment participants in Turkish.

alacaksınız. Sizden toplanan veriler ileride başka çalışmalar için de kullanılabilir. Bütün çalışma ve raporlarda isminiz tamamen gizli tutulacaktır.

Çalışmaya katılmanız tamamen isteğe bağlıdır. Dilediğiniz zaman, sebep göstermeksizin çalışmadan çekilebilirsiniz. Sizden ücret talep etmiyoruz ve size herhangi bir ödeme yapmayacağız.

Yapmak istediğimiz araştırmanın size risk getirmesi beklenmemektedir. Ölçüm cihazlarının insan sağlığı üzerine hiçbir zararı bulunmamaktadır.

Bu formu imzalamadan önce, çalışmayla ilgili sorularınız varsa lütfen sorun. Daha sonra sorunuz olursa, Doç. Dr. Mahmut Ekşioğlu'ya (Tel: 0533 390 2035) sorabilirsiniz. Araştırmayla ilgili haklarınız konusunda yerel etik kurullarına da danışabilirsiniz.

Adres ve telefon numaranız değişirse, bize haber vermenizi rica ederiz.

Bana anlatılanları ve yukarıda yazılanları anladım. Bu formun bir kopyasını aldım.
Çalışmaya katılmayı kabul ediyorum.

Katılımcı ismi ve imzası Tarih

Varsa, Katılımcının vasisinin adı, soyadı Tarih

Figure B.2. Consent form for experiment participants in Turkish (cont.).

B.2. Participant Physiological Results Form

PARTICIPANT INFORMATION

Date:	Height:	Weight:
Age:		Resting Heart Rate:
Gender:		Max. Heart Rate:

PHYSIOLOGICAL RESULTS OF METHODS

Method 1:

Heart Rate (at the end of task):	Borg score (6-20):
Heart Rate Increase ($HR_{task} - HR_{rest}$):	Brouha Guideline:
HR Increase(%) [(HR_{inc}/HR_{rest})x100]:	HR (between 30-60 sec):
$\%HR_{max}$ [(HR_{task}/HR_{max})x100]:	HR (between 150-180 sec):

Method 2:

Heart Rate (at the end of task):	Borg score (6-20):
Heart Rate Increase ($HR_{task} - HR_{rest}$):	Brouha Guideline:
HR Increase(%) [(HR_{inc}/HR_{rest})x100]:	HR (between 30-60 sec):
$\%HR_{max}$ [(HR_{task}/HR_{max})x100]:	HR (between 150-180 sec):

Method 3:

Heart Rate (at the end of task):	Borg score (6-20):
Heart Rate Increase ($HR_{task} - HR_{rest}$):	Brouha Guideline:
HR Increase(%) [(HR_{inc}/HR_{rest})x100]:	HR (between 30-60 sec):
$\%HR_{max}$ [(HR_{task}/HR_{max})x100]:	HR (between 150-180 sec):

Figure B.3. Physiological results form for participants.

KATILIMCI BİLGİSİ

Tarih:	Boy:	Kilo:
Yaş:		Dinlenme Nabız:
Cinsiyet:		Maksimum Nabız:

METOTLARIN FİZYOLOJİK SONUÇLARI

Metot 1:

Kalp Hızı (Görev sonunda):	Borg skoru (6-20):
Kalp Hızı Artışı ($KH_{görev} - KH_{dinlenme}$):	Brouha Kriterleri:
KH Artış(%) [$(KH_{artış}/KH_{dinlenme})$x100]:	KH (30-60 saniye arası):
%KH_{maks} [$(KH_{görev}/KH_{maks})$x100]:	KH (150-180 saniye arası):

Method 2:

Kalp Hızı (Görev sonunda):	Borg skoru (6-20):
Kalp Hızı Artışı ($KH_{görev} - KH_{dinlenme}$):	Brouha Kriterleri:
KH Artış(%) [$(KH_{artış}/KH_{dinlenme})$x100]:	KH (30-60 saniye arası):
%KH_{maks} [$(KH_{görev}/KH_{maks})$x100]:	KH (150-180 saniye arası):

Method 3:

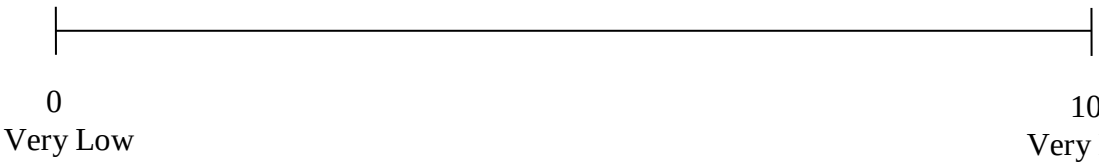
Kalp Hızı (Görev sonunda):	Borg skoru (6-20):
Kalp Hızı Artışı ($KH_{görev} - KH_{dinlenme}$):	Brouha Kriterleri:
KH Artış(%) [$(KH_{artış}/KH_{dinlenme})$x100]:	KH (30-60 saniye arası):
%KH_{maks} [$(KH_{görev}/KH_{maks})$x100]:	KH (150-180 saniye arası):

Figure B.4. Physiological results form for participants in Turkish .

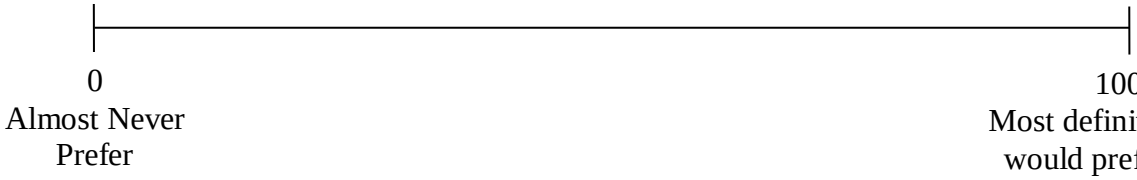
B.3. Participant Psychophysical Results Form

PSYCHOPHYSICAL QUESTIONS OF VAS

- Rate the effort you spend during task on 0-100 scale below:



- Assume that, you will be doing this upstairs load carrying task many times during an eight-hour workday. What would be your preference level for this method on a 0-100 scale, 100 means most definitely would prefer?



- Think about an 8-hour workday which you have to carry weights heavier than 20 kg. What would be your preference rate over a scale of 0-100, 100 means most definitely would prefer?

- Make an assessment about the ease of use for the method while conducting the task on a 0-100 scale, 100 being very easy.

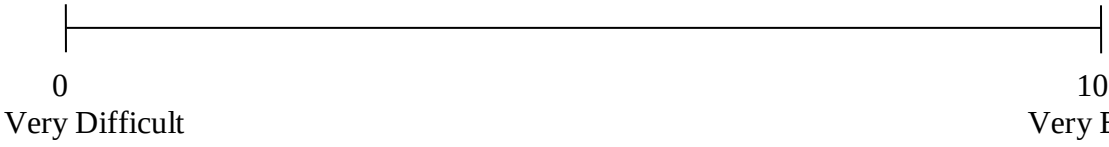
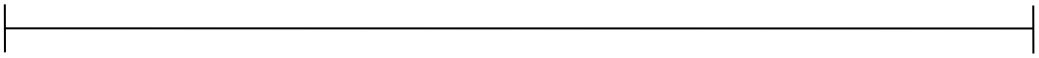


Figure B.5. Psychophysical results form for participants.

VAS İLE İLGİLİ PSİKOFİZİKSEL SORULAR

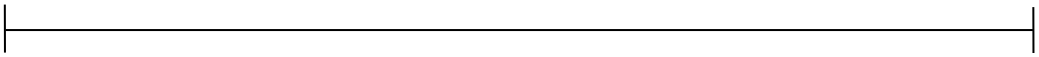
- Görev esnasında harcadığınız eforu aşağıdaki 0-100 ölçeğinde belirtiniz:



0 — Çok Düşük

100 — Very High

- Bu işi günde 8 saat, defalarca yukarıya yük taşıyarak yaptığınızı düşünün. Bu yöntemleri ne ölçüde tercih ederdiniz, aşağıdaki 0-100 skalası üzerinde gösteriniz, 100 kesinlikle tercih ederim demektir.



0 — Neredeyse hiç tercih etmezdim

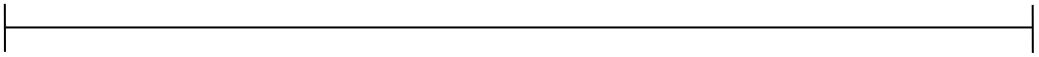
100 — Kesinlikle tercih ederdim

- 20 kg'dan daha ağır yükleri taşıdığınız bir durumu düşünün. Bu yöntemleri ne ölçüde tercih ederdiniz, aşağıdaki 0-100 skalası üzerinde gösteriniz, 100 kesinlikle tercih ederim demektir:

0 — Neredeyse hiç tercih etmezdim

100 — Kesinlikle tercih ederdim

- 3 metodu da kullanım rahatlığı açısından, 0-100 skalası üzerinde değerlendiriniz, 100 çok kolay demektir:



0 — Çok zor

100 — Çok kolay

Figure B.6. Psychophysical results form for participants in Turkish.

B.4. Borg Scale

BORG'S RATINGS OF PERCEIVED EXHAUSTION SCALE

Rating	Verbal Anchor
6	No exertion at all
7	
8	Extremely light
9	
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure B.7. Borg scale (Borg and Linderholm,1967).

