Ergonomic Analysis of Selected Lifting Tasks

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Abstract

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Lifting is a common task that many people face every day. Some jobs, like manual garbage collecting, require considerably more frequent lifting. Heavy weight, improper posture and repetition can apply excessive forces to different body parts, especially on the lower back, which is one of the most affected parts during lifting.

The current study focuses on infrequent, symmetric lifting. A box, weight 2, 60, or 130 N, is picked up from the floor and lifted to different heights using either knee or hip lifting. Ergonomic checklists are used to evaluate these lifts. They typically take into account body posture, weight lifted and frequency. WISHA determined that all lifting tasks were acceptable, REBA identifies most as medium or high risk.

Biomechanical analyses, using LifeMOD, 3DSSPP and CATIA, are used determine loading of the lower back and shoulder when a female lifts 2 or 60 N. OptiTrack hardware and software were used to obtain 3D body marker coordinates during these lifting tasks. LifeMOD calculates higher lumbar moment and compression force in hip lifting compared to knee lifting. 3DSSPP shows that lumbar moment, compression force and shear force are all higher in hip lifting than in knee lifting. CATIA calculates lower compression forces and higher shear forces in hip lifting than in knee lifting, while there is little change in the lumbar moment. LifeMOD, 3DSSPP and CATIA all show that when a heavier load is lifted, lumbar moment, compression force and shear force increase.

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My family's true love and support is a relief at all the times. I thank them for being with me from far away.

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List of symbols and abbreviations

ASIS	Anterior Superior Iliac Spine
3DSSPP	Three Dimensional Static Strength Prediction Program
CATIA	Computer-Aided Three Dimensional Interactive Analysis
L4	Fourth lumbar vertebra
L5	Fifth lumbar vertebra
LBP	Lower Back Pain
MMH	Manual Material Handling
NIOSH	National Institute for Occupational Safety and Health
REBA	Rapid Entire Body Assessment
S1	First sacral vertebra
WISHA	Washington Industrial Safety and Health Act

Glossary of selected anatomical terms

Abduction	angular movement away from the middle
Adduction	angular movement towards the middle
Anterior	closer to the front
Anthropometry	study of human body measurements
Extension	straightening
Flexion	bending
Frontal	plane dividing the body into front and back sections
Inferior	closer to the foot
Lateral	farther away from the mid-sagittal plane
Medial	closer to the mid-sagittal plane
Mid-sagittal	plane dividing the body into equal left and right sections
Posterior	closer to the back
Sagittal	any plane parallel to the mid-sagittal plane
Superior	closer to the head
Transverse	plane dividing the body into upper and lower sections

1 Introduction

Lower back pain is a common problem for people from all ages and social groups. Various methods have been used to recognize the main factors that cause disorders of the spine. Frequent lifting in daily activities is a well-known cause of lower back pain. Improper postures and methods during lifting tasks can result in serious back pain for short or long periods and influence the normal life of the affected person. Individuals that are faced with more frequent lifting tasks are more at risk of lower back pain and losing work hours.

The objective of this study is to analyze the lifting task by focusing on the job of garbage collectors, as a group that is more involved with lifting tasks in awkward situations. To satisfy this objective, predetermined load magnitude, load size and origin and destination levels used. Specifically, this study is based on a hypothetical paper-recycling task, using blue recycling boxes and mobile bins as the emptying site.

Many methods are used to investigate the body movement and analyze joint and muscle forces during the lifting task, considering knee lifting and hip lifting methods for different hand loads and different load destination levels (waist or shoulder level). Various biomechanical software programs are currently on the market. These computer programs are able to calculate joints forces and torques for different static postures or dynamic movement. In the present study, different software packages and checklist solutions are examined. Static postures in 3D static strength prediction program (3DSSPP) and biomechanical static analysis in CATIA are used to analyze different body position during the lifting task and joint forces and torques are calculated. For dynamic analysis of the task, LifeMOD software is used. This software is able to simulate the body movement by getting joint coordinates in different frames during the task. Finally, ergonomic checklists are used to simply evaluate the job hazard level, for both knee lifting and hip lifting methods.

1.1 Thesis outline

Chapter 2 reviews the garbage collector duties and relative occupational problems and dangers and gives overall information about this job. Lifting task as a frequent activity in this job is discussed later. The nature of lower back pain as a widespread problem is studied thereafter. In the next section, different methods that are used to study the lower back pain from invasive methods and non-invasive methods are discussed. In this study, checklists and biomechanical modeling are chosen as non-invasive methods to study.

Chapter 3 is devoted to the methodology discussion. First, the lifting task is defined by predicting the load magnitude, size and transferring distance. The lifting task is performed using either knee lifting or hip lifting using specific weights. Four methods are chosen to look into the lifting task and related lower back disorders. The first method uses quick checklists (WISHA, REBA, Liberty Mutual and NIOSH equation) to estimate the hazard level. The other methods use joint coordinates obtained during an actual lifting task using an OptiTrack 3D motion capture system. The joint coordinates are input into LifeMOD, which performs a dynamic analysis of the lifting task. Three postures in lifting are selected from a model generated in LifeMOD by using the same joint angles to create static postures in 3DSSPP and CATIA. These three postures are initial posture (the picking up moment), the final posture (holding the load) and one middle posture to study the lower back forces in static postures. In each section the result of these four methods for both knee lifting and hip lifting using certain loading magnitudes are presented. Comparisons between methods are shown in tables.

Chapter 4 presents conclusions of this study and offers suggestions for future work.

2 Background and literature review

The aim of this study is to evaluate the lower back forces during a task. To satisfy this goal, garbage-collecting job selected as a task, which is involved by high frequent lifting activity. After examining this specific job, a study has done to show that lower back pain is a most probable problem that may occur during the lifting. Methods and material that other researchers used to study the lumbar region pains are discussed afterward. Two non-invasive methods, checklists and biomechanical modeling are used to analyze the lower back forces.

2.1 Garbage collector work

Garbage collectors perform different activities as a part of their job. This job is classified in "Helpers, Handlers and Laborers" according to the Department of Labor in the United States. The job mainly contains lifting garbage and handling materials, dumping garbage from containers into the truck that may be accompanied by throwing plastic bags into the back of the truck. In occupational classification system, the garbage collector driver and truck driver sort at the same group (Department of Labor in the United States). For a single personnel collecting system where a single worker performs the driving and collecting task, the occupational problems for truck drivers such as whole body vibration and awkward postures can be taken into account as garbage collectors problems. In the Occupational Classification System Manual for United States Labor Department, the garbage waste collecting job is defined as "H875 Garbage collectors" that are responsible for collecting refuse on a designated route and dump refuse from containers into the truck (Bureau of Labor, October 2001). It also includes transportation and material moving occupations and motor vehicle operators' job as a truck driver as explained in labor library 2001 in single worker task (U.S. Department of Labor, Bureau of Labor Statistics, October 2001).

Among the most frequent work-related fatal events for a garbage collector are highway incidents, struck by object and falls. As figure 1 shows these groups of work-related problems caused the most number of fatalities in 2005 for all ages (Centers for Disease Control and Prevention, 2005). Garbage collectors usually work alone, so they have to drive, get off the truck at any station and collect garbage, carry carts from their place to truck for a distance and empty those in truck compartment. In some places, they have to run behind the truck for about 30 km to accomplish the task. Heavy cans are another part of the job, which compels a huge body stress on the workers. What makes the situation worse is that, garbage collectors do not know what situation they may face: slippery floor, bags and cans with very different weight and size and unexpected dangerous materials and hazardous smells are some of these unforeseen conditions (Kuijer and Frings-Dresen, 2004).

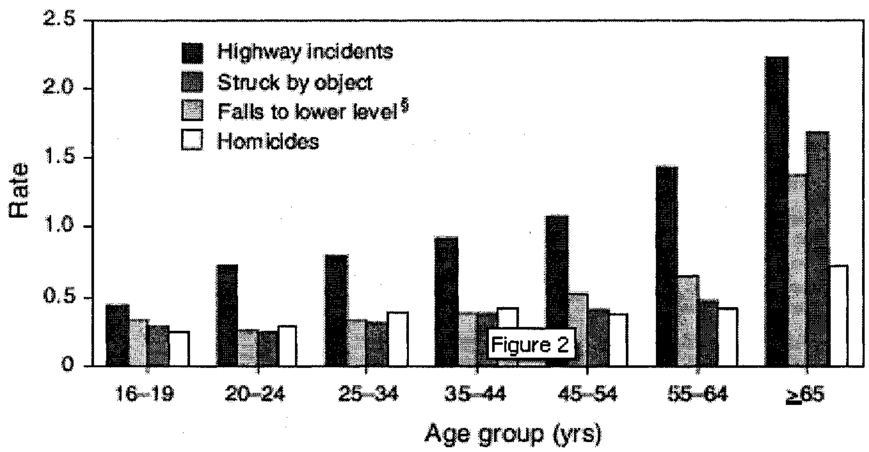


Figure 1 Fatal occupational injuries, United States, 2005

The National Institute for Occupational Safety and Health (NIOSH,1994) publication regarding fatal occupational accidents shows that between 1980 and 1992, 450 garbage collectors died in incidents related to the garbage collecting truck. Most of these accidents were caused by their own vehicle when they were struck or ran over by the truck after falling down (Kuijer and Frings-Dresen, 2004).

That is why, in 2004, NIOSH reported waste collecting job is in the top six riskiest jobs considering number of fatalities. Musculoskeletal disorders are probable in this job. Because of high risk in this activity, the solid waste collectors are two times more likely to loose working day than the average service sector workers (Bureau of Labor Statistics, Census of Fatal Occupational Injuries Summary, 2004).

2.1.1 Residential Refuse Collectors: Risk Factors and Tasks of Concern

Domestic garbage collectors in Quebec distribute work in 350 companies, some rent and others own their truck and hire workers as garbage collector. Trash collector's salary has a flat rate and, because the system of garbage collecting is not totally mechanized, workers are in direct contact with garbage (Cloutier, 2004).

Each truck has an assigned territory for a workday. The amount of garbage piles changes in different days and seasons and affects the workers work burden. An experienced worker usually trains new workers in the real work place. To estimate the job load for workers for a 9 hour work shift per day 16 tones of load is carried and for a 6 hours work shift they walk 11 kilometers and the total energy expenditure is at least 2500 kilocalories (Cloutier, 2004), that is much higher than energy consumption for miners, forestry workers and material handlers (Spitzer and Hettinger, 1966).

Occupational problems for garbage collectors can be listed in two groups: musculoskeletal problems caused by different activities in this job and accidental problems because of unsafe devices and a nonstandard working station.

The most vulnerable parts of the body at risk of injury during the task are the lower limbs due to falling, hitting solid objects in non-transparent plastic bags, hitting street barriers or different parts of the truck during loading garbage or getting in or out of the truck cab (McHugh, 2006).

Upper limb problems happen during grabbing plastic bags, handling material with sharp edges and using extra forces while handling because of thick gloves. The most involved body part in the lifting task which repeats frequently in this job is the back. Lifting and handling materials are the main activity in this job so the spine is always of concern during the task. The most affected part in the spine is the lumbar region; therefore, lower back pain (LBP) is the most prevalent occupational disease in this job. Twisting while lifting amplifies the back forces (An et al., 1999).

An unprotected face can cause problems too, especially eyes when the collector works by the compactor auger part of the collecting truck to compact the garbage. Extra tension in the hands during reaching out of reach material in bins or handling heavy materials (over 60 lbs) and jumping causes ligaments injury in extremities, back and neck. Most frequent injuries are wounds and cuts caused by handling sharp materials. Trauma, contusion, hematomas and bleeding, can happen because of falling or slipping (Robazzi et al., 1997). Some dangerous behaviors such as handling more than one garbage bag at the same time with hands, under arms or chest may increase the severity of these types of the problems. Also poor hand and foot protection can cause cutting and bruising of bare parts.

These problems can cause by devices and materials that workers are working with or the street problems that can be assumed as workstation for this job. The following problems describe the hazardous sides of the work briefly (Faria and Silva, 1986).

1. Garbage packaging: This may cause cutting and piercing, awkward handling, unsafe walking and carrying postures because of bulky or heavy garbage.

2. Collecting truck: Compactor auger (used for compacting garbage) shavings from this part can cause injury for eyes. Workers usually stand in an unstable situation behind the truck.

3. Picking up recycle bins from low heights and emptying them at a high level, happens frequently with heavy bins.

4. Hazardous materials (chemical and biological wastes).

5. Awkward neck postures while looking at mirrors or camera monitors when operating joystick controls.

6. Street accidents: holes, street barriers and street water drains are unexpected obstacles in the street.

7. Animal bites: garbage piles are good places for animal congestion. Animal bites can cause different infectious diseases.

8. Rain makes open bins, especially paper bins, heavier.

From a group of 251 manual solid waste collectors, 75% reported being injured and 70% reported illness in a year (An et al., 1999). National Institute for Occupational Safety and Health (NIOSH) published a report showing that between 1980 and 1992, 450 garbage collectors died in incidents related to garbage collecting truck. Their own vehicles caused most of these problems when they slipped or fell down (NIOSH Alert, 1997).

Some suggestions were published in late 70's to decrease the hazard level in this job. Avoid large pushing and pulling forces when not necessary, for example manually moving dumpsters, particularly in the case that they are not wheeled. To accommodate 75% of male workers the maximum initial push force is 62 lbs (275 N) and the maximum initial pull force is 47 lbs (209 N) (Snook et al., 1978).

Even in the safest conditions, lifting heavy loads at a high frequency is an unavoidable task for manual garbage handling. Serious lower back pain and spine deformation can appear because of awkward posture, one hand lifting, force shock or heavy load lifting that may all occur during this task.

2.1.2 Job hazard evaluation

Garbage collectors are exposed to all sorts of toxic odors and materials and perform a repetitive work in high frequency, so it has named as the third hazard work as a NIOSH report reveals (Kuijer and Frings-Dresen, 2004).

Solid waste haulers ranked third on the list of the riskiest jobs in the United States (An et al., 1999). 90 deaths per 100,000 workers annually, shows the high risk in this task that comes just behind timber cutting (178 deaths) and fishing (178 deaths) and this mortality rate is 100 times higher considering any acceptable standard. The death rate for garbage collectors is 5 to 7 times higher than average workers in other industries (An et al., 1999). The nature of work contains high frequency lifting and lowering that causes the most significant problems in this job. Back injuries and lacerations are highly prevalent among workers. In more details, risk factors for this job, from ergonomic point of view, can be categorized in five major parts (Eppes, 2004):

- Awkward posture: workers have no idea about the weight and homogeneous load distribution in plastic bags or recycling boxes, they must be prepared to change their posture on purpose to keep their balance. Rapid changes in posture cause muscle extension in involved body parts and more significantly, in the back region ends in lower back pain. In this case the load is not necessarily heavy or bulky, but just rapid changes in posture are problematic.
- Highly repetitive motion: repetition of tasks causes muscle fatigue in certain parts and means overusing a body part.
- High hand forces: there is no limit for the weight of plastic bags and recycling boxes. People fill them up as much as possible and it can get to 60 kg for compact paper in a 15 gallon recycle box (Anjos et al., 2007). Lifting is often done one-handed, especially for plastic bags.
- Lifting task: lifting is the main activity in this job. Garbage collectors lift plastic bags and recycle boxes from floor level to higher than waist level in order to empty them into trucks or dumpsters.
- Whole body vibration: standing at the back of the truck causes whole body vibration for garbage collectors. Truck drivers face vibration too and because in most cases all the tasks is done by one person (single worker), the driver can be assumed as the garbage collector. Standing position for driving causes more whole body vibration (Maeda and Morioka, 1998).

The level of hazards is very high. As an ergonomic solution in some countries, automated systems have replaced manual garbage handling.

As a conclusion, lifting task in manual solid waste collecting is a repetitive, unavoidable activity and causes many problems from back muscle tensions to spinal disorders.

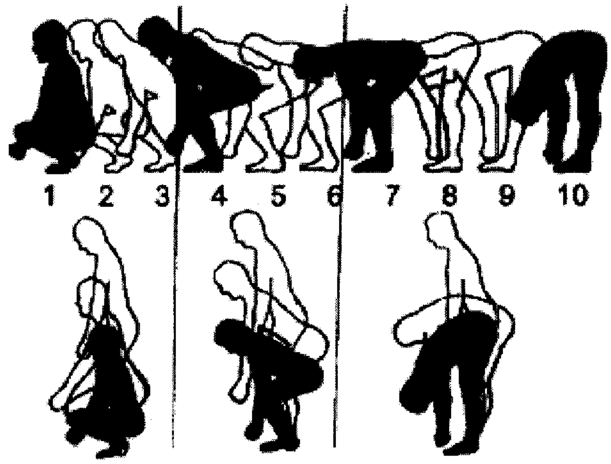
2.2 Lifting task

Lifting manually is known as a hazardous activity. The risk is more serious if the origin is lower than the knee (Sedgwick, 1997). Lifting materials, which are located out of the sagittal plan and placed on ground level, is the worst case in back muscle tension. 7.7% of the medical diagnoses in garbage collecting jobs is related to the spine injuries that mainly happens during lifting task (Robazzi et al, 1997). Training for a suitable lifting method and load magnitude limitation are two factors that can reduce the musculoskeletal problems in task.

The National Institute of Occupational Safety and Health (NIOSH) published guidelines in 1980 to limit the allowed lifting load. It recommended a hand loading which produce L5/S1 compression force not more than 6361 N and for loading which this amount rise to 3425 N administrative controls are required. In addition, it recommends for the entire lifting task, more than 25% of population must be able to perform the task (NIOSH, 1981).

Using a proper technique is a preventive method for reducing lower back pain. A suitable method can be used for a wide range of population and an unsuitable method increase a risk in occupational disorders (Hsiang, 1995). Therefore training specifically for certain lifting tasks has a significant effect on occupational injuries and disorders and researchers have carried out extensive studies in this field. They tried to find methods and postures, which help workers to reduce undesirable excessive stresses, strains in back muscles, ligaments and joints, and as a result reduce the occupational disorder problems. Biomechanical and physiological research concerning body performance and energy consumptions are developed to find an optimized method for this certain task.

Various methods for lifting have been suggested to reduce muscle force expenditure and joint forces. Lifting methods can be categorized by which body part initiates movement during the lifting task: stoop lifting and squat lifting, in which torso and leg are primary mover respectively (Garg and Herrin, 1979; Kumar, 1984; Toussaint et al., 1992). Sedgwick's (1997) considered three lifting methods: leg lift, semi squat and stoop lift. His experience of different methods for lifting on a group of workers shows that 80-90% of the participants suggest the lifting method in the following order as an appropriate model for training: leg-lift (80-90%), semi squat (25%) and stoop lift (10%), as shown in Figure 1. Table 1 shows a comparison between these different lifting methods.



1 2 3

Figure 2 Three methods for lifting
1. leg lift 2. semi squat 3. stoop lift (Sedgwick, 1997)

Table 1 Lifting method comparison (Sedgwick, 1997)

Factor \ Lifting method	Leg lift	Semi-Squat lift	Stoop-lift
Center of gravity height	Low	Moderate	High
Heel location	Raised	Grounded	Grounded
Trunk inclination	Low	Moderate	High
Knee flexion	High	Moderate	None
Knee protruding from shoulder line	In front	Same line	Behind

During lifting, bending torque in lumbar affect intervertebral discs and ligaments. Excessive bending torque may result in ligament injuries (Dolan et al., 1994). In the same posture fatigue failure of disks occurs if the compressive force exceeds 3.5 kN (Adam and Hutton, 1985). Back lifting posture consumes the least level of energy and the least amount of strength in the lower extremities (Troup, 1977). In contrary back lifting or hip lifting method causes ligamentous injuries because of hyper-flexion in back or muscle strain, (Adams and Hutton, 1982) and causes disk injuries due to high acceleration forces caused during the truck flexion (Troup, 1977).

Anderson and Chaffin (1986) studied different lifting techniques by focusing on required strength in lower back disc compression (L5/S1 disc) and low-back ligament strain. Different lifting strategies are obtained by feet placement on ground, knee flexion, back curvature and hand placement on the load. One healthy male performed the experiment using two load types, bulky and compact for 5 lifting methods and 3 repetitions for each lifting. The subject after training by watching videotapes, photographed in sagittal plane by speed of three frames per second for each task and from a 5 meter distance. These five lifting methods are listed in the following table.

Table 2 Five alternative lifting techniques (Anderson and Chaffin, 1986)

Method	Foot Placement	Knee orientation	Back orientation
Stoop	Parallel	Straight	Curved
Parallel/Flat (Squat)	Parallel	Bent	Flat
Parallel/ Curved	Parallel	Bent	Curved
Straddle/Flat	Straddle	Bent	Flat
Straddle/Curved	Straddle	Bent	Curved

Markers were placed on hands, center of gravity, elbow, shoulder, hip, knee and ankle and angular orientation were digitized for different body segments to be used in biomechanical modeling. Lifting in a slow and controlled manner means that inertia and acceleration can be ignored and the lifting method can be considered static.

For compact loading, L5/S1 disc compression is almost twice in stoop lifting to squat lifting but for the bulky loading magnitudes are almost at the same level for both methods. Straddle/flat back shows lowest L5/S1 disc compression and lowest lumbodorsal fascia strain, which is found the most vulnerable ligament in this task because of high flexion level in bending posture. Lifting methods which have a curved back posture can raise the ligaments strains and increase the risk. The authors suggest avoiding stoop lifting even for bulky loads because of high percentile tension in back ligaments.

For foot placement, Imrie (1983) suggested a posture that one foot is located behind the load and another one beside that to provide more stability.

Comparing two most known lifting methods, squat and stoop lifting, reveals some advantages for knee lifting versus back lifting in presenting lower back pain (Adam and Hutton, 1982). Shifting load during lifting from the back to the legs, which are stronger, is one advantage of leg lifting. Troup et al. (1983) named less load distance from body for squat lifting. For bulky loads stoop lifting is preferred because the moment arm is reduced. From postural point of view, squat lifting causes less tension in the back ligaments (Anderson, 1983).

Some studies indicate a specific hand location for lifting a box. Coury and Drury (1982) suggested a hand position to make balance in handling load. One hand is located on upper outer side and another on inner lower part to provide a good balance on the box. The problem with this posture is applying more force to the lower hand and providing asymmetric lifting.

All these studies insist on keeping the load near to the body to decrease the moments on lower back and keep the back aligned like the back posture neutral position.

Finding maximum acceptable force in lifting and lowering for different lifting methods and different frequency can protect worker from lower back problems by avoiding extra tension in back ligaments and muscles and intense compression force in lower back region.

Aghazade et al. (1993) developed a formula to get the maximum acceptable force in lifting task. This formula needs to get a rating factor by using operator feeling during lifting. The strain at the first phase was rated 100. Depending on the magnitude of stress that worker feels during lifting with a defined frequency, a certain amount will add to or subtract from the 100 in percentile. The following equation indicates the method.

$$\text{Maximum acceptable weight=Base (kg)}*[1-\frac{Rating-100}{100}]$$

The following table shows suggested rating amount in different frequency (from 1 to 5 lifting or lowering per minutes).

Table 3 Rating values for different frequencies

Frequency (lifts/min)	1	2	3	4	5
Lifting	70.46	79.55	100	120.46	136.36
Lowering	61.36	73.64	90	115.91	128.18

Knowing these rating values, the multiplying amounts are calculated in table 4.

Table 4 Basic weight multiple

Frequency (lifts/min)	1	2	3	4	5
Lifting	1.3	1.2	1	0.8	0.64
Lowering	1.4	1.3	1.1	0.84	0.72

The maximum amount in lowering is about 7% more than lifting and maximum amount changes from 16 kg to 7 kg in 1 lift/min and 17 kg to 9 kg for 1 lowering/min. They used students for this study and long distance (61 cm) for lifting and lowering task. These two factors result lower suggested weight respect to Snook and Ciriello (1993).

Sharp et al. (1995) did the same research for lifting load limitation at different frequencies and continuing by carrying 7.2 meter. Their study group was a group of male and female soldiers. Following table shows the maximum load in lifting for two different frequencies. Using soldiers as the study group, results in higher limitation for lifted load.