BORG ALGILANAN ZORLUK DERECESİ SKALASI

Skor	Sözel İfadesi
6	Hiç zorlanma yok
7	
8	Çok hafif iş
9	
10	
11	Hafif iş
12	
13	Biraz zor
14	
15	Ağır iş
16	
17	Çok ağır iş
18	
19	Oldukça ağır iş
20	Maksimum zorlanma

Figure B.8. Borg scale in Turkish (Borg and Linderholm,1967).

APPENDIX C: STATISTICAL RESULTS REGARDING THE SURVEY

Figure C.1 is the final regression table of the survey data regression analysis which shows significant information about that.

Regression Analysis: Fatigue versus Age; # of Bottles

Stepwise Selection of Terms

α to enter = 0,15; α to remove = 0,15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	73,39	36,694	10,75	0,000
Age	1	52,63	52,627	15,41	0,000
Nb.Bottles	1	13,89	13,887	4,07	0,047
Error	92	314,13	3,414		
Lack-of-Fit	75	261,19	3,483	1,12	0,417
Pure Error	17	52,94	3,114		
Total	94	387,52			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1,84783	18,94%	17,18%	13,69%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3,397	0,688	4,94	0,000	
Age	0,0649	0,0165	3,93	0,000	1,01
Nb.Bottles	0,01545	0,00766	2,02	0,047	1,01

Regression Equation

Fatigue = 3,397 + 0,0649 Age + 0,01545 Nb.Bottles

Durbin-Watson Statistic

Durbin-Watson Statistic = 1,67488

Figure C.1. Regression analysis of exhaustion variable in survey.

APPENDIX D: RAPID ENTIRE BODY ASSESSMENT EVALUATION WORKSHEET

Rapid Entire Body Assessment evaluation chart is a pre-determined chart used to evaluate tasks according to REBA analysis. There are various questions regarding some body positions adopted during the task stage, these positions has their own risk scores for each. They are determined and then cumulative risk scores are calculated from the risk score tables. REBA worksheet can be seen on Figure D.1 at the next page.

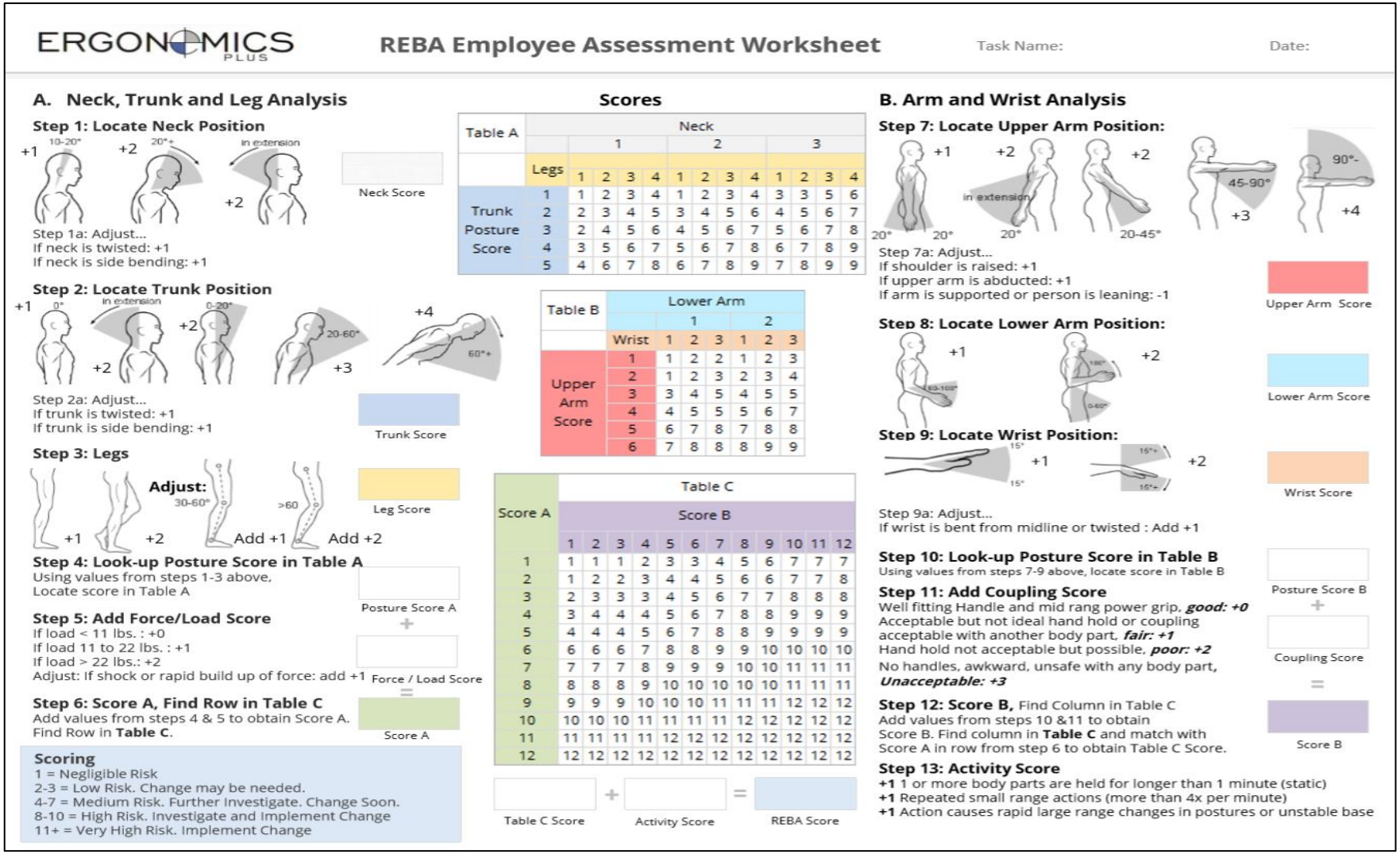


Figure D.1. Rapid Entire Body Assessment (REBA) evaluation worksheet (Ergonomics Plus, 2015).

APPENDIX E: INPUT DATA AND ANGLE REFERANCES ABOUT BIOMECHANICAL ANALYSIS

Table E.1 shows the hand loads according to three methods. These values are used as inputs for both pilot study and 3DSSPP evaluation. For method 1, force per hand = [19 kgx(10 kg/m/sec^2)]/2 = 95 N per hand. Hand forces for other methods are based on dynamometer pull force measurement. Tables E.2-3 show the angle and anthropometric input variables for pilot biomechanical study. Figure E.1 shows the reference angles of 3DSSPP software. Figure E.2 is input variables that are used for regression equations about 3DSSPP evaluation. Figure E.3 is graph of Anderson-Darling normality tests about regression equations and Figure E.4 shows residual plots of these regressions. Figures E.5-12 show the final regression analysis results of biomechanical regressions.

Table E.1. Hand load per hand and angles.

	Method 1	**Method 2**	**Method3**
Force per Hand	95 N	160 N	90 N
Angle with Hor. Line (y)	(-90) ^{0}	(-50) ^{0}	(-38) ^{0}
(y) Component of Force	0	102.8 N	70.9 N
(z) Component of Force	(-95) N	(-122.6) N	(-55.4) N

Table E.2. All angles used for 3DSSPP calculations of pilot study.

		Left Hand		Right Hand		LowB to Shoulder	Torso Angle	Knee Angle
		Hor.	Vert.	Hor.	Vert.			
S1-M1	**Forearm**	90^0	$(-70)^0$	150^0	$(-60)^0$	10^0	72^0	135^0
	Upper	$(-90)^0$	$(-80)^0$	$(-40)^0$	$(-45)^0$			
S1-M2	**Forearm**	102^0	$(-68)^0$	102^0	$(-68)^0$	72^0	16^0	155^0
	Upper	70^0	$(-76)^0$	70^0	$(-76)^0$			
S1-M3	**Forearm**	104^0	$(-40)^0$	104^0	$(-40)^0$	77^0	12^0	160^0
	Upper	69^0	$(-75)^0$	69^0	$(-75)^0$			
S2-M1	**Forearm**	90^0	$(-70)^0$	150^0	$(-60)^0$	0^0	82^0	155^0
	Upper	$(-90)^0$	$(-80)^0$	$(-40)^0$	$(-45)^0$			
S2-M2	**Forearm**	104^0	$(-60)^0$	104^0	$(-60)^0$	69^0	19^0	160^0
	Upper	69^0	$(-82)^0$	69^0	$(-82)^0$			
S2-M3	**Forearm**	104^0	$(-52)^0$	104^0	$(-52)^0$	68^0	20^0	160^0
	Upper	69^0	$(-75)^0$	69^0	$(-75)^0$			
S3-M1	**Forearm**	90^0	$(-70)^0$	120^0	$(-60)^0$	7^0	76^0	155^0
	Upper	$(-70)^0$	$(-70)^0$	$(-40)^0$	$(-40)^0$			
S3-M2	**Forearm**	104^0	$(-70)^0$	104^0	$(-70)^0$	68^0	20^0	164^0
	Upper	69^0	$(-85)^0$	69^0	$(-85)^0$			
S3-M3	**Forearm**	104^0	$(-50)^0$	104^0	$(-50)^0$	80^0	10^0	163^0
	Upper	69^0	$(-85)^0$	69^0	$(-85)^0$			
S2-Squat	**Forearm**	90^0	$(-70)^0$	170^0	$(-40)^0$	42^0	40^0	84^0
	Upper	$(-90)^0$	$(-80)^0$	$(-10)^0$	$(-50)^0$			
S2-Stand	**Forearm**	90^0	60^0	110^0	10^0			
	Upper	70^0	$(-40)^0$	0^0	$(-50)^0$			

Table E.3. Weight (kg) and length (cm) data of three participants used for pilot study, source: 3DSSPP Software Database.