Table 5 Maximum load in lifting (Sharp, 1995)

Frequency (lifts/min)	1	4
Men	35.7 N	25.5 N
Women	23.7 N	18.4 N

Davis (1996) tried to find the maximum tolerable load in L5/S1 for two eccentric and concentric loads by applying electromyogram electrodes. They categorized the task in concentric lifting, which muscles are shortening for generating force, and eccentric lowering which muscles are lengthening to generate the force. The following table shows the results of their study.

Table 6 Maximum imposed force in spine L5/S1 region (Davis, 1996)

Maximum Load	Sagittal moment on spine (N-m)	Anterior posterior shear force (N)	Compression force (N)
Eccentric	140	700	3500
Concentric	120	800	2600

Karwowski (1996) suggests another method as a worker-self- report to determine the maximum load that worker feels it is safe for an 8 hours shift period. He used a weight adjustable box by removing or adding weights to the box and considering workers abilities and skills. He used two definitions. Maximum acceptable weight of lift (MAWL) derived by Snook and Irvine (1967) and maximum safe weight of lift (MSWL) presented by himself in 1995 to preserves the worker safety and prevents lower back pain. For a group of 10 male students, the mean value for MAWL was 46.02 lb (20.87 kg) and for MSWL the mean value was 38.3 lb (17.36 kg).

As a result, studies show that lifting task affects the lumbar region and causes occupational disorders in lower back pain. In the next section different method that used to study the lower back pains has reviewed.

2.3 Lower back pain, an occupational disorder

Lower back pain is a common problem for all ages. Acute lower back pain is the fifth most physical problems that make people to visit a physician (Patel and Ogle, 2000). Fymoyer and Cats-Baril in 1987 revealed that 5% of American adult faced with LBP problems each year. This amount is higher in working population and reaches to 50% (Patel and Ogle, 2000). Frymoyer and Cats-Baril, continuing their study in 1991, showed a highly increasing rate in LBP from 1960 to 1980, which is 14 times more than population rise. For a certain number of employees (100 full-time workers) lower back pain rate have decreased by 70% and occupational injuries rate decreased by 40% from 1986 to 1994 (Koda and Ohara, 1999).

Back strain, acute disc herniation, spinal stenosis and spondylolisthesis (displacement of a vertebra) are some disorders which involve different parts of the spine like discs in spinal column or ligaments and muscles. Lower back pain, as a widespread problem in workstations, is one of the employer's concerns. Depending on the type of pain (acute or chronic pain) it can take from weeks to three months for rehabilitation and causes 50 million working days lost which costs industry $11 billion annually (Snook and Jensen, 1984).

A wide range of occupational and non-occupational facts are reported as a cause of lower back pain. Handling heavy and bulky materials, which can get worse by improper lifting methods, unsuitable humidity and temperature situations, fatigue effects and whole body vibration as occupational problems and on the other hand aging, workers relation and family situation as non-occupational risk factors affect LBP and consequently the worker performance (Riihimaki, 1991).

Aging and degradation are key problems, which can increase the possibility of LBP. Muscle elasticity, ligament strength and discs flexibility decreases by aging and can end in more risk for sprain during lifting. When comparing young people to people age 60 and over, trunk axial rotation decreases by 15%, neck extension by 41% and trunk lateral flexion by 29%. (Doriot and Wang, 2006). For garbage collector the falling rate increases from 1.6 for workers younger than 35 years to 2.8, a 75% increase, for 35 years and older workers (Cloutier, 1994).

Lower back pain can occur during different activities, which are associated with flexion, bending and twisting in spinal column and lumbar. Lifting is one of these sorts of activities that applies a combination of forces on back and lower back pain (LBP) is frequently reported in this task (Snook et al., 1978).

Lifting task applies both compression and bending to spinal column. Most affected part in vertebrae in this task is intervertebral discs (Dolan et al., 1994). The combination of loads on spine increases the risk of lower back disorders (Fathallah et al., 1998) but does not affect the intradiscal pressure. Load combination mostly affects the shear strain especially in posterolateral area (Schmidt et al., 2007). Intervertebral discs pressure shows the maximum amount in the combination of flexion and rotation (Steffen et al., 1996). This posture is highly frequent in lifting task.

Invasive and noninvasive methods are available for measuring the forces in the spine. Invasive methods cannot be used in many dynamic activities that apply critical loads to erector spinea in vivo experiment. Nachemson (1981) used a pressure sensitive needle for disk pressure measurement in the lumbar region. As muscles generate most compressive force in back, speed and posture have a significant effect on back tension and forces (Adam et al., 1994). Hence, invasive methods are not always applicable for studying the joint forces in real performance.

Another method applied in measuring complex spinal muscle load during dynamic activities is electromyography. Fathalla et.al. (1998), used force plate and electromyogram assisted free dynamic lifting model in vivo study to provide a quantitative, 3 dimensional pattern of applied load to spinal column in lifting task as a specific dynamic activity. Velocity, acceleration and 3D positions of trunk accompanied by 3D external forces and torques in the L5-S1 region derived from force plate data. Trunk location and L5-S1 orientation are determined by two electrogoniometers. This device estimate the internal moments for balancing equilibrium conditions by balancing the external moment around L5-S1 by internal moment of musculature. The method applied to male object and effects of asymmetric and symmetric lifting, performance speed and weight magnitude in force and torque generated on L5/S1 facet studied. The study group contained 11 male subjects with no back disorder background, performing the task. They used 3D diagram to show the quantities in spinal load combination. They did the study in three categories to cover different lifting in industry: lifting method, speed and load magnitude. For method, they present two techniques of lifting: symmetric loading (sagittal loading) as used in low risk activities in industry and asymmetric loading to model complex loading as appears in medium or high risk lifting tasks. For different speeds, three levels were used: 2 seconds per lift as slow lifting, 1.5 seconds per lift as medium lifting and 1 second per lift as rapid lifting to replicate three risk levels in a job. As a result of their study, they introduced the loading rate as a better indicator of applied load to spine to show both duration and magnitude of spinal loading during task and instead of statistical terms such as average and maximum spinal loading, investigated to find the conjunct occurrence effect

Marras et al. (1993) suggested hand loads of 22, 67 and 156 N, representative of low, medium and high load percentile respectively, located just above the knee. Spinal loading at L5/S1 in three different terms of compression, anteroposterior shear and mediolateral shear were studied. Their study result showed that shear force in the worst case (heavy load, asymmetric lifting and rapid lifting) exceeded 1800 N and the compression force was about 7000 N. The loading rate at high speed was reported to be twice that at low speed. This study is fully depended on the subject performance and electromyograms did not get all the internal muscle forces that contribute to the lifting task and therefore their effect was neglected.

Dolan et al. (1994) did a similar study to find the bending and compressive stress and risk factors in lifting task in a large group of 21 men and 18 women .They considered lifting methods (squat or stoop), weight, handle distance from sagittal plane and trunk speed. To find the maximum spinal compression the maximum extensor moment generated by back muscles and fascia was calculated.

The result showed 10% lower peak for extensor moment for stoop lifting compared to squat lifting but 75% more for bending torque. These two factors increases by non-sagittal lifting, hand loading, bulkiness and distance from leg. Speed only affects the peak in extensor moment but not in bending torque. Flexion moments on the lumbar spine are measured by '3-space Isotrak' which give estimation for bending moment applied to intervertebral discs and ligaments . By connecting the Isotrak device to the skin surface in the L5-S1 location back curvature can be found. Other bioelectrical electrodes are attached to the erector spinae at the T10 and L3 level. Lumbar curvature is established to find the lumbar flexion. Some correction is done for EMG electro-machinery delay and different velocity for muscle contraction. They indicate three peaks in lumbar curvature, the first one at the end of forward bending moment second one at picking up moment and the third one at the trunk extension. Dolan et al. (1994) showed that trunk extension is accompanied by rapid shortening of erector spinae so muscle contraction velocity correction which was used for all muscle velocity decreases in this case therefore the peak in the picking up moment is the largest one. Maximum bending torque and extensor moment occur at the same time and the peak in flexion and extensor moment differ only 10-20%. Their experimental results for male subjects are compared in table 7. For the twisting experiment, the peak bending point increases by 30% for 90 degree twisting to the left or right. Table 7 also shows the results under different conditions. Considering the extensor moment, more accurate comparisons can be made between lift methods rather than the compressive force (Dolan et al., 1994).

Table 7 Maximum lumbar loading for different conditions (Dolan et al., 1994)

	Mass from 0-30 kg	Stoop to squat	Bulkiness	Distance from feet	Speed from – quasi static to fast
Peak bending torque	50% increase	75% increase	20 - 25% increase	95% increase 30 - 60 cm	slight decrease
Peak extensor moment	100% increase	10% decrease	20 - 25% increase	90% increase 0 - 60 cm	60% increase

There are several self-reporting methods using checklists, diagrams or questionnaires, filled out by subjects to find the peak values of forces in different parts.

Andrews et al. (1996) used a non-invasive method to estimate the peak force in L4/L5 lumbar spine compression by self–report forms filled out by the participants. 27 persons did the lifting tasks with different complexity. The lifting tasks were photographed or videotaped to get the joint coordinates and used as input data into a biomechanical program to analyze the compression force in the lower back. Subjects chose the more realistic posture in the more complex lifting task from a series of diagrams, which were used to calculate the joint coordinates.

Participant did different tasks repetitively and at the end they were asked to identify the most difficult posture. Slides which were taken from right side in the statical holding position. After that the subject filled out a questionnaire to report different body parts posture. The slide showing the posture for the most difficult instant is used to get the metatarsal, ankle, knee, hip, shoulder, elbow, wrist, hand, L4/L5 joint and C7 joints coordinate by using a 2D digitizing table .These coordinates are used as an input into a standard static biomechanical model to get the L4/L5 compression force.

For 90 percentile person and hand loading of 13.4 kg, L4/L5 bending moment and compression is calculated in the worst posture about 237.8 (N-m) and 4280 N for downward straight hand. Reliable and repeatable results with minor differences were obtained in self-reported and criterion posture.

Results from these groups of studies help to understand human body mechanical properties and the effect of external forces in creation of internal forces in joints and ligaments and help to the development of biomedical analysis programs.

2.4 Non-invasive methods for studying the lumbar force

Ergonomic checklists and biomechanical modeling can be used to study lumbar forces. Because they are the focus of the current research they are introduced briefly in this section, and they are explained in greater detail in the next chapter.

2.4.1 Ergonomic checklists

Checklists are useful tools to identify potential ergonomic problems. These work sheets help managers to consider some hidden problems that affect the job performance quality and employee's health. Ergonomic checklists offer a simple and quick method that let the employer and employee understand potential ergonomic problems of a certain work activities. While checklists do not offer a solution about how to remove the risky condition, they make supervisors and workers aware of the need to change their working environment in a way that reduces the risks.

WISHA, REBA, Liberty Mutual tables for manual material handling, or formerly Snook tables, and the NIOSH lifting equation are some of the most popular checklists. They are presented and used in the following chapter. The WISHA checklist is discussed below as an example of these checklists.

Washington State's occupational safety and health program was established in 1973 by the Washington State Legislature to ensure that the entire worker in a workstation have a safe and healthy working condition. This program forces the employer to control the working condition. WISHA present some standards about workstation arrangement and worker health and safety by considering the accidental problem, employees complain about safety in a certain working area. WISHA examines the report of work place hazard that cause death or serious musculoskeletal harm to the employee, they try to eliminate the problem and control the working condition and personal health after removing the problematic situation (WISHA, 2008).

Safety and health core rules provided by WISHA explain the minimum requirement that must be applied to provide a safe environment for the workers during the working hour. These rules are about employers' responsibility to keep the place safe considering the work station arrangement, controlling use of hazard material and devices, apply appropriate personal protective equipments and preventive program to train the workers. The aim of this study is to eliminate the hazard condition before accidents occur (WISHA, 2008).

The following figure shows the WISHA lifting analysis checklist:

WISHA Lifting Analysis 1

Job	Date / /
Notes	Analyst(s)

The lifting analysis on the following page is performed when one or more of the Caution Level job risk factors in the following checklist is present. This checklist is taken from the adapted WISHA checklist.