		Low Back to Shoulder + Head	Upper Arm	Forearm and Hand
Sample 1	**Weight (kg)**	31.5	2.17	1.78
	Total Length (cm)	39.2	31.7	34
	CoM to Prox (cm)	34.8	16.7	19
Sample 2	**Weight (kg)**	32.77	2.25	1.85
	Total Length (cm)	40.6	32.8	35.2
	CoM to Prox (cm)	36.1	17.3	19.3
Sample 3	**Weight (kg)**	43.82	3	2.47
	Total Length (cm)	43.3	35.1	37.6
	CoM to Prox (cm)	38.6	18.5	21
CoM to Prox: Distance of mass center to proximal end; moment point				

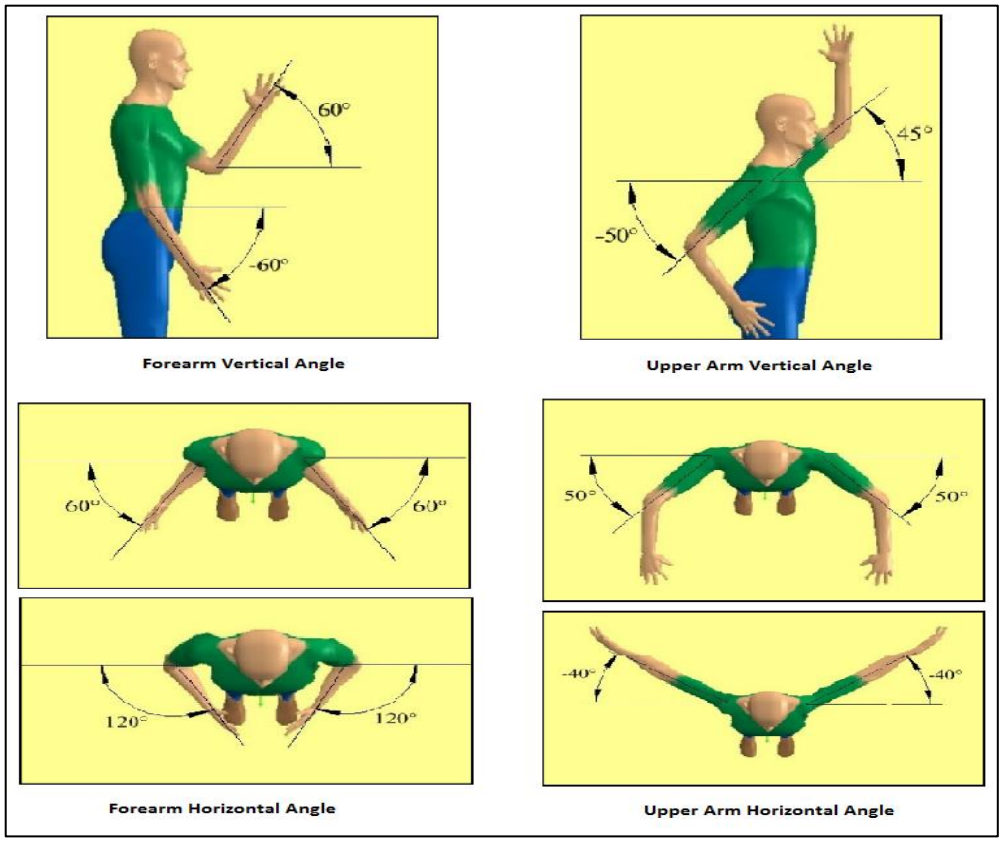


Figure E.1. Angles and their meanings that are used for 3DSSPP calculations.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Stoop Lift	Elbow Angle (deg)	50	25	-8	-21	55	10	58	35	45	38	72	51	55	58	36	30	50	45	30	36	35	72	50	68	17	56	43	47	55	64
	Shoulder Angle (deg)	-28	-15	-9	-10	-29	-25	-30	-50	-50	-24	-23	-13	-19	-34	7	-30	-17	-5	-45	-28	-33	-20	-15	3	5	-24	-13	-35	-40	-6
	Trunk Angle (deg)	70	75	69	104	67	66	81	75	82	98	86	76	77	82	90	92	81	73	92	95	90	91	95	80	72	75	85	92	75	85
	Hip Angle (deg)	54	38	82	22	50	62	40	57	41	21	27	35	35	34	41	50	43	49	51	28	26	30	34	21	65	34	46	25	44	33
	Knee Angle (deg)	75	77	60	95	75	71	93	68	81	93	90	88	81	86	85	75	86	83	78	84	90	78	82	91	74	93	82	75	78	94
	Height (cm)	174	175	178	175	177	176	177	175	170	176	183	180	178	177	181	189	180	180	175	178	178	176	178	187	169	175	183	187	185	180
	Weight (kg)	71	104	73	72	62	98	85	71	65	83	82	76	62	70	96	76	85	67	75	67	82	79	81	79	64	69	87	82	72	69
	Compression Force (N)	3948	5413	5246	3669	3783	5416	4383	4000	3448	3874	4207	4417	3740	3841	5599	4607	4671	4219	4036	3619	4229	3967	4431	4279	4452	3758	4959	4244	4202	4054
	Shear Force (N)	497	678	465	548	449	594	608	505	507	613	604	552	481	535	677	574	605	493	570	533	608	592	601	580	463	517	621	608	522	536
	Shoulder Moment (N.m.)	4,4	22,7	32,4	26,9	9,3	19,0	1,8	3,8	6,5	12,3	5,1	14,4	8,3	4,1	35,6	12,9	12,1	22,7	6,3	11,5	7,9	3,2	13,2	16,5	36,6	4,3	18,4	3,4	8,3	12,1
	Left Hand Distance (cm)	41,8	50,2	73,5	55,8	49,9	52,2	42,6	44,9	40,8	46,6	46,9	51,8	46,9	45,8	55,4	53,6	46,3	40,8	47,0	44,6	42,0	41,2	45,2	45,5	53,5	43,6	47,1	44,5	47,2	44,6
	Right Hand Distance (cm)	45,6	64,6	73,5	65,3	45,3	60,3	44,7	45,9	37,8	55,0	42,3	57,5	51,8	43,3	75,3	60,2	52,3	64,1	48,0	50,0	52,9	42,1	56,6	60,1	73,8	47,2	62,6	50,3	46,3	54,4
	Total Hand Distance (cm)	87,4	114,8	147,0	121,1	95,2	112,5	87,3	90,8	78,6	101,6	89,2	109,3	98,7	89,1	130,7	113,8	98,6	104,9	95,0	94,6	94,9	83,3	101,8	105,6	127,3	90,8	109,7	94,8	93,5	99,0

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Squat Lift	Elbow Angle (deg)	22	25	25	-26	30	25	28	25	10	14	10	22	16	41	25	20	40	10	5	9	-2	50	45	57	18	54	44	32	20	26
	Shoulder Angle (deg)	-25	-10	-10	18	-22	-25	-13	-10	-20	6	-20	-11	2	-39	22	5	-33	-15	-15	5	-6	-5	-9	11	32	-15	25	-6	-15	11
	Trunk Angle (deg)	43	53	60	58	41	44	53	34	53	36	42	42	24	46	52	43	62	36	48	16	66	59	71	47	48	62	35	54	45	50
	Hip Angle (deg)	74	69	61	88	82	79	70	80	73	83	85	83	87	65	87	81	63	86	86	80	80	70	47	70	99	54	70	61	81	67
	Knee Angle (deg)	50	50	62	54	45	60	57	48	59	42	63	55	47	58	65	60	74	62	53	37	69	55	73	67	56	72	54	37	33	57
	Height (cm)	174	175	178	175	177	176	177	175	170	176	183	180	178	177	181	189	180	180	175	178	178	176	178	187	169	175	183	187	185	180
	Weight (kg)	71	104	73	72	62	98	85	71	65	83	82	76	62	70	96	76	85	67	75	67	82	79	81	79	64	69	87	82	72	69
	Compression Force (N)	3621	5259	4408	4827	3455	4603	4689	3404	3877	4166	4343	4326	2984	3595	5833	4628	4620	3539	4400	3779	5040	4674	4699	4626	4695	3988	4328	4752	4402	4336
	Shear Force (N)	368	528	457	406	316	471	465	335	388	383	405	377	279	393	490	389	524	337	384	303	504	461	549	434	333	461	410	443	342	398
	Shoulder Moment (N.m.)	17,1	26,3	26,4	34,8	17,1	15,5	23,5	26,0	21,4	35,8	23,0	26,8	36,2	12,0	49,5	39,0	6,4	26,2	25,8	38,9	32,9	20,1	19,8	25,9	50,7	11,0	44,2	28,6	25,2	36,2
	Left Hand Distance (cm)	36,20	42,90	43,70	58,30	39,70	43,30	49,40	38,50	44,10	42,80	45,90	50,20	34,90	47,50	55,00	52,00	44,60	37,90	51,30	49,00	48,70	51,50	45,90	55,00	64,90	46,60	43,60	46,30	54,10	48,20
	Right Hand Distance (cm)	48,70	58,20	62,10	69,30	49,00	46,70	54,00	45,90	55,70	58,30	53,90	59,30	54,00	37,90	81,50	66,40	50,20	53,30	58,20	62,70	69,30	56,70	61,50	56,60	80,80	48,90	68,00	60,60	57,60	66,60
	Total Hand Distance (cm)	84,90	101,10	105,80	127,60	88,70	90,00	103,40	84,40	99,80	101,10	99,80	109,50	88,90	85,40	136,50	118,40	94,80	91,20	109,50	111,70	118,00	108,20	107,40	111,60	145,70	95,50	111,60	106,90	111,70	114,80