Heavy, Frequent or Awkward Lifting				Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Combined with**	**Duration**	
Back and shoulders	Lifting 75 or more pounds	No other risk factors	One or more times per day	Caution ❑
	Lifting 55 or more pounds	No other risk factors	More than 10 times per day	Caution ❑
	Lifting more than 10 pounds	More than 2 times per minute	More than 2 hours total per day	Caution ❑
	Lifting more than 25 pounds	Above the shoulders Below the knees At arm's length	More than 25 times per day	Caution ❑
	WISHA Lifting Analysis – Perform if any Caution condition exists. Actual Weight (Step 1) is greater than the Weight Limit (Step 4) (See separate work sheet)			Hazard ❑

Adapted from State of Washington Department of Labor and Industries Ergonomics Rule
See http://www.lni.wa.gov/wisha/ergo/ergorule.htm
This version focuses on the lifting section. See www.hsc.usf.edu/~tbernard/ergotools for electronic copy of form.

After the lifting checklist is filled out a lifting analysis is performed using the form shown in the following figure to determine if there is a hazard:

Figure 3 WISHA lifting checklist

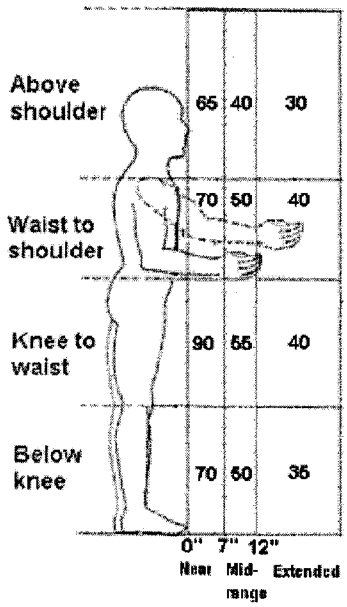
WISHA Lifting Analysis 2

This analysis pertains to jobs where employees lift 10 lbs. or more.

Step 1 Find out the actual weight of objects that the employee lifts.

Actual Weight = ________ lbs.

Step 2 Determine the Unadjusted Weight Limit. Where are the employee's hands when they begin to lift or lower the object? Mark that spot on the diagram below. The number in that box is the Unadjusted Weight Limit in pounds.



Unadjusted Weight Limit: _______ lbs.

Step 3 Find the Limit Reduction Modifier. Find out how many times the employee lifts per minute and the total number of hours per day spent lifting. Use this information to look up the Limit Reduction Modifier in the table below.

How many lifts per minute?	For how many hours per day? 1 hr or less	1 hr to 2 hrs	2 hrs or more
1 lift every 2-5 mins.	1.0	0.95	0.85
1 lift every min	0.95	0.9	0.75
2-3 lifts every min	0.9	0.85	0.65
4-5 lifts every min	0.85	0.7	0.45
6-7 lifts every min	0.75	0.5	0.25
8-9 lifts every min	0.6	0.35	0.15
10+ lifts every min	0.3	0.2	0.0

Note: For lifting done less than once every five minutes, use 1.0

Limit Reduction Modifier: ____.______

Step 4 Calculate the Weight Limit. Start by copying the Unadjusted Weight Limit from Step 2.

Unadjusted Weight Limit: = ______ lbs.

If the employee twists more than 45 degrees while lifting, reduce the Unadjusted Weight Limit by multiplying by 0.85. Otherwise, use the Unadjusted Weight Limit

Twisting Adjustment: = _____.____

Adjusted Weight Limit: = ______ lbs.

Multiply the Adjusted Weight Limit by the Limit Reduction Modifier from Step 3 to get the Weight Limit. X

Limit Reduction Modifier: _____.___

Weight Limit: = _____ lbs.

Step 5 Is this a hazard? Compare the Weight Limit calculated in Step 4 with the Actual Weight lifted from Step 1. If the Actual Weight lifted is greater than the Weight Limit calculated, then the lifting is a WMSD hazard.

Note: If the job involves lifts of objects with a number of different weights and/or from a number of different locations, use Steps 1 through 5 above to:
1. Analyze the two worst case lifts – the heaviest object lifted and the lift done in the most awkward posture.
2. Analyze the most commonly performed lift. In Step 3, use the frequency and duration for all of the lifting done in a typical

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Figure 4 WISHA lifting analysis

2.4.2 Biomechanical modeling

The first biomechanical model, based on interconnected links, was developed by Braune and Fischer in 1889. Whitsett (1962) shows in the figure below how the complex three-dimensional shape of the human body can be approximated by simple geometric structures.

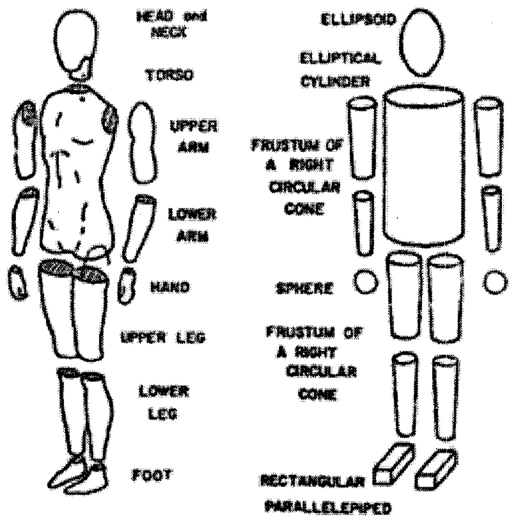


Figure 5 Human body segments and models (Whitsett, 1962)

Chaffin (1969) developed a seven link two dimensional model to calculate joint forces and moments. This model was later extended for three dimensional static strength prediction (3DSSPP) (Chaffin, 1977). 3DSSPP can be used to predict the posture, given the location of the hands relative to the feet and the loading of the hands. It also calculates various muscle forces and joint loads. A limitation is that 3DSSPP can only be used for static analysis.

CATIA is a software package that is used extensively for design in especially aerospace and automotive industries. It has an ergonomic module that can be used to evaluate, for example, if an operator can reach certain controls. This module also allows for biomechanical analyses.

Today biomechanical modeling and movement simulation plays an important role in studying the kinematics and dynamics of the body. LifeMOD is one of the programs that can be used for this. It requires specific joint coordinate data as input. This means that a 3D motion capture system must be used to obtain the required 3D joint coordinates while a subject performs the activity that needs to be analyzed. LifeMOD uses this coordinate information together with anthropometric data to perform kinematic and dynamic analyses of the body.

In this research, LifeMOD, 3DSSPP and CATIA are used to analyze selected lifting tasks during manual paper recycling. The following chapter describes these tasks, as well as the motion capture system used to obtain the 3D joint coordinates.

3 Analysis of selected lifting tasks during manual paper recycling

In this chapter, different methods used to study the garbage-collecting job in lifting are discussed. As the loads, size and weight vary over a wide range in this task, collecting paper from blue recycling box by using large mobile bins for emptying chose. By knowing the containers size and material weight, the box weight, size, and destination level estimate to define the task.

3.1 Garbage weight and volume in recycling

Regular garbage containers have different weight depending on material and container volume. The weight normally varies from 10 to 22 kg in domestic sites but can weigh as much as 30 kg when completely filled. The volume of garbage containers that need to be emptied manually is typically 100 liters or less.

Usually, in residential use, there is no compact packing in containers. The restriction for using blue recycling boxes is that they must not hold more that 18 kg with recyclable materials for manual garbage collecting.

The study presented here uses recycling containers commonly used at Concordia. They are a blue recycling box, 51 x 38 x 34 (cm), used for paper recycling, a storage box, 39 x 31 x 24 (cm), used to file/store papers, and a wheeled mobile dumpster, about 1100 liters capacity, with a height of 113 cm when the lid is open. These containers are shown in the figure below.

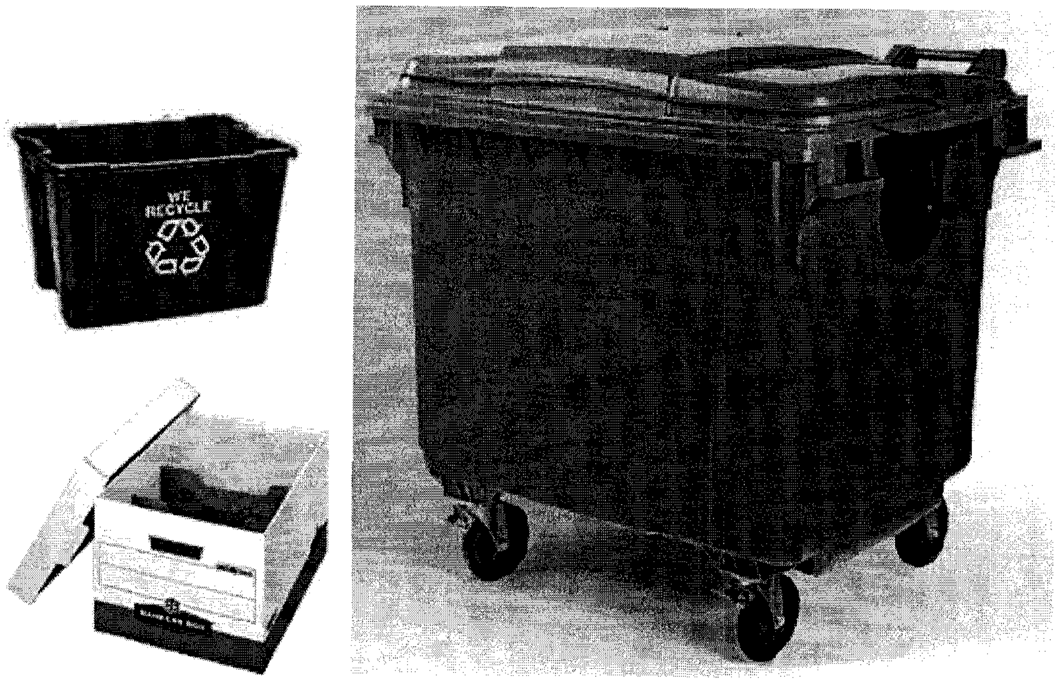


Figure 6 Blue recycling box, storage box and wheeled mobile dumpster

3.2 Methodology

Two sets of experiments were performed. One whereby a female subject of average height lifted, and then lowered, an empty storage box, weighing 2 N, and a storage box filled with papers, weighing 60 N, from ground level to waist level and from ground level to shoulder level. Two different lifting techniques were used: knee lifting and hip lifting. This task was analyzed using ergonomic checklists as well as biomechanical analyses under quasi-static and dynamic conditions, focusing on the loading of the back and shoulders. In the second set of experiments male subjects of average height lifted, and then lowered, a recycling box weighing 130 N from ground level to a height of 113 cm. This task too was analyzed using ergonomic checklists, while the biomechanical analysis focused on kinematic analysis. All lifts were carried out using symmetric, two handed lifting.

The ergonomic checklists can be filled out easily through observation of the task together with some basic measurements, such as hand location at the origin and end of the lifting task. For the biomechanical analyses, however, more detailed information of the posture during the lifting task is required. A motion capture system, acquired in winter 2008, was used to obtain 3D coordinates of selected body marker positions as a function of time while the subject performed the lifting task.

The following sections in the chapter describe the ergonomic checklists used for the analysis, give a description of the motion capture system used and the procedure followed to obtain the necessary data, and describe the biomechanical analyses programs used. Results and discussions are presented in the following chapter.

3.3 Analysis using ergonomic checklists

Ergonomic checklists can be used for a rapid evaluation of hazard factors in the work place. They help employers and employees to recognize ergonomic problems in the job. The checklists can also be used to evaluate any change in hazard level if a certain task is performed in another way or learn to apply the ergonomic aspects in their job.

There are many different quick checklists that can be used to verify the job hazard level. WISHA, REBA, Liberty Mutual tables and the NIOSH lifting equation are some of the most popular ones.

3.3.1 WISHA checklist

The WISHA checklist for work related musculoskeletal disorders was developed by the Washington State Department of Labor and Industries. It is shown in Figures 7 and 8.