Figugre E.2. Biomechanical Regression Equations Variable Values

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Stair Climber	Elbow Angle (deg)	49	57	61	60	62	72	67	48	47	62	59	55	58	54	58	67	60	54	52	58	67	63	56	59	54	45	57	62	61	60
	Shoulder Angle (deg)	21	22	24	8	-2	3	5	9	15	17	4	21	14	9	13	-3	9	15	6	23	-13	5	1	-6	6	10	20	15	2	-10
	Trunk Angle (deg)	4	15	9	18	28	20	30	15	15	32	23	20	11	8	24	42	36	16	26	33	20	46	23	23	26	30	22	17	19	52
	Hip Angle (deg)	25	30	18	26	35	43	36	28	42	33	45	32	23	30	24	48	19	41	45	57	24	30	20	26	24	27	34	20	14	35
	Knee Angle (deg)	104	77	97	94	55	85	93	96	67	98	84	87	105	87	96	94	96	99	53	95	95	104	96	97	92	102	68	97	97	94
	Height (cm)	174	175	178	175	177	176	177	175	170	176	183	180	178	177	181	189	180	180	175	178	178	176	178	187	169	175	183	187	185	180
	Weight (kg)	71	104	73	72	62	98	85	71	65	83	82	76	62	70	96	76	85	67	75	67	82	79	81	79	64	69	87	82	72	69
	Compression Force (N)	1452	2324	1566	1669	1783	1787	2256	1839	1975	2670	2171	2324	1389	1277	2502	2590	2635	1907	2437	2952	1290	2703	1989	1820	1955	2545	2579	1927	1598	2452
	Shear Force (N)	547	667	558	566	532	653	631	558	529	629	602	581	523	547	661	618	647	545	567	565	604	645	605	598	549	574	616	599	567	611
	Shoulder Moment (N.m.)	13,2	18,1	22,6	36,3	47,5	51,9	45,8	24,1	17,2	29,5	40,5	19,4	29,8	30,1	29,6	56,4	35,9	25,0	30,5	20,9	60,3	41,9	39,3	49,9	31,5	20,5	22,2	33,4	45,1	51,8

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Track Type	Elbow Angle (deg)	38	30	40	41	41	35	39	43	49	46	49	38	43	48	37	46	29	39	35	34	42	40	55	41	34	19	54	42	54	41
	Shoulder Angle (deg)	10	15	43	30	23	5	13	-2	21	21	12	30	15	28	13	22	19	18	39	33	-8	11	1	15	15	16	20	14	17	18
	Trunk Angle (deg)	23	8	11	2	20	10	22	29	38	16	22	6	14	6	22	9	23	17	16	30	25	28	33	20	10	21	27	7	24	34
	Hip Angle (deg)	35	17	18	20	38	27	31	27	44	32	39	20	24	29	24	24	23	30	40	29	28	25	21	24	19	22	38	13	28	38
	Knee Angle (deg)	90	78	105	100	47	90	97	99	96	98	84	93	102	90	95	100	101	100	67	104	101	98	101	92	97	102	57	97	90	101
	Height (cm)	174	175	178	175	177	176	177	175	170	176	183	180	178	177	181	189	180	180	175	178	178	176	178	187	169	175	183	187	185	180
	Weight (kg)	71	104	73	72	62	98	85	71	65	83	82	76	62	70	96	76	85	67	75	67	82	79	81	79	64	69	87	82	72	69
	Compression Force (N)	1762	1608	1757	1055	1728	1452	1976	1713	2095	1681	1844	1374	1270	1110	2178	1314	2242	1590	2071	2319	1733	2032	1875	1851	1222	1979	2238	1187	1722	2221
	Shear Force (N)	429	525	423	414	382	507	478	439	427	463	464	430	390	411	518	433	481	410	428	426	473	467	483	455	393	421	479	450	435	438
	Shoulder Moment (N.m.)	17,3	8,5	3,0	7,6	12,6	17,5	15,7	26,0	17,3	14,9	22,9	5,7	18,2	13,0	14,3	15,9	6,9	14,1	2,4	2,5	27,9	17,6	31,5	16,9	12,4	5,3	20,7	18,0	23,6	15,2

Figure E.2. Biomechanical Regression Equations Variable Values (cont.)

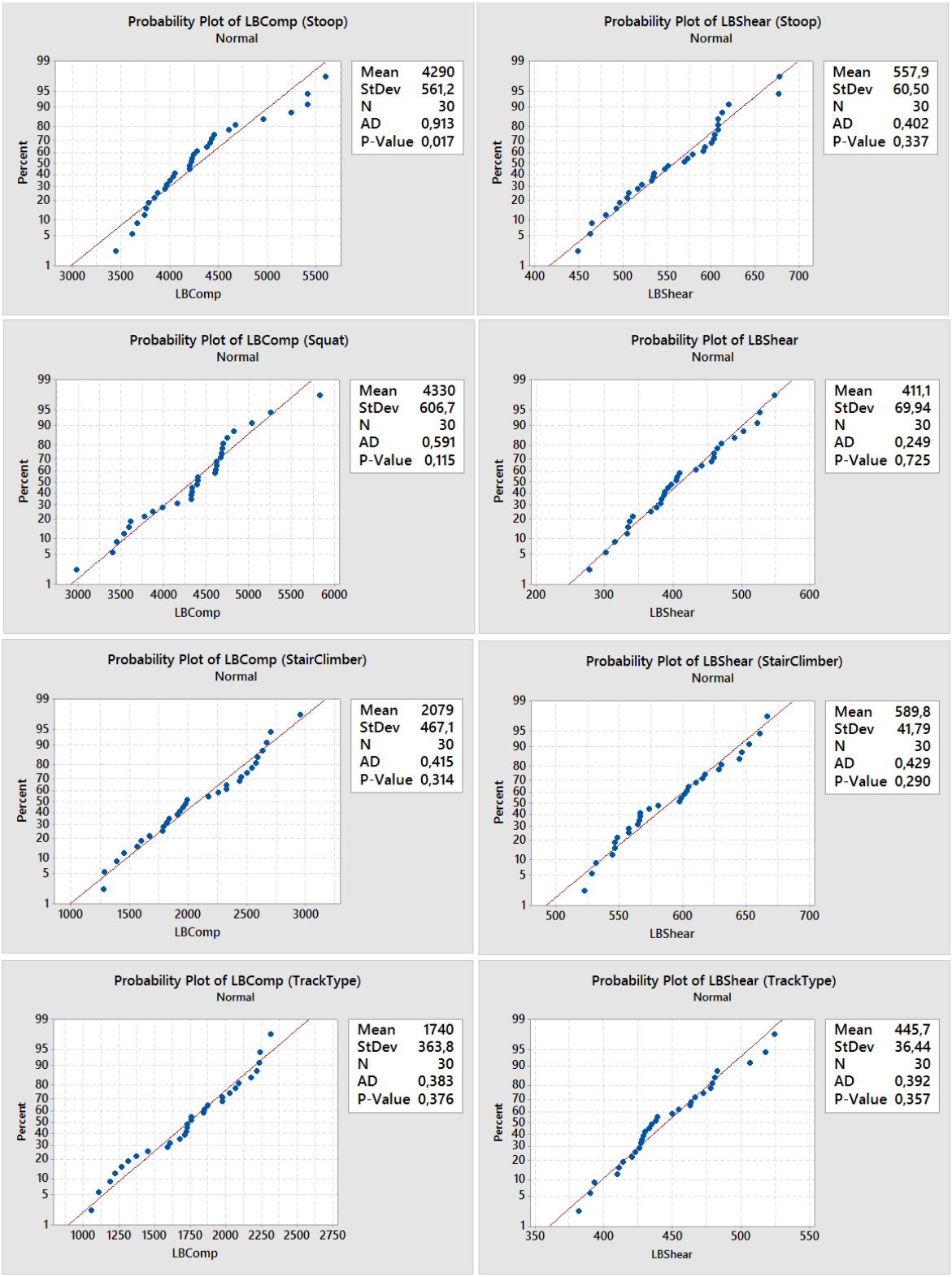


Figure E.3. Anderson-Darling test results for low back compression and shear variables.

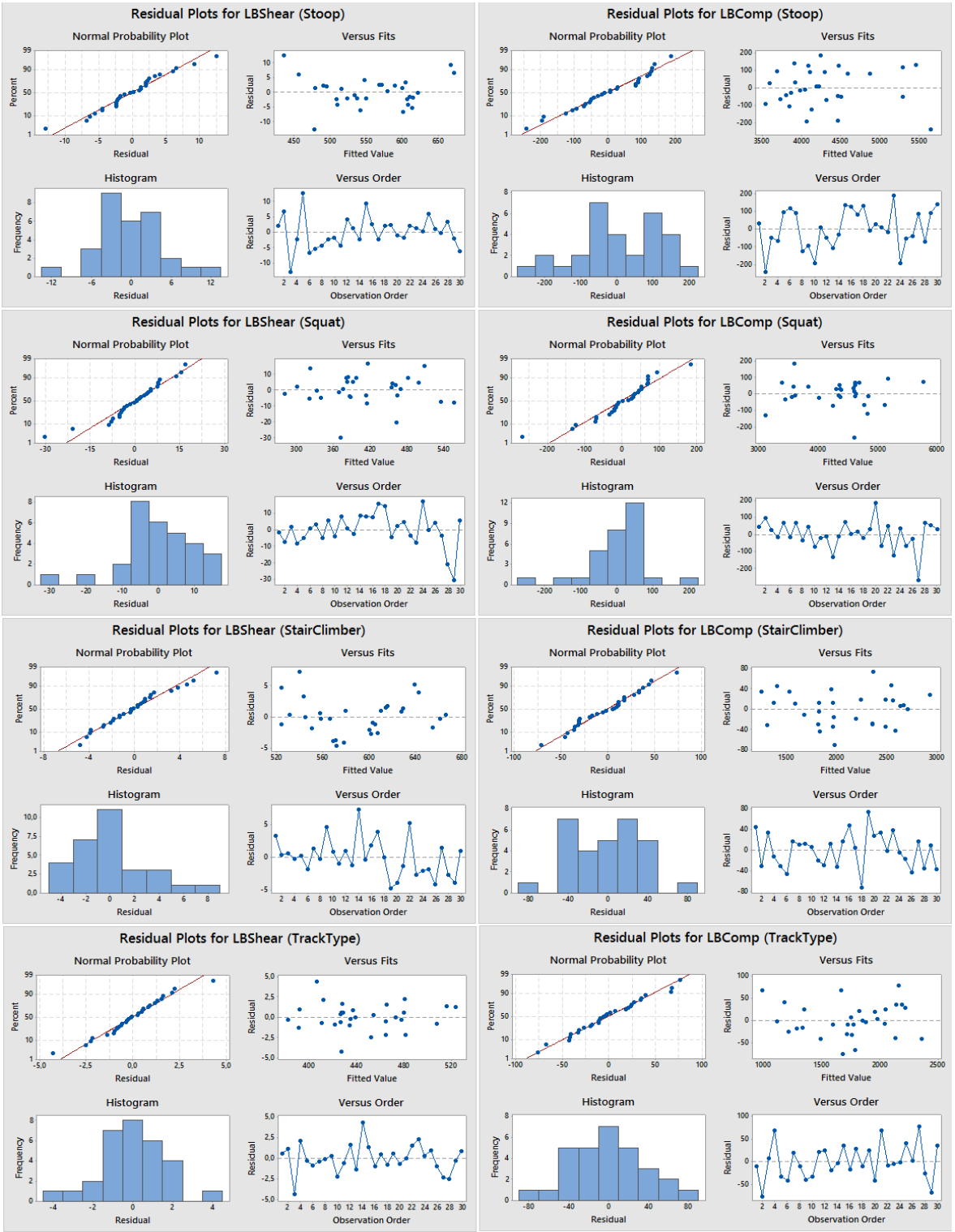


Figure E.4. Residual plots for all biomechanical regression equations.

Regression Analysis: LBComp versus TrunkAng; KneeAng; HandsDist; Height; Weight

Stepwise Selection of Terms

α to enter = 0,15; α to remove = 0,2
The stepwise procedure added terms during the procedure in order to maintain a hierarchical model at each step.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	5	8784116	96,17%	8784116	1756823	120,56	0,000
TrunkAng	1	523752	5,73%	281869	281869	19,34	0,000
KneeAng	1	587493	6,43%	153800	153800	10,55	0,003
HandsDist	1	3419660	37,44%	1890284	1890284	129,72	0,000
Weight	1	3927769	43,00%	3390408	3390408	232,67	0,000
TrunkAng*TrunkAng	1	325442	3,56%	325442	325442	22,33	0,000
Error	24	349729	3,83%	349729	14572		
Total	29	9133845	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
120,715	96,17%	95,37%	617968	93,23%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-6562	1741	(-10156; -2969)	-3,77	0,001	
TrunkAng	182,0	41,4	(96,6; 267,4)	4,40	0,000	335,51
KneeAng	-10,27	3,16	(-16,79; -3,74)	-3,25	0,003	1,44
HandsDist	19,72	1,73	(16,15; 23,29)	11,39	0,000	1,37
Weight	34,83	2,28	(30,12; 39,54)	15,25	0,000	1,14
TrunkAng*TrunkAng	-1,160	0,246	(-1,667; -0,654)	-4,73	0,000	330,05

Regression Equation

LBComp(Stoop) = -6562 + 182,0 TrunkAng - 10,27 KneeAng + 19,72 HandsDist + 34,83 Weight
- 1,160 TrunkAng*TrunkAng

Durbin-Watson Statistic = 1,65000

Figure E.5. Details of stoop lifting low back compression regression.

Regression Analysis: LBShear versus TrunkAng; KneeAng; HandsDist; Height; Weight

Stepwise Selection of Terms

α to enter = 0,15; α to remove = 0,2

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	6	105416	99,30%	105416	17569,4	546,67	0,000
TrunkAng	1	25459	23,98%	2089	2089,1	65,00	0,000
KneeAng	1	1301	1,23%	620	619,6	19,28	0,000
HandsDist	1	1571	1,48%	265	264,8	8,24	0,009
Height	1	5117	4,82%	74	73,6	2,29	0,144
Weight	1	70296	66,22%	66224	66224,4	2060,57	0,000
TrunkAng*TrunkAng	1	1673	1,58%	1673	1673,1	52,06	0,000
Error	23	739	0,70%	739	32,1		
Total	29	106155	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
5,66912	99,30%	99,12%	1898,57	98,21%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-686,1	82,5	(-856,8; -515,3)	-8,31	0,000	
TrunkAng	16,76	2,08	(12,46; 21,06)	8,06	0,000	383,96
KneeAng	0,652	0,148	(0,345; 0,959)	4,39	0,000	1,44
HandsDist	-0,2379	0,0829	(-0,4093; -0,0665)	-2,87	0,009	1,42
Height	0,382	0,252	(-0,140; 0,904)	1,51	0,144	1,24
Weight	4,901	0,108	(4,677; 5,124)	45,39	0,000	1,15
TrunkAng*TrunkAng	-0,0887	0,0123	(-0,1142; -0,0633)	-7,22	0,000	375,41

Regression Equation

LBShear (Stoop) = -686,1 + 16,76 TrunkAng + 0,652 KneeAng - 0,2379 HandsDist + 0,382 Height
+ 4,901 Weight - 0,0887 TrunkAng*TrunkAng

Durbin-Watson Statistic = 2,15989

Figure E.6. Details of stoop lifting low back compression regression.

Regression Analysis: LBComp versus TrunkAng; HipAng; HandDist; Height; Weight

Stepwise Selection of Terms

α to enter = 0,15; α to remove = 0,2

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	5	10476198	98,13%	10476198	2095240	252,49	0,000
TrunkAng	1	3753326	35,16%	610378	610378	73,55	0,000
HipAng	1	867615	8,13%	22137	22137	2,67	0,115
HandDist	1	2540696	23,80%	1713822	1713822	206,52	0,000
Height	1	432180	4,05%	51824	51824	6,25	0,020
Weight	1	2882381	27,00%	2882381	2882381	347,34	0,000
Error	24	199163	1,87%	199163	8298		
Total	29	10675361	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
91,0959	98,13%	97,75%	440557	95,87%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-3339	775	(-4938; -1739)	-4,31	0,000	
TrunkAng	17,89	2,09	(13,58; 22,19)	8,58	0,000	2,19
HipAng	3,61	2,21	(-0,95; 8,17)	1,63	0,115	2,22
HandDist	21,16	1,47	(18,12; 24,20)	14,37	0,000	1,64
Height	10,18	4,07	(1,77; 18,59)	2,50	0,020	1,25
Weight	32,55	1,75	(28,95; 36,16)	18,64	0,000	1,17

Regression Equation

LBComp (Squat)= -3339 + 17,89 TrunkAng + 3,61 HipAng + 21,16 HandDist + 10,18 Height + 32,55 Weight

Durbin-Watson Statistic = 2,28582

Figure E.7. Details of stoop lifting low back shear regression.

Regression Analysis: LBShear versus ElbowAng; TrunkAng; HipAng; KneeAng; Weight

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	5	38423,8	99,79%	38423,8	7684,8	2303,15	0,000
ElbowAng	1	21,1	0,05%	12,2	12,2	3,65	0,068
TrunkAng	1	1042,1	2,71%	2027,0	2027,0	607,51	0,000
HipAng	1	2452,4	6,37%	7,4	7,4	2,23	0,149
KneeAng	1	1395,1	3,62%	229,3	229,3	68,73	0,000
Weight	1	33513,0	87,04%	33513,0	33513,0	10043,96	0,000
Error	24	80,1	0,21%	80,1	3,3		
Total	29	38503,9	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
1,82665	99,79%	99,75%	131,008	99,66%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	131,11	5,70	(119,35; 142,86)	23,02	0,000	
ElbowAng	0,0888	0,0465	(-0,0071; 0,1847)	1,91	0,068	1,12
TrunkAng	1,1657	0,0473	(1,0681; 1,2633)	24,65	0,000	1,70
HipAng	-0,1019	0,0683	(-0,2429; 0,0391)	-1,49	0,149	2,43
KneeAng	0,2625	0,0317	(0,1972; 0,3279)	8,29	0,000	1,62
Weight	3,4805	0,0347	(3,4088; 3,5521)	100,22	0,000	1,15

Regression Equation

LBShear (Track Type) = 131,11 + 0,0888 ElbowAng + 1,1657 TrunkAng - 0,1019 HipAng + 0,2625 KneeAng
+ 3,4805 Weight

Durbin-Watson Statistic = 2,17598

Figure E.8. Details of squat lifting low back compression regression.