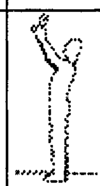
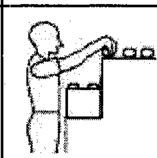
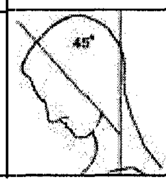
WISHA Checklist for Work-Related Musculoskeletal Disorders 1

Job Lifting task	Date 10/04/2008
Notes lifting paper recycling box -full shift	Analyst(s) Saba Pasha

Reading across the page, determine if any of the conditions are present in the work activities. For many of the risk factors, two conditions are presented, which are the indicators for Caution (a lower level of risk) and Hazard (a higher level of risk). Most of the conditions are based on duration. If the lower threshold condition is not met, no box is checked. If the lower condition is met but the higher is not, then Caution is checked. If the higher condition is met (generally a longer period of time), then Hazard is checked.

If only Caution boxes are checked, the risk is present but immediate action (further analysis or interventions) are not recommended. It is worthwhile to continue to monitor Caution level jobs for changes that might increase the risk and for injuries or symptoms that may occur.

If one or more Hazard boxes are checked, a work-related musculoskeletal disorder (WMSD) hazard exists, and further action is recommended.

Awkward Posture				Check (✓) as applicable
Body Part	Physical Risk Factor	Duration	Visual Aid	
Shoulders	Working with the hand(s) above the head or the elbow(s) above the shoulder(s)	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐
	Repetitively raising the hand(s) above the head or the elbow(s) above the shoulder(s) more than once per minute	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐
Neck	Working with the neck bent more than 45° (without support or the ability to vary posture)	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐

Adapted from State of Washington Department of Labor and Industries Ergonomics Rule
See http://www.lni.wa.gov/wisha/ergo/ergorule.htm
This version includes some format changes, inclusion of caution zones and revisions to lifting and vibration sections. See http://www.hsc.usf.edu/~tbernard/ergotools for electronic copy of form.

Figure 7 WISHA checklist for musculoskeletal disorders

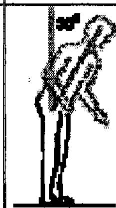
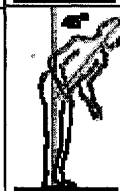
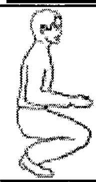
Awkward Posture (continued)				Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Duration**	**Visual Aid**	
Back	Working with the back bent forward more than 30° (without support, or the ability to vary posture)	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐
	Working with the back bent forward more than 45° (without support or the ability to vary posture)	More than 2 hours total per day		Hazard ☐
Knees	Squatting	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐
	Kneeling	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐

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Figure 7 WISHA checklist for musculoskeletal disorders (cont.)

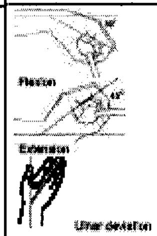
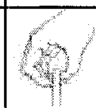
High Hand Force – Pinch					Check (✓) as applicable
Body Part	Physical Risk Factor	Combined with	Duration	Visual Aid	
Arms, wrists, hands	Pinching an unsupported object(s) weighing 2 or more pounds per hand, or pinching with a force of 4 or more pounds per hand (comparable to pinching half a ream of paper)	Highly repetitive motion	More than 3 hours total per day		Hazard ☐
		Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 3 hours total per day		Hazard ☐
		No other risk factors	More than 2 hours total per day		Caution ☐
			More than 4 hours total per day		Hazard ☐

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Figure 7 WISHA checklist for musculoskeletal disorders (cont.)

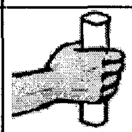
High Hand Force – Grasp					Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Combined with**	**Duration**	**Visual Aid**	
Arms, wrists, hands	Gripping an unsupported object(s) weighing 10 or more pounds per hand, or gripping with a force of 10 pounds or more per hand (comparable to clamping light duty automotive jumper cables onto a battery)	Highly repetitive motion	More than 3 hours total per day		Hazard ☐
		Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 3 hours total per day		Hazard ☐
		No other risk factors	More than 2 hours total per day More than 4 hours total per day		Caution ☐ Hazard ☐

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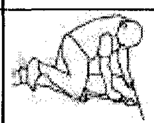
Figure 7 WISHA checklist for musculoskeletal disorders (cont.)

WISHA Checklist for Work-Related Musculoskeletal Disorders 5

Highly Repetitive Motion				Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Combined with**	**Duration**	
Neck, shoulders, elbows, wrists, hands	Using the same motion with little or no variation every few seconds (excluding keying activities)	No other risk factors	More than 2 hours total per day	Caution ☐
			More than 6 hours total per day	Hazard ☐
	Using the same motion with little or no variation every few seconds (excluding keying activities)	Wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more **AND** High, forceful exertions with the hand(s)	More than 2 hours total per day	Hazard ☐
	Intensive keying	Awkward posture, including wrists bent in flexion 30° or more, or in extension 45° or more, or in ulnar deviation 30° or more	More than 4 hours total per day	Hazard ☐
		No other risk factors	More than 4 hours total per day	Caution ☐
			More than 7 hours total per day	Hazard ☐

Repeated Impact				Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Duration**	**Visual Aid**	
Hands	Using the hand (heel/base of palm) as a hammer more than 10 times per hr	More than 2 hours total per day		Caution ☐
	Using the hand (heel/base of palm) as a hammer more than 60 times per hr			Hazard ☐
Knees	Using the knee as a hammer more than 10 times per hour	More than 2 hours total per day		Caution ☐
	Using the knee as a hammer more than 60 times per hour			Hazard ☐

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See http://www.lni.wa.gov/wisha/ergo/ergorule.htm
This version includes some format changes, inclusion of caution zones and revisions to lifting and vibration sections. See http://www.hsc.usf.edu/~tbernard/ergotools for electronic copy of form.

Figure 7 WISHA checklist for musculoskeletal disorders (cont.)

Heavy, Frequent or Awkward Lifting				Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Combined with**	**Duration**	
Back and shoulders	Lifting 75 or more pounds	No other risk factors	One or more times per day	Caution ☐
	Lifting 55 or more pounds	No other risk factors	More than 10 times per day	Caution ☐
	Lifting more than 10 pounds	More than 2 times per minute	More than 2 hours total per day	Caution ☐
	Lifting more than 25 pounds	Above the shoulders Below the knees At arm's length	More than 25 times per day	Caution ☐
	WISHA Lifting Analysis – Perform if any Caution condition exists. Actual Weight is greater than the Weight Limit (See separate work sheet)			Hazard ☐

Moderate to High Hand-Arm Vibration			Check (✓) as applicable
Body Part	**Physical Risk Factor**	**Duration**	
Hands, wrists, and elbows	Using impact wrenches, carpet strippers, chain saws, percussive tools (jack hammers, scalers, riveting or chipping hammers) or other hand tools that typically have high vibration levels	More than 30 minutes total per day	Caution ☐
	Using grinders, sanders, jig saws or other hand tools that typically have moderate vibration levels	More than 2 hours total per day	Caution ☐
	WISHA HAV Analysis – Perform if any Caution condition exists. Actual exposure time is greater than the Hazard Level Exposure Time (See separate work sheet)		Hazard ☐

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See http://www.lni.wa.gov/wisha/ergo/ergorule.htm
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Figure 7 WISHA checklist for musculoskeletal disorders (cont.)

WISHA Lifting Analysis 1

Job Lifting recycling box	Date 10/04/2008
Notes lifting paper recycling box -full time shift	Analyst(s) Saba Pasha

The lifting analysis on the following page is performed when one or more of the Caution Level job risk factors in the following checklist is present. This checklist is taken from the adapted WISHA checklist.

Heavy, Frequent or Awkward Lifting				Check (✓) as applicable
Body Part	Physical Risk Factor	Combined with	Duration	
Back and shoulders	Lifting 75 or more pounds	No other risk factors	One or more times per day	Caution ❑
	Lifting 55 or more pounds	No other risk factors	More than 10 times per day	Caution ❑
	Lifting more than 10 pounds	More than 2 times per minute	More than 2 hours total per day	Caution ❑
	Lifting more than 25 pounds	Above the shoulders Below the knees At arm's length	More than 25 times per day	Caution ❑
	WISHA Lifting Analysis – Perform if any Caution condition exists. Actual Weight (Step 1) is greater than the Weight Limit (Step 4) (See separate work sheet)			Hazard ❑

Adapted from State of Washington Department of Labor and Industries Ergonomics Rule
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This version focuses on the lifting section. See www.hsc.usf.edu/~tbernard/ergotools for electronic copy of form.

Figure 8 WISHA lifting analysis

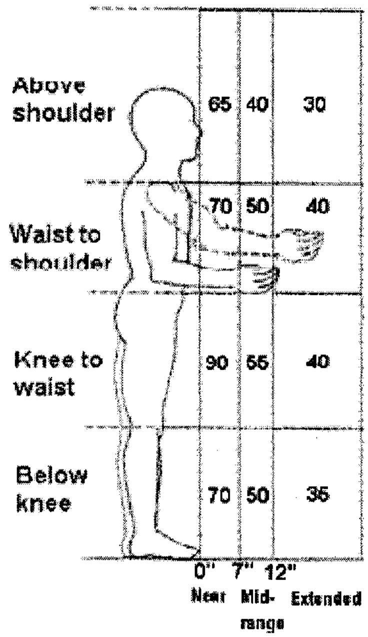
WISHA Lifting Analysis 2

This analysis pertains to jobs where employees lift 10 lbs. or more.

Step 1 **Find out the actual weight of objects that the employee lifts.**

Actual Weight = ________ lbs.

Step 2 **Determine the Unadjusted Weight Limit.** Where are the employee's hands when they begin to lift or lower the object? Mark that spot on the diagram below. The number in that box is the Unadjusted Weight Limit in pounds.



Unadjusted Weight Limit: _______ lbs.

Step 3 **Find the Limit Reduction Modifier.** Find out how many times the employee lifts per minute and the total number of hours per day spent lifting. Use this information to look up the Limit Reduction Modifier in the table below.

How many lifts per minute?	For how many hours per day? 1 hr or less	1 hr to 2 hrs	2 hrs or more
1 lift every 2-5 mins.	1.0	0.95	0.85
1 lift every min	0.95	0.9	0.75
2-3 lifts every min	0.9	0.85	0.65
4-5 lifts every min	0.85	0.7	0.45
6-7 lifts every min	0.75	0.5	0.25
8-9 lifts every min	0.6	0.35	0.15
10+ lifts every min	0.3	0.2	0.0

Note: For lifting done less than once every five minutes, use 1.0

Limit Reduction Modifier: ____.______

Step 4 **Calculate the Weight Limit.** Start by copying the Unadjusted Weight Limit from Step 2.

Unadjusted Weight Limit: = ______ lbs.

If the employee twists more than 45 degrees while lifting, reduce the Unadjusted Weight Limit by multiplying by 0.85. Otherwise, use the Unadjusted Weight Limit

Twisting Adjustment: = _____.____

Adjusted Weight Limit: = ______ lbs.

Multiply the Adjusted Weight Limit by the Limit Reduction Modifier from Step 3 to get the Weight Limit. **X**

Limit Reduction Modifier: _____.___

Weight Limit: = _____ lbs.

Step 5 **Is this a hazard?** Compare the Weight Limit calculated in Step 4 with the Actual Weight lifted from Step 1. If the Actual Weight lifted is greater than the Weight Limit calculated, then the lifting is a WMSD hazard.

Note: If the job involves lifts of objects with a number of different weights and/or from a number of different locations, use Steps 1 through 5 above to:

1. Analyze the two worst case lifts – the heaviest object lifted and the lift done in the most awkward posture.
2. Analyze the most commonly performed lift. In Step 3, use the frequency and duration for all of the lifting done in a typical

Adapted from State of Washington Department of Labor and Industries Ergonomics Rule
See http://www.lni.wa.gov/wisha/ergo/ergorule.htm
This version focuses on the lifting section. See www.hsc.usf.edu/~tbernard/ergotools for electronic copy of form.

Figure 8 WISHA lifting analysis (cont.)