Regression Analysis: LBComp versus ElbowAng; ShouldAng; TrunkAng; HipAng; Height; Weight

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	7	6294555	99,50%	6294555	899222	621,47	0,000
ElbowAng	1	389	0,01%	339818	339818	234,85	0,000
ShouldAng	1	227521	3,60%	1033942	1033942	714,57	0,000
TrunkAng	1	5197597	82,16%	967022	967022	668,32	0,000
HipAng	1	99582	1,57%	116662	116662	80,63	0,000
Height	1	86990	1,38%	57574	57574	39,79	0,000
Weight	1	511405	8,08%	340963	340963	235,65	0,000
TrunkAng*TrunkAng	1	171071	2,70%	171071	171071	118,23	0,000
Error	22	31833	0,50%	31833	1447		
Total	29	6326387	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
38,0386	99,50%	99,34%	69008,2	98,91%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-1135	285	(-1725; -544)	-3,99	0,001	
ElbowAng	-23,24	1,52	(-26,38; -20,09)	-15,32	0,000	1,77
ShouldAng	24,029	0,899	(22,165; 25,894)	26,73	0,000	1,55
TrunkAng	68,84	2,66	(63,31; 74,36)	25,85	0,000	17,10
HipAng	6,861	0,764	(5,276; 8,446)	8,98	0,000	1,19
Height	10,66	1,69	(7,15; 14,16)	6,31	0,000	1,23
Weight	12,432	0,810	(10,752; 14,111)	15,35	0,000	1,44
TrunkAng*TrunkAng	-0,4951	0,0455	(-0,5895; -0,4006)	-10,87	0,000	15,94

Regression Equation

LBComp (StairClimber) = -1135 - 23,24 ElbowAng + 24,029 ShouldAng + 68,84 TrunkAng + 6,861 HipAng
+ 10,66 Height + 12,432 Weight - 0,4951 TrunkAng*TrunkAng

Durbin-Watson Statistic = 2,23676

Figure E.9. Details of squat lifting low back shear regression.

Regression Analysis: LBShear versus TrunkAng; HipAng; KneeAng; Weight

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	50407,1	99,53%	50407,1	12601,8	1314,24	0,000
TrunkAng	1	10662,4	21,05%	8083,1	8083,1	842,99	0,000
HipAng	1	1122,8	2,22%	49,3	49,3	5,14	0,032
KneeAng	1	54,6	0,11%	568,8	568,8	59,32	0,000
Weight	1	38567,2	76,15%	38567,2	38567,2	4022,18	0,000
Error	25	239,7	0,47%	239,7	9,6		
Total	29	50646,8	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
3,09655	99,53%	99,45%	368,331	99,27%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	253,34	7,17	(238,58; 268,10)	35,35	0,000	
TrunkAng	1,6360	0,0563	(1,5200; 1,7521)	29,03	0,000	1,16
HipAng	-0,1526	0,0673	(-0,2913; -0,0140)	-2,27	0,032	1,40
KneeAng	0,3713	0,0482	(0,2720; 0,4705)	7,70	0,000	1,26
Weight	3,5079	0,0553	(3,3940; 3,6219)	63,42	0,000	1,01

Regression Equation

LBShear (StairClimber) = 253,34 + 1,6360 TrunkAng - 0,1526 HipAng + 0,3713 KneeAng + 3,5079 Weight

Durbin-Watson Statistic = 1,87919

Figure E.10. Details of stair climber trolley pulling low back compression regression.

Regression Analysis: LBComp versus ElbowAng; ShoulderAng; TrunkAng; HipAng; KneeAng; ...

Stepwise Selection of Terms

α to enter = 0,15; α to remove = 0,2

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	7	3797022	98,92%	3797022	542432	288,12	0,000
ElbowAng	1	39809	1,04%	142649	142649	75,77	0,000
ShoulderAng	1	2394	0,06%	557024	557024	295,87	0,000
TrunkAng	1	3077869	80,19%	483043	483043	256,57	0,000
KneeAng	1	92791	2,42%	4321	4321	2,30	0,144
Height	1	149241	3,89%	6909	6909	3,67	0,068
Weight	1	367716	9,58%	397626	397626	211,20	0,000
TrunkAng*TrunkAng	1	67201	1,75%	67201	67201	35,69	0,000
Error	22	41419	1,08%	41419	1883		
Total	29	3838441	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
43,3899	98,92%	98,58%	96805,9	97,48%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-686	336	(-1382; 10)	-2,04	0,053	
ElbowAng	-11,72	1,35	(-14,51; -8,92)	-8,70	0,000	1,67
ShoulderAng	15,657	0,910	(13,769; 17,545)	17,20	0,000	1,55
TrunkAng	66,88	4,18	(58,22; 75,54)	16,02	0,000	23,51
KneeAng	-1,019	0,673	(-2,414; 0,376)	-1,51	0,144	1,30
Height	4,09	2,13	(-0,34; 8,51)	1,92	0,068	1,51
Weight	13,046	0,898	(11,185; 14,908)	14,53	0,000	1,36
TrunkAng*TrunkAng	-0,637	0,107	(-0,858; -0,416)	-5,97	0,000	24,24

Regression Equation

LBComp (Track) = -686 - 11,72 ElbowAng + 15,657 ShoulderAng + 66,88 TrunkAng - 1,019 KneeAng
+ 4,09 Height + 13,046 Weight - 0,637 TrunkAng*TrunkAng

Durbin-Watson Statistic = 2,38162

Figure E.11. Details of stair climber trolley pulling low back shear regression.

Regression Analysis: LBShear versus ElbowAng; TrunkAng; HipAng; KneeAng; Weight

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	5	38423,8	99,79%	38423,8	7684,8	2303,15	0,000
ElbowAng	1	21,1	0,05%	12,2	12,2	3,65	0,068
TrunkAng	1	1042,1	2,71%	2027,0	2027,0	607,51	0,000
HipAng	1	2452,4	6,37%	7,4	7,4	2,23	0,149
KneeAng	1	1395,1	3,62%	229,3	229,3	68,73	0,000
Weight	1	33513,0	87,04%	33513,0	33513,0	10043,96	0,000
Error	24	80,1	0,21%	80,1	3,3		
Total	29	38503,9	100,00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
1,82665	99,79%	99,75%	131,008	99,66%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	131,11	5,70	(119,35; 142,86)	23,02	0,000	
ElbowAng	0,0888	0,0465	(-0,0071; 0,1847)	1,91	0,068	1,12
TrunkAng	1,1657	0,0473	(1,0681; 1,2633)	24,65	0,000	1,70
HipAng	-0,1019	0,0683	(-0,2429; 0,0391)	-1,49	0,149	2,43
KneeAng	0,2625	0,0317	(0,1972; 0,3279)	8,29	0,000	1,62
Weight	3,4805	0,0347	(3,4088; 3,5521)	100,22	0,000	1,15

Regression Equation

LBShear (Track Type) = 131,11 + 0,0888 ElbowAng + 1,1657 TrunkAng - 0,1019 HipAng + 0,2625 KneeAng
+ 3,4805 Weight

Durbin-Watson Statistic = 2,17598

Figure E.12. Details of track type trolley pulling low back compression regression.

APPENDIX F: REMAINING RESULTS OF PHYSIOLOGICAL AND PSYCHOPHYSICAL COMPARISON TESTS

Figures F.1-6 are remaining statistical test analyses about physiological and psychophysical comparisons. Table F.7 shows the experimental data of physiological and psychophysical experiments. Figures F.8-9 shows the graphs of Anderson-Darling normality tests for these statistical evaluations. Figure F.10 shows the boxplots about data of these response variables. Table F.1 is about power analysis results of statistical tests.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
psycho1_factors	,972	,507	2	,776	,973	1,000	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: psycho1_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
psycho1_factors	Sphericity Assumed	2059,03	2,00	1029,52	9,57	,000	,335
	Greenhouse-Geisser	2059,03	1,95	1058,11	9,57	,000	,335
	Huynh-Feldt	2059,03	2,00	1029,52	9,57	,000	,335
	Lower-bound	2059,03	1,00	2059,03	9,57	,006	,335
Error(psycho1_factors)	Sphericity Assumed	4088,97	38,00	107,60			
	Greenhouse-Geisser	4088,97	36,97	110,59			
	Huynh-Feldt	4088,97	38,00	107,60			
	Lower-bound	4088,97	19,00	215,21			

Figure F.1. Remaining test statistics for psychophysical question one.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
psycho3_factors	,846	3,016	2	,221	,866	,946	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: psycho3_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
psycho3_factors	Sphericity Assumed	8156,10	2,00	4078,05	20,63	,000	,521
	Greenhouse-Geisser	8156,10	1,73	4707,23	20,63	,000	,521
	Huynh-Feldt	8156,10	1,89	4312,98	20,63	,000	,521
	Lower-bound	8156,10	1,00	8156,10	20,63	,000	,521
Error(psycho3_factors)	Sphericity Assumed	7512,57	38,00	197,70			
	Greenhouse-Geisser	7512,57	32,92	228,20			
	Huynh-Feldt	7512,57	35,93	209,09			
	Lower-bound	7512,57	19,00	395,40			

Figure F.2. Remaining test statistics for psychophysical question three.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
psycho4_factors	,797	4,090	2	,129	,831	,901	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: psycho4_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
psycho4_factors	Sphericity Assumed	9498,53	2,00	4749,27	14,98	,000	,441
	Greenhouse-Geisser	9498,53	1,66	5714,59	14,98	,000	,441
	Huynh-Feldt	9498,53	1,80	5271,06	14,98	,000	,441
	Lower-bound	9498,53	1,00	9498,53	14,98	,001	,441
Error(psycho4_factors)	Sphericity Assumed	12044,80	38,00	316,97			
	Greenhouse-Geisser	12044,80	31,58	381,39			
	Huynh-Feldt	12044,80	34,24	351,79			
	Lower-bound	12044,80	19,00	633,94			