Table 8 shows the result for lifting a 60 N box from the ground, 7" in front of the body, to above shoulder level, 7" in front of the body and lifting a 130 N load, 7" in front of the body, to between knuckle and shoulder height, 12" in front of the body. The task is considered as infrequent and symmetric lifting. Only the starting and ending positions are analyzed.

Table 8 WISHA lifting analysis

Analysis steps	60 N		130 N	
	Start	End	Start	End
Step1: Actual weight	13 lb	13 lb	30 lb	30 lb
Step2: Unadjusted weight limit	70	40	70	40
Step3: Limit reduction modifier	1	1	1	1
Step4: Weight limit	70	40	70	40
Step5: Is this a hazard	No	No	No	No

As the results show, the WISHA lifting analysis determines no hazard condition for these certain lifting tasks. If the lifting is 1 lift/minute for 2 hours or more the limit reduction modifier is 0.75 and the weight limit of 40 changes to 30 lb, which is still considered no hazard. The WISHA lifting analysis does not take into account body posture. Destination, origin and actual weights are the most important factors. The same conclusion can be drawn from the Heavy, Frequent or Awkward lifting section of the WISHA checklist.

3.3.2 REBA worksheet

The Rapid Entire Body Analysis (REBA) employee assessment worksheet was developed by Hignett and McAtamney in 2000. It takes into account the postures of the neck, trunk and legs to calculate a trunk posture score, the posture of the arms and wrists to calculate an upper arm score as well as force, coupling and activity score to determine the REBA score. The higher the REBA score the higher the risk. The REBA worksheet is shown in the following figure.

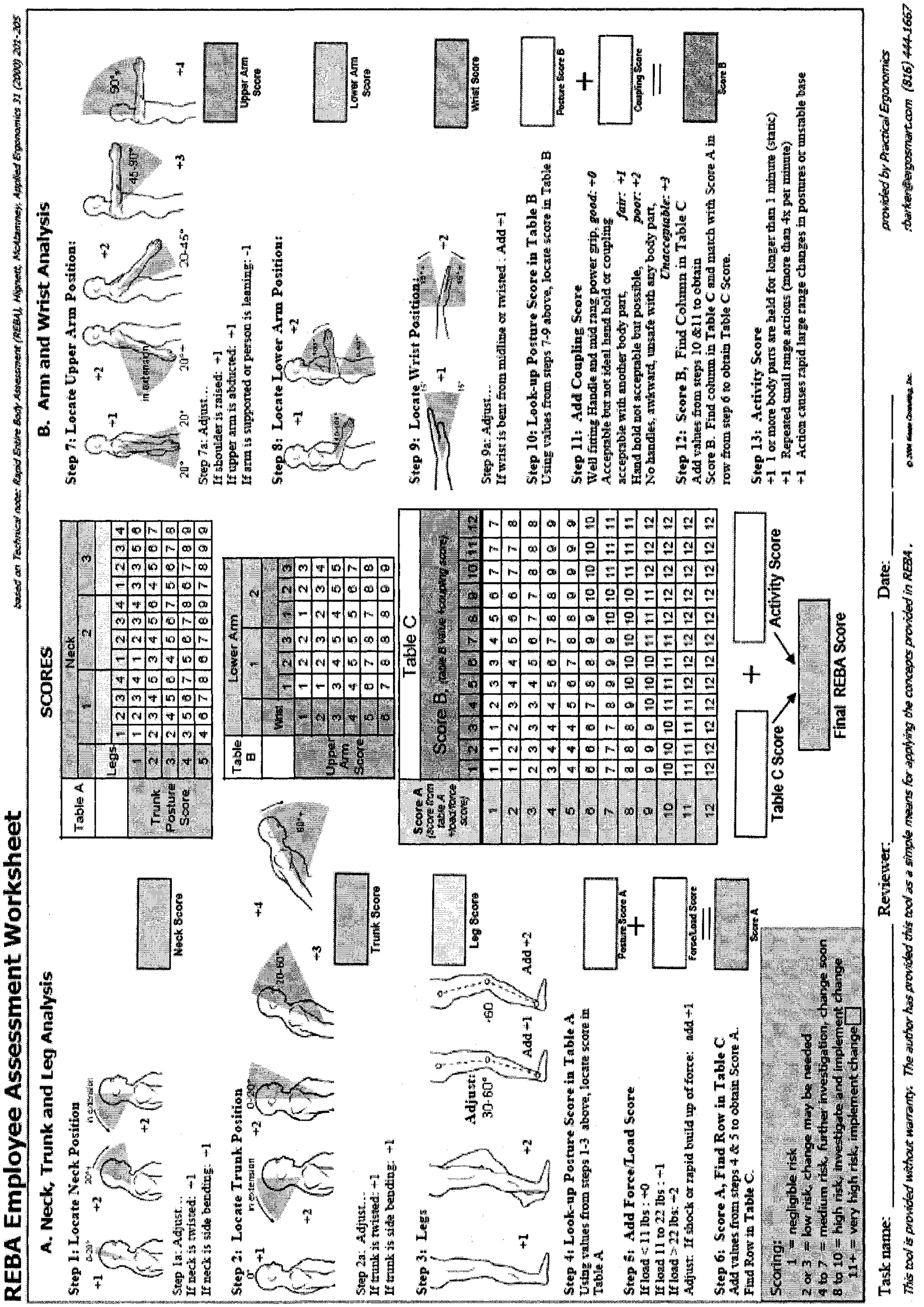


Figure 9 REBA employee assessment worksheet

The various angles that are used in the REBA analysis were determined based upon visual observation. During all lifting tasks the head remains more or less neutral relative to the trunk. When picking up the box, the trunk is almost horizontal and the legs straight during hip-lifting, while the trunk is in the 20-60° range and the knees completely bent during knee lifting. Leg flexion in knee joint is more than 60 degrees in knee lifting but straight knee for hip lifting method. In the ending position trunk and legs are about vertical.

The knee lifting and hip lifting tasks analyzed. Forearm, upper arm and wrist position for upper limb analysis and leg flexion for lower limb studied. Depending on the bin height and the performer anthropometrics data, arm flexion angle changes. For a mobile garbage collecting bin, upper arm flexion is between 20-45 degrees and forearm position is between 60-100 degrees from vertical position. Wrist flexion is in the range of ±15 degrees in frontal plane in the ergonomic posture.

Finding the scores in tables A, B and C result the final scores. Table 9 shows the scores for the knee lifting and hip lifting methods with a 60 N hand load picking up the box at ground level and ending just above shoulder level, and for lifting a 130 N load using the knee lifting method applied from ground level to between knuckle and shoulder height.

Table 9 REBA analysis

Analysis steps	60 N			130 N, knee lifting	
	Start, knee lifting	Start, hip lifting	End	Start	End
Step 1: neck score	2	2	1	2	1
Step 2: trunk score	3	4	1	3	1
Step 3: leg score	3	1	1	3	1
Step 4: table A score	6	5	1	6	1
Step 5: load score	1	1	1	2	2
Step 6: score A	7	6	2	8	3
Step 7: upper arm score	2	1	4	2	3
Step 8: lower arm score	2	2	2	2	2
Step 9: wrist score	2	1	2	2	2
Step 10: table B score	3	1	6	3	5
Step 11: coupling score	0	0	0	0	0
Step 12: score B	3	1	6	3	5
Step 13: activity score	1	1	1	1	1
Table C score	7	6	4	8	2
REBA score	8	7	5	9	3
risk	high	medium	medium	high	low

The REBA analysis shows that the risk at the start is always higher than at the end of the lift. The knee-lifting and hip lifting methods at the starting posture have a high risk and the lifting task should be changed. Also the weight increases at the second task but ending posture for lifting the 130 N load has lower risk because of lower destination level.

3.3.3 Library Mutual manual material handling tables

The Liberty Mutual checklists (Liberty Mutual, 2008) are used to determine what percentage of the male or female working population can perform a manual material handling task. Tables are defined based on the task characteristics as lifting, lowering, carrying, pulling and pushing, with separate tables for males and females. To analyze a lifting task, one must first determine where the lift ends, e.g. between knuckle and shoulder height or above shoulder height. Next the distance of the hands in front of the body, the object weight and the vertical distance travelled must be determined. Finally, the frequency of lift must be specified. The average female is lifting a 60 N (13 lb) storage box to an ending position above the shoulders. The average male is lifting a 130 N (30 lb) recycling box to a level just below the shoulders. The Liberty Mutual tables for lifting do not list object weight of 13 lb for females and 30 lb for males, so values of 14 lb and 32 lb respectively are used. The table below shows an extract of the Liberty Mutual tables for these values.

Liberty Mutual Manual Materials Handling Guidelines

TABLE 2M - MALE POPULATION PERCENTAGES FOR LIFTING TASKS

ENDING BETWEEN KNUCKLE AND SHOULDER HEIGHT (≥31" AND ≤57")

		HAND DISTANCE	7 INCHES					10 INCHES					15 INCHES				
		FREQUENCY ONE LIFT EVERY	15s	30 s	1m	5m	8h	15s	30 s	1m	5m	8h	15s	30 s	1m	5m	8h
Object weight	32	D 30	84	87	+	+	+	77	81	86	88	+	53	60	70	74	87
		20	87	+	+	+	+	81	85	+	+	+	61	69	79	83	+
		10	+	+	+	+	+	89	+	+	+	+	75	82	88	+	+

Liberty Mutual Manual Materials Handling Guidelines

TABLE 3F - FEMALE POPULATION PERCENTAGES FOR LIFTING TASKS

ENDING ABOVE SHOULDER HEIGHT (>53")

		HAND DISTANCE	7 INCHES					10 INCHES					15 INCHES				
		FREQUENCY ONE LIFT EVERY	15s	30 s	1m	5m	8h	15s	30 s	1m	5m	8h	15s	30 s	1m	5m	8h
object weight	14	D 30	83	86	+	+	+	73	78	86	+	+	42	50	64	73	+
		20	+	+	+	+	+	86	88	+	+	+	66	70	76	82	+
		10	+	+	+	+	+	86	+	+	+	+	66	73	83	88	+

Figure 10 Liberty Mutual manual materials handling guidelines for specified task

If the lifts occur once every 5 min or less frequently and the hand distance is 10" or less 100% of the female population is able to perform this task. If the hand distance is 15", and taking the maximum travel of 30", 73% of the female population can perform this task. The same conclusions can be drawn for the male subjects lifting the higher weight, except that 74% of the male population can perform the lifting task at 1 lift per 5 min and a hand location of 15".

Table 10 Liberty Mutual analysis

	Female	Male
Object weight (Pounds)	14	32
Lifting distance (inches)	30	30
Hand distance (inches)	15	15
Frequency (one lift every)	5 min	5 min
Population capable (percentile)	73	74

3.3.4 NIOSH lifting equation

The NIOSH Work Practices Guide for Manual Lifting was first published in 1981 and revised in 1994. (NIOSH, Applications Manual For the Revised NIOSH Lifting Equation, 1994) The NIOSH lifting equation uses object weight (L), hand location at origin and destination (H and V), total vertical load translation (D), asymmetric twisting of the back (A), frequency, duration and object coupling with the hands to calculate the recommended weight limit (RWL) for a lifting task. The lifting index (LI) is evaluated by dividing the original weight (L) by RWL. The lifting index is calculated separately at the origin and the destination. For RWL higher than 1, more caution is needed.

The NIOSH lifting equation can be expressed as follows:

RWL= LC*HM*VM*DM*AM*FM*CMand LI = L/RWL

where LC is the load constant (23 kg), HM is the horizontal multiplier, VM is the vertical multiplier, DM is the distance multiplier, AM is the asymmetry multiplier, FM is the frequency multiplier and CM is the coupling multiplier. All multipliers have values between 0 and 1. In the case of infrequent lifting FM = 1. Since the storage box and the recycling box have good handles, CM = 1. The table below evaluates the multipliers and calculates the lifting index for the case where an average female lifts the 60 N storage box and an average male lifts the 130 N recycling box. Note that H is the horizontal distance in front of the ankles.