Figure F.3. Remaining test statistics for psychophysical question four.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
HR_factors	,833	3,285	2	,194	,857	,934	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: HR_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
HR_factors	Sphericity Assumed	636,133	2	318,067	8,012	,001	,297
	Greenhouse-Geisser	636,133	1,714	371,123	8,012	,002	,297
	Huynh-Feldt	636,133	1,868	340,632	8,012	,002	,297
	Lower-bound	636,133	1,000	636,133	8,012	,011	,297
Error(HR_factors)	Sphericity Assumed	1508,533	38	39,698			
	Greenhouse-Geisser	1508,533	32,567	46,320			
	Huynh-Feldt	1508,533	35,483	42,515			
	Lower-bound	1508,533	19,000	79,396			

Figure F.4. Remaining test statistics for heart rate.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
HRInc_factors	,821	3,552	2	,169	,848	,922	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: HRInc_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
HRInc_factors	Sphericity Assumed	1399,633	2	699,817	7,635	,002	,287
	Greenhouse-Geisser	1399,633	1,696	825,144	7,635	,003	,287
	Huynh-Feldt	1399,633	1,845	758,630	7,635	,002	,287
	Lower-bound	1399,633	1,000	1399,633	7,635	,012	,287
Error(HRInc_factors)	Sphericity Assumed	3483,033	38	91,659			
	Greenhouse-Geisser	3483,033	32,228	108,074			
	Huynh-Feldt	3483,033	35,054	99,362			
	Lower-bound	3483,033	19,000	183,318			

Figure F.5. Remaining test statistics for heart rate increase percentage.

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
HRMax_factors	,715	6,033	2	,049	,778	,835	,500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: HRMax_factors

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
HRMax_factors	Sphericity Assumed	148,233	2	74,117	5,086	,011	,211
	Greenhouse-Geisser	148,233	1,557	95,224	5,086	,019	,211
	Huynh-Feldt	148,233	1,670	88,753	5,086	,016	,211
	Lower-bound	148,233	1,000	148,233	5,086	,036	,211
Error(HRMax_factors)	Sphericity Assumed	553,767	38	14,573			
	Greenhouse-Geisser	553,767	29,577	18,723			
	Huynh-Feldt	553,767	31,734	17,451			
	Lower-bound	553,767	19,000	29,146			

Figure F.6. Remaining test statistics for percentage of maximum heart rate.

Table F.1. Statistical tests power analysis inputs and results.

	Partial Eta Squared	**Effect Size f**	**Alfa Prob.**	**Nb. of Subjects**	**Nb. of Groups**	**Nb. of Measurements**	**Nonsphericity Correction**	**Correlation (Approximate)**	**Power of the Test**
Psycho1	0.335	0.710	0.05	20	1	3	1	0.65	1
Psycho2*	_	_	_	_	_	_	_	_	*
Psycho3	0.521	1.04	0.05	20	1	3	1	0.35	1
Psycho4	0.441	0.888	0.05	20	1	3	1	0.5	0.99
HR	0.297	0.650	0.05	20	1	3	1	0.5	1
HRInc	0.287	0.634	0.05	20	1	3	1	0.7	1
HRMax	0.211	0.517	0.05	20	1	3	0.8	0.4	0.99
Borg*	_	_	_	_	_	_	_	_	*

*: Power for Friedman's ANOVA tests was not able to be evaluated.

			Subjects																			
	Criteria	Method	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PSYCHOPHYSICAL EVAL.	Q1	M1	41	30	64	66	49	67	46	59	54	30	41	83	71	33	68	59	77	14	73	23
		M2	55	62	72	64	82	79	76	63	75	20	77	78	79	49	78	42	67	33	93	55
		M3	47	41	55	56	57	60	39	63	59	49	47	68	65	30	75	37	43	30	83	49
	Q2	M1	83	57	26	20	10	33	40	31	54	16	31	1	59	39	25	25	42	27	80	75
		M2	8	9	9	10	5	13	7	41	14	31	4	12	47	19	20	15	15	6	5	0
		M3	38	66	32	36	22	45	61	41	44	50	15	23	71	63	33	28	39	16	15	29
	Q3	M1	9	43	9	2	0	15	35	3	36	4	35	1	55	13	23	22	3	17	21	50
		M2	41	49	17	1	0	17	31	52	12	46	37	9	62	23	18	26	52	31	10	0
		M3	49	77	34	47	4	33	73	59	51	34	59	14	74	51	43	37	81	45	19	61
	Q4	M1	82	74	32	66	51	42	43	51	33	25	13	15	53	51	62	27	69	80	24	97
		M2	24	17	18	32	15	29	13	35	7	53	10	30	37	33	45	9	51	13	3	0
		M3	39	68	27	54	61	50	57	59	27	47	87	42	68	73	61	41	59	46	19	39
	Borg	M1	13	12	13	15	15	15	13	14	14	13	12	16	14	13	11	15	15	11	15	9
		M2	13	15	16	14	18	17	17	15	16	10	15	15	15	15	15	15	16	12	19	15
		M3	13	12	15	13	15	13	12	13	14	13	13	14	13	12	13	14	14	13	17	13
PHYSIOLOGIC EVALUATION	HR (bpm)	M1	165	151	150	139	164	150	147	138	158	147	153	158	163	168	150	153	152	158	150	143
		M2	153	131	130	115	160	152	144	143	150	124	153	136	159	163	148	157	149	161	155	152
		M3	146	127	137	135	160	155	136	133	152	140	148	138	151	157	151	155	148	153	148	137
	30-60 sec	M1	141	132	75	90	143	112	95	113	109	103	122	121	147	133	113	120	128	115	115	92
		M2	130	106	85	89	132	115	96	111	104	97	145	117	134	142	114	139	122	126	114	107
		M3	130	105	83	80	133	112	90	108	94	110	136	110	125	130	122	136	120	111	111	98
	150-180 sec	M1	101	82	68	74	111	75	67	68	84	72	91	98	98	89	95	98	101	80	75	76
		M2	112	81	70	75	106	90	84	91	92	72	102	95	108	110	99	116	105	86	98	87
		M3	99	75	80	75	116	94	79	80	82	76	103	91	98	106	103	110	96	80	84	62
	HR Inc %	M1	106	148	150	101	95	111	133	134	136	130	122	123	112	124	88	89	95	132	105	123
		M2	91	115	117	67	90	114	129	142	124	94	122	92	106	117	85	94	91	137	112	138
		M3	82	108	128	96	90	118	116	125	127	119	114	94	96	109	89	91	90	125	103	114
	HRMax%	M1	85	77	76	71	85	77	75	71	81	75	79	81	84	86	77	78	78	81	77	73
		M2	78	67	66	59	82	78	74	73	77	64	79	92	82	84	76	81	77	83	79	78
		M3	75	65	70	69	82	80	70	68	78	72	76	71	77	81	77	79	76	78	76	70
	HRrest	All	80	61	60	69	84	71	63	59	67	64	69	71	77	75	80	81	78	68	73	64
	HRmax	All	195	195	197	195	194	194	195	195	196	195	194	195	195	195	195	195	194	195	196	196

Figure F.7. All physiological and psychophysical response values.