Table 11 NIOSH lifting analysis

	Start	End	Start	End
L, kg	6	6	13	13
H, cm	35	35	35	70
V, cm	20	150	27	140
$D = V_{end} - V_{start}$, cm	130		113	
A, degrees	0	0	0	0
LC, kg	23	23	23	23
HM = 25/H	0.71	0.71	0.71	0.36
VM = 1 – 0.003|V–75|	0.84	0.78	0.86	0.81
DM = 0.82 + 4.5/D	0.85	0.85	0.85	0.85
AM = 1 – 0.0032A	1	1	1	1
FM	1	1	1	1
CM	1	1	1	1
RWL	11.65	10.82	11.94	5.70
LI = L/RWL	0.52	0.55	1.09	2.28

As can be seen in the table, only the ending position of the 130 N lift is cause for concern, mostly because of the long forward reach at that point. The NIOSH lifting formula presents the same results for knee lifting and hip lifting because all the factors remain the same. That is a drawback when using the NIOSH method for different methods of lifting because it does not consider body posture; only hand locations at the start and the end.

3.3.5 Comparison of the checklists results

Four checklists were used to evaluate the lifting of a 60 N storage box above the shoulder level by an average height female and a 130 N recycling box between shoulder and knuckle by average height males. The table below summarizes the results:

Table 12 Checklist comparison

	60 N load, female			130 N load, male	
	Start, knee lifting	Start, hip lifting	End	Start	End
WISHA	OK	OK	OK	OK	OK
REBA	High risk	Medium risk	Medium risk	High risk	Low risk
Liberty Mutual	Acceptable for 73% of female workers			Acceptable for 74% of male workers	
NIOSH	OK		OK	OK	Caution

Above table shows that the ergonomic checklists give very different results. The NIOSH and WISHA lifting analyses show that there are no problems. This is also confirmed by the Liberty Mutual analysis, which indicates that about three quarters of the workers can perform the specific lifting task. The REBA analysis, on the other hand, shows medium or high risk for most cases. This is because REBA puts a lot of emphasis on the posture.

The following table shows the differences between these checklists and compares the sensitivity level for different worksheets.

Table 13 Checklists comparison table

sensitivity	**Gender**	**Population**	**Posture**	**Task frequency**	**Weight**
WISHA	poor	poor	good	good	excellent
REBA	poor	poor	excellent	good	good
Liberty Mutual	excellent	excellent	poor	good	good
NIOSH	poor	poor	poor	excellent	excellent

3.4 Biomechanical Analyses

A number of different software packages were used to do a biomechanical analysis of the experiments performed. LifeMOD allows for a dynamic analysis and is used to determine the lumbar loading and shoulder load while an average female lifts 2 or 60 N using the knee or hip lifting method. LifeMOD also calculates joint angles as a function of time during the lifting activity. These joint angles are used as input to

3DSSPP (3D Static Strength Prediction Program) and CATIA to do a quasi-static load analysis at the start and the end of the lift. In order to do an analysis in LifeMOD the 3D coordinates of specific body markers needs to be supplied. An OptiTrack system, acquired in winter 2008, was used to capture these data. The following section describes the motion capture using this system. The sections thereafter present and discuss the results of the analysis using LifeMOD, 3DSSPP and CATIA. In the final section LifeMOD is used to do a kinematic analysis of average males lifting a 130 N recycling box.

3.4.1 Motion capture using the OptiTrack system

The OptiTrack system, acquired in winter 2008, can be used to obtain 3D coordinates of body markers from a subject while the subject performing a certain task. The cameras are synchronized and collect data at the rate of 100 frames per second. The following figure shows a typical experiment set up, cameras and connections, a subject in a body suit with markers and a recycling box used as the weight during the experiment. The frame in the picture indicates the height that the box must be lifted. The following figure shows the set up.

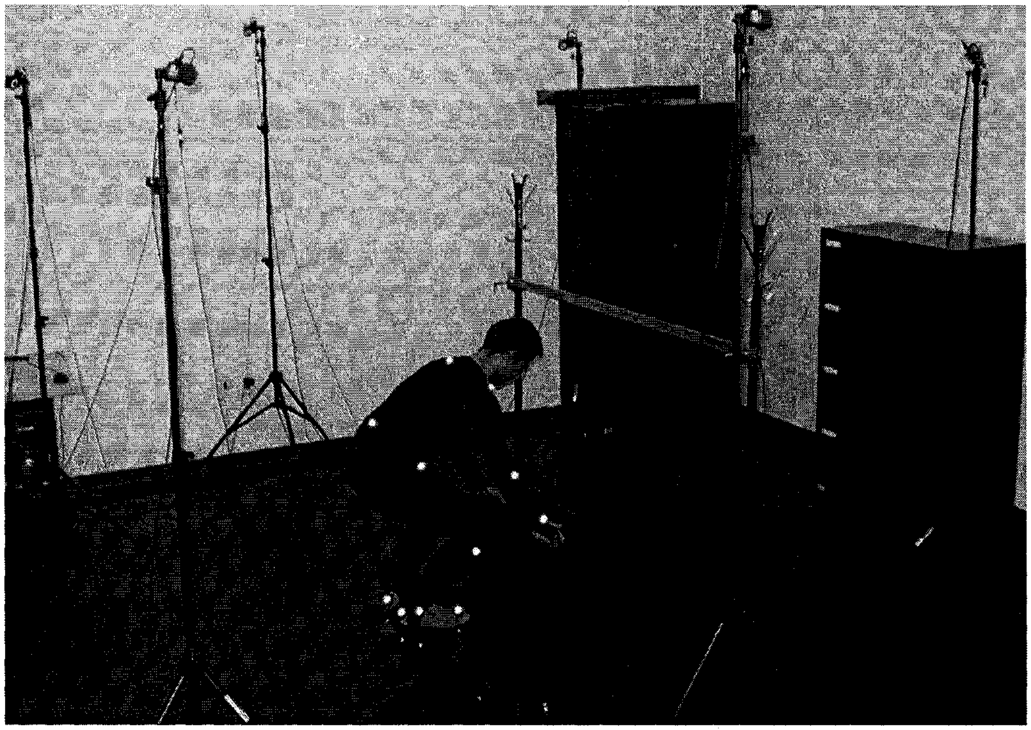


Figure 11 Experiment set up

Following figure presents a close-up of an OptiTrack camera, a 1.5" Velcro base with a 7/16" spherical reflective marker, and the calibration wand and calibration square.

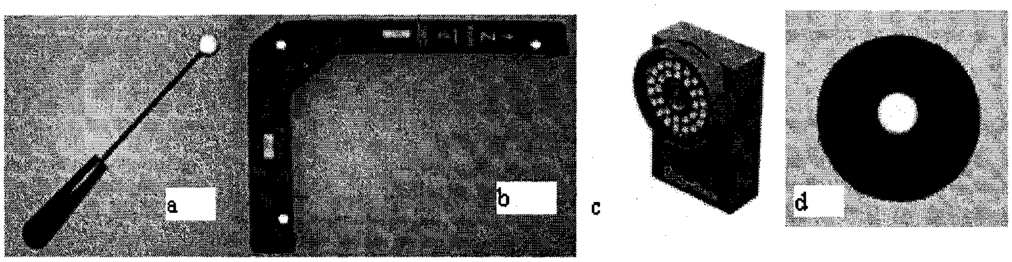


Figure 12 Calibration devices

a-Calibration wand, b- Calibration square,
c- OptiTrack camera, d- Marker with Velcro base

Description of the experimental setup

At least three cameras are necessary to obtain the 3D coordinates of a marker. Because markers are placed on the front, the back, the left side and the right side of the subject a total of six cameras is used. The six cameras are located in a rectangular area, 510 by 420 cm, to create the work space. Their height, orientation and tilt angle are selected such that the work volume contains all the markers during the lifting task. As can be seen in figure 11 the cameras are placed on tall tripods which vary in height from 195 cm for the back and front cameras to 230 cm for side cameras. Because the cameras have a wider field of view (FOV) in the horizontal than in the vertical position, the horizontal position is used for the motion capture. The camera head tilt angle chooses depends on the camera location and the area that is supposed to cover. This angle varies from 30 to 50 degrees depending on the camera. The cameras are connected by external synchronizing cables in such a way that the output (sync out) of the first camera connects to the input (sync in) of the second camera and so on. Note that no connection is made from the last one back to the first one. The connection between each camera and the computer is by a USB cable via a standard USB hub.

System Calibration

After the cameras have been positioned and all the connections have been made, the cameras must be calibrated to be ready for motion capturing. The OptiTrack point cloud calibration software is run to calibrate the cameras. There are two steps to calibrate the cameras. In the first step the calibration wand (see figure 12) is moved around to define the work volume. The wand should move in along the path at a medium speed to cover all the performance area. In the next step the calibration square is placed on the ground, making sure the square is level, to define the coordinate system.

Procedure for data collection

First the subject must put on the black body suit. Next reflective markers are attached to the suit through Velcro bases. For the lifting experiments carried out as part of this research 18 marker positions were chosen to define the movement as follows: shoulders, elbows, wrists, T4, L5, hips (actually ASIS), knees, ankles, heels and the first metatarsal joints provide this set of markers.

The OptiTrack rigid body software monitors the marker movement as bright dots on the screen. The following figure shows the screen output and the subject in the standing position with 18 markers.

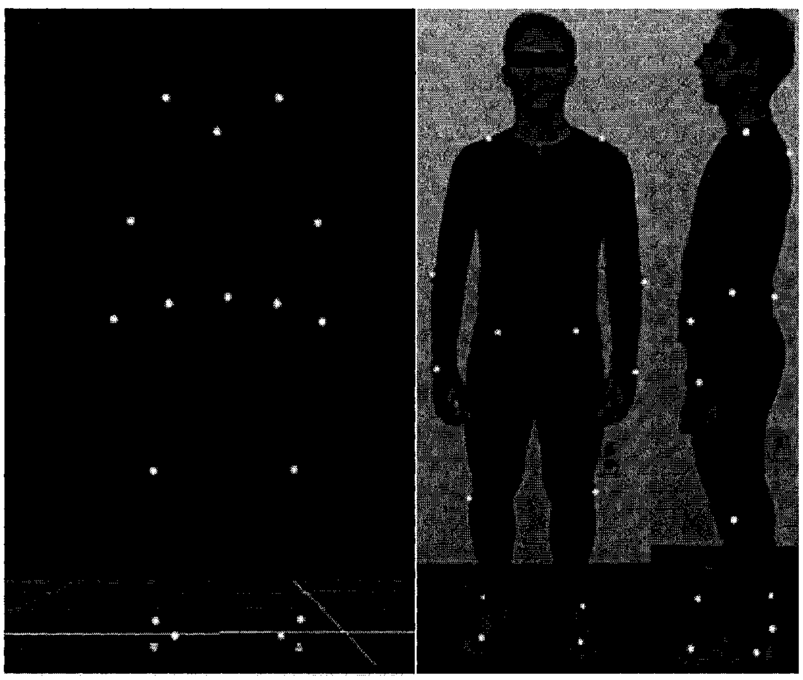


Figure 13 Subject with 18 markers

During data capture problems may arise. These include losing markers or observing extra markers. An extra marker may appear because the cameras may pick up the reflection of an object other than one of the 18 markers in the screen. Covering these reflective points can help to get better results. Sometimes poor calibration provides extra shiny points in the screen. In this case recalibrating the cameras is the solution.

Losing markers is another problem. Markers may be covered by the recycling box, bar or other body parts or two markers may overlap and thus seen as one. Rearranging the cameras can help get better results, though this also requires recalibration. In some cases, the cameras are not able to get all the markers during the task even by changing the camera position. In this case, the spline interpolation in MATLAB is applied to obtain good estimates for the X, Y and Z coordinates of the lost marker. Three interpolations need to be applied for each lost marker, namely between time or frame number and X and Y and Z coordinate separately.

After data collection, the marker coordinates can be output using the comma separated format. However, there is no guarantee that the markers appear in the same order from one frame to the next. Because the cameras sample at 100 Hz and the movements are relatively slow, there is little change in marker coordinates from one frame to the next. To get these data in order, a code used in the MATLAB to compare the x, y and z coordinates in sequential frames for a single marker. Depending on the movement speed, a number of the order of 0.1 is chosen as the maximum allowable difference of the coordinates of a single marker coordinates in two sequence frame. If the markers are not in the same order, the difference is usually much larger than 0.1 and the marker order must be switched.