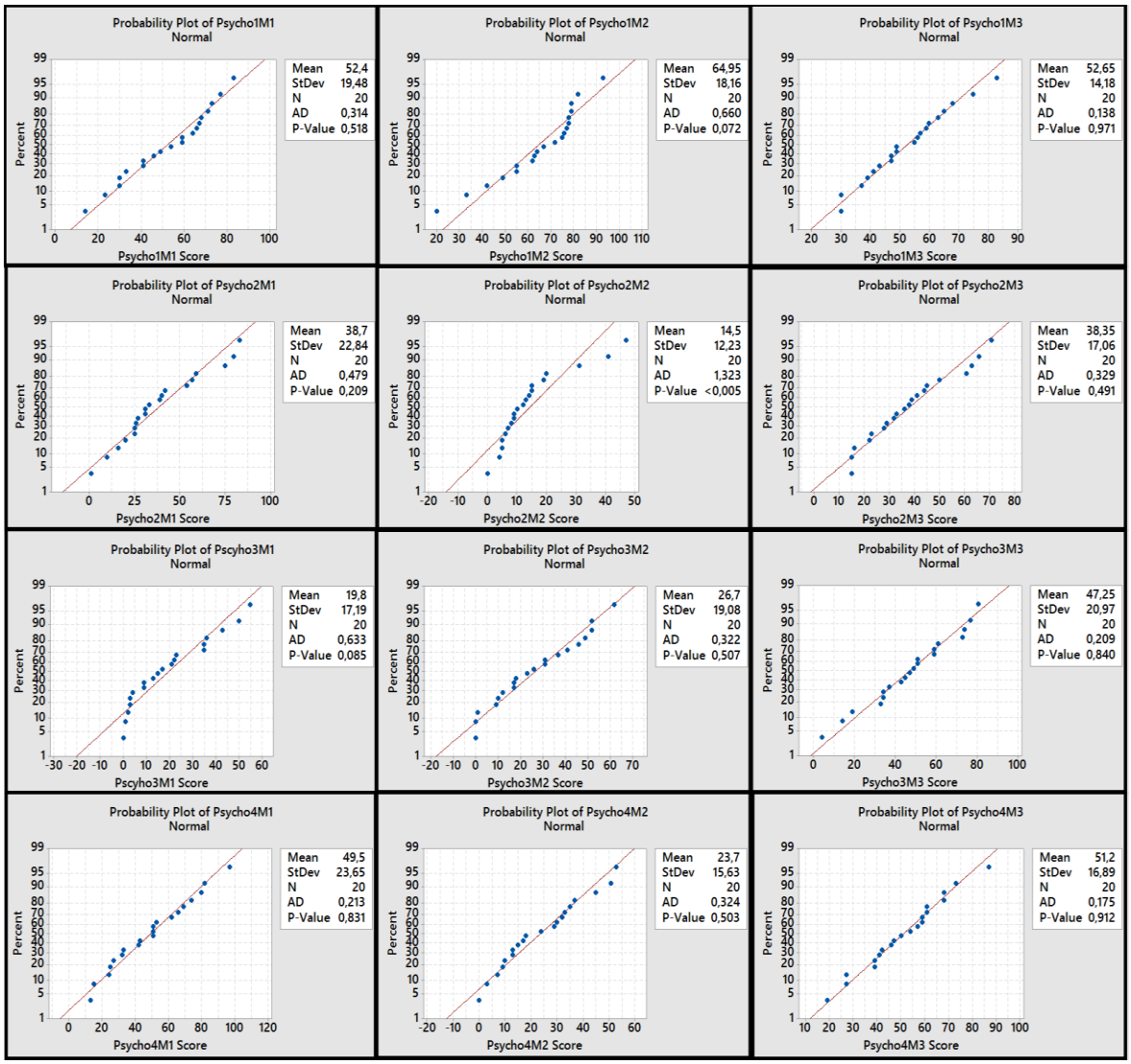


Figure F.8. Anderson-Darling normality test results-1.

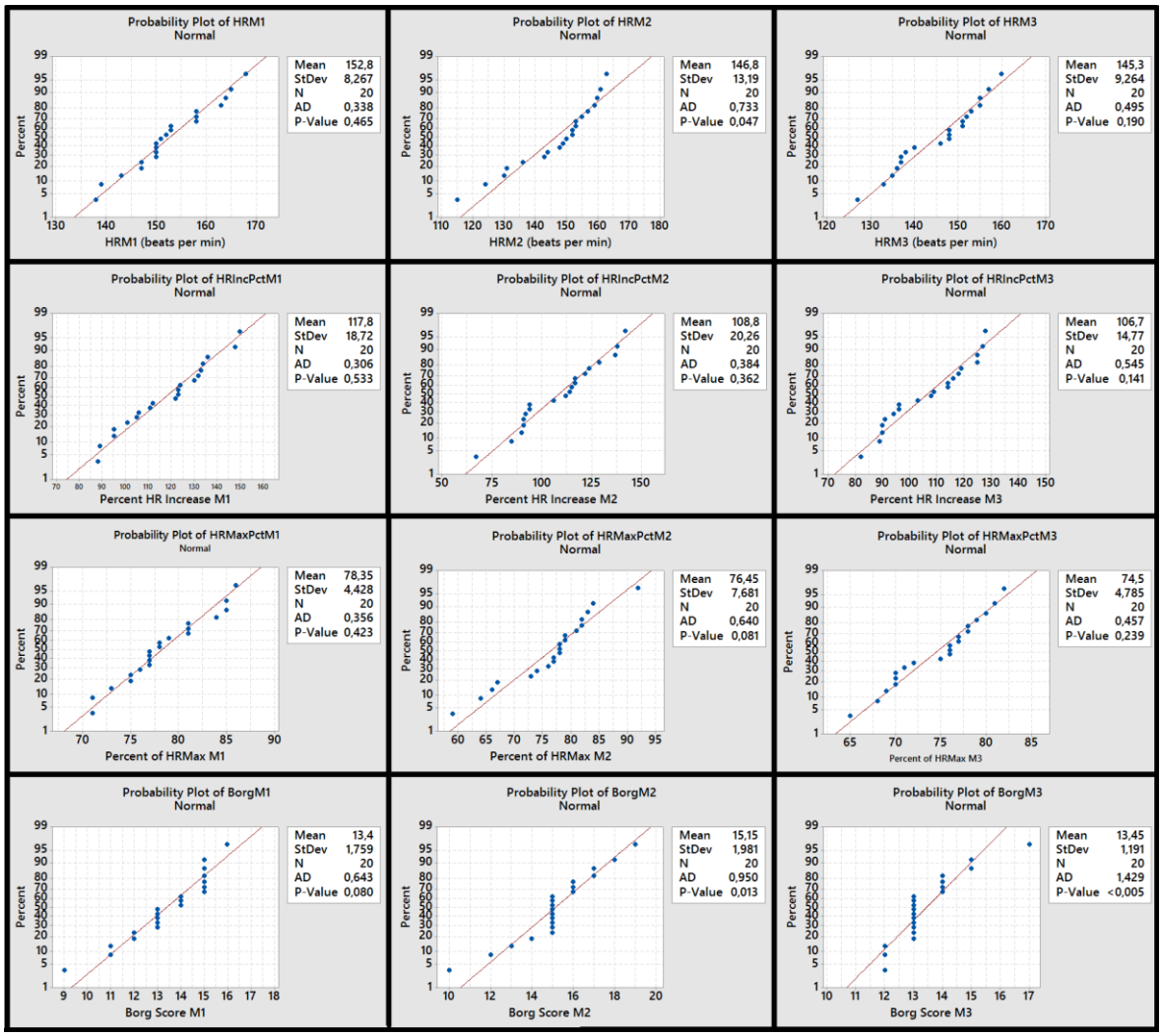


Figure F.9. Anderson-Darling normality test results-2.

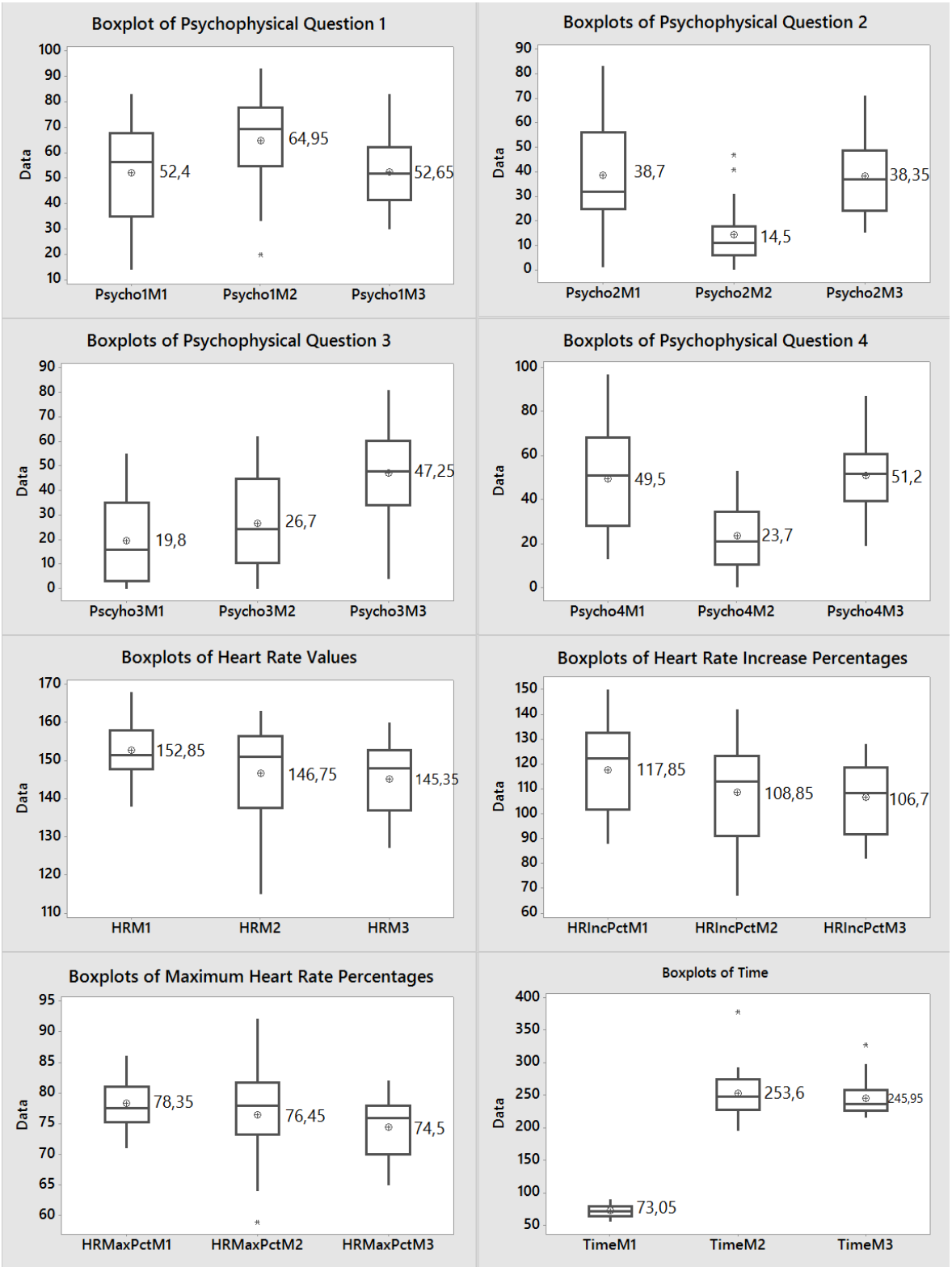


Figure F.10. Boxplots of the response variables.