Real time tracking of the subject is one of the advantages of this equipment. The recorded movement can be saved and played back frame by frame and unnecessary frames can be deleted. Markers attachments do not cause any limitation on object movement and the task can be done in a natural way. The possibility of replaying the motion in the software can help to define and verify the movement.

3.4.2 Biomechanical analysis using LifeMOD

To do a biomechanical analysis in LifeMOD, it requires as input 3D coordinate data of specific body markers as a function of time. For the lifting experiments carried out as part of this research, 18 marker positions were chosen, namely: shoulders, elbows, wrists, T4, L5, hips (actually ASIS), knees, ankles, heels and the first metatarsal joints provide this set of markers, as discussed in the previous section. The OptiTrack package (cameras and software) was used to record the body movement during the lifting tasks and obtain the required marker/joint coordinates. Two methods for load lifting were studied: knee lifting and hip lifting and for each two sets of hand loads, 2 and 60 N, were studied, and two destination levels, waist level and above shoulder level. The lifting occurred in the sagittal plane and the total hand load was divided equally over the two hands. The study can be categorized in four groups:

Results A: Knee lifting destination waist level, 2 N and 60 N hand load.

Results B: Hip lifting, destination at waist level, 2 N and 60 N hand load.

Results C: Knee lifting, destination above shoulders, 2 N and 60 N hand load.

Results D: Hip lifting, destination above the shoulders, 2 N and 60 N hand load.

Dolan et al. (1994) showed that the greatest peak in back muscle activity during the lifting task occurs when the person picks up the weight. The current research studies the lumbar compression force and torques, as well as shoulder torques. All the graphs show high error values and many unrealistic peaks especially at the end of the task, which is performed at a higher speed compared to the rest of the task. The following sections present the LifeMOD results. During the first part of each graph the subject bends down from a standing position. The vertical line plotted in the figure shows the moment that the box is picked up. This picking up time was derived by running the animation in the LifeMOD software. The value immediately after this line is the time when the lumbar force and torques or the shoulder torques were evaluated.

Results A: Knee lifting method, floor to waist level

The knee lifting method with waist destination has been modeled in this section. Two different hand loads are used. A 2 N hand load is used as a light load for lifting and 60 N is chosen to represent heavy hand loading.

Knee lifting, floor to waist level for 2 N hand load

Compression force, lumbar moments in all planes and shoulder torques are shown in the following graphs. The picking up happens at 2.3 seconds, indicated by the vertical line.

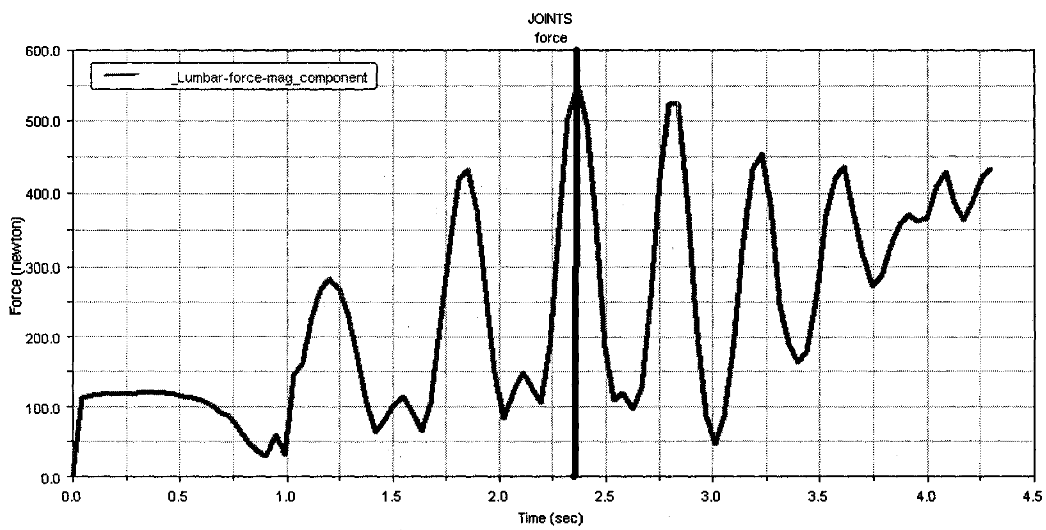


Figure 14 Lumbar compression force-knee lifting method, 2 N hand load

The next plot shows the lumbar torques in three planes.

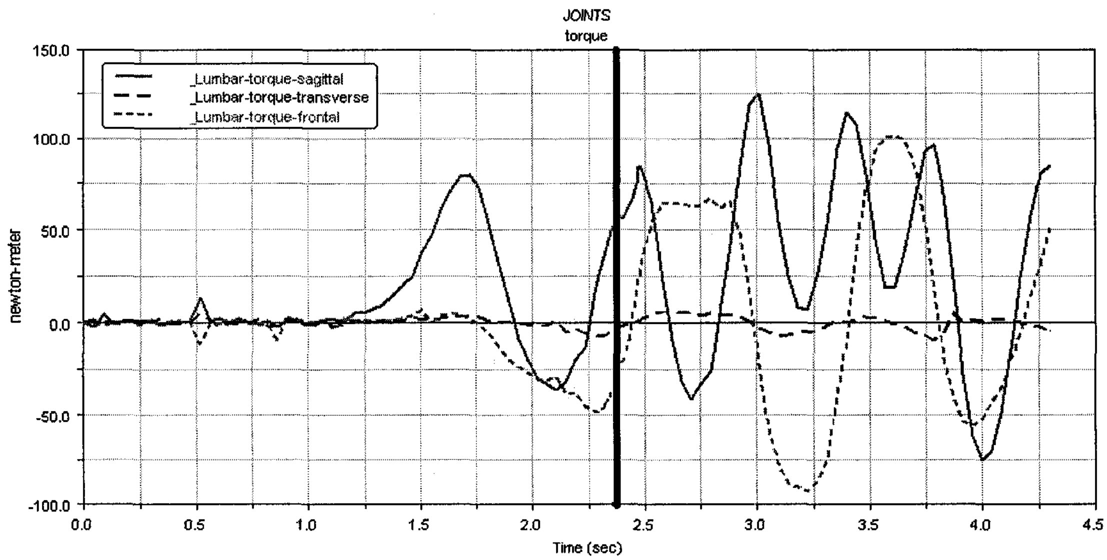


Figure 15 Lumbar sagittal, transverse and frontal torque- knee lifting method, 2 N hand load

The sagittal torque is presented as a continuous line and the transverse and frontal torques are shown as big and small dashed lines respectively. At the picking up moment, the sagittal torque is 50 N-m. The frontal and transverse torques are 20 and 5 N-m, as shown in the graph. The sagittal torque has the greatest value.

The following graph shows the shoulder torques in the sagittal, transverse and frontal planes.

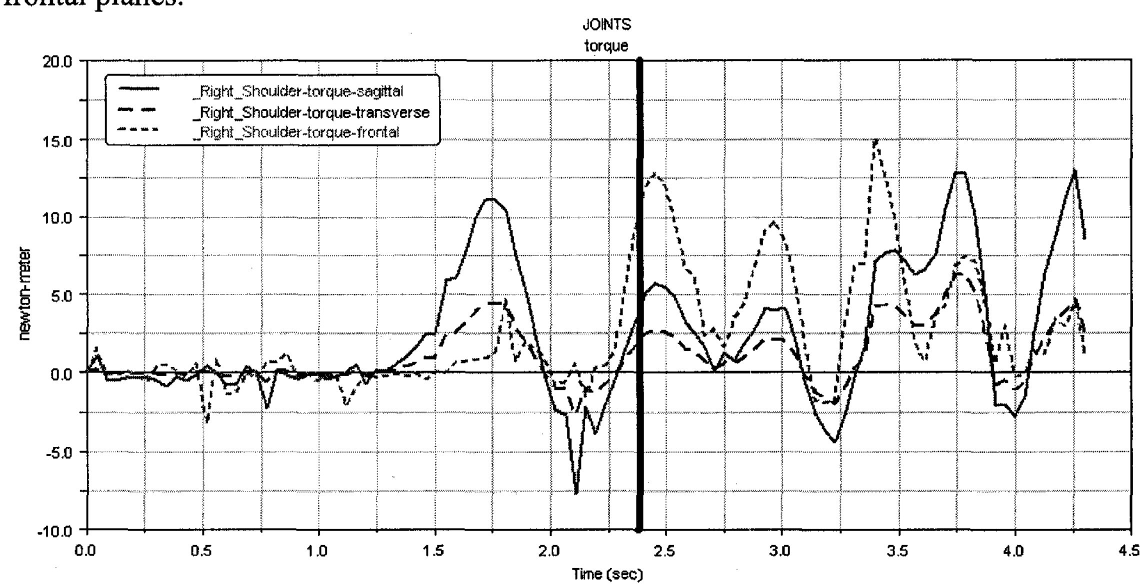


Figure 16 Sagittal, frontal and transverse torque at right shoulder, knee lifting method, 2 N hand load

The total torque at the shoulder joint is calculated from these three vector components. The sagittal torque is presented as a continuous line and the transverse and frontal torques as big and small dashed line respectively.

At the picking up moment, the sagittal torque is 5 N-m. The frontal and transverse torques are 12 and 2 N-m as shown in the graph. The frontal torque has the greatest value.

Knee lifting, floor to waist level for 60 N hand load

Compression force, lumbar moments in all planes and shoulder torques are shown in following graphs. The picking up happens at almost the third second. The vertical line in the middle shows the moment that the lifting task started. The peak value at the picking up moment shows the greatest lumbar compression force.

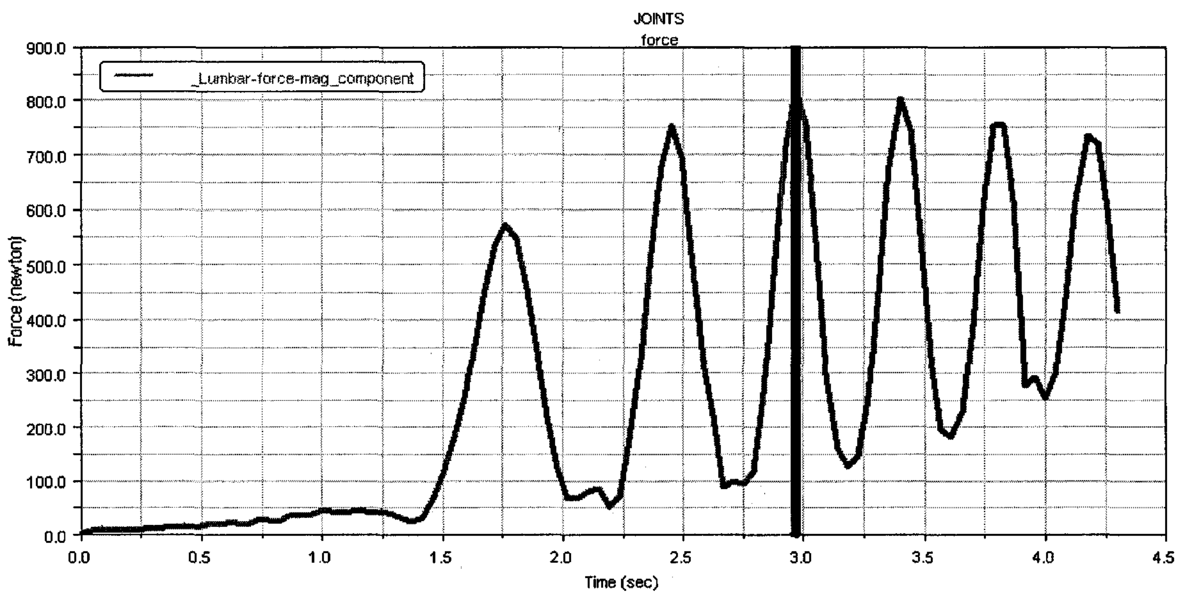


Figure 17 Lumbar compression force-knee lifting method, 60 N hand load

The torque in the sagittal plane has the greatest value among lumbar torques in three planes. There is no clear peak at the third second for transverse and frontal torques. The lumbar torques in the three planes are 100, 20 and 25 N-m respectively.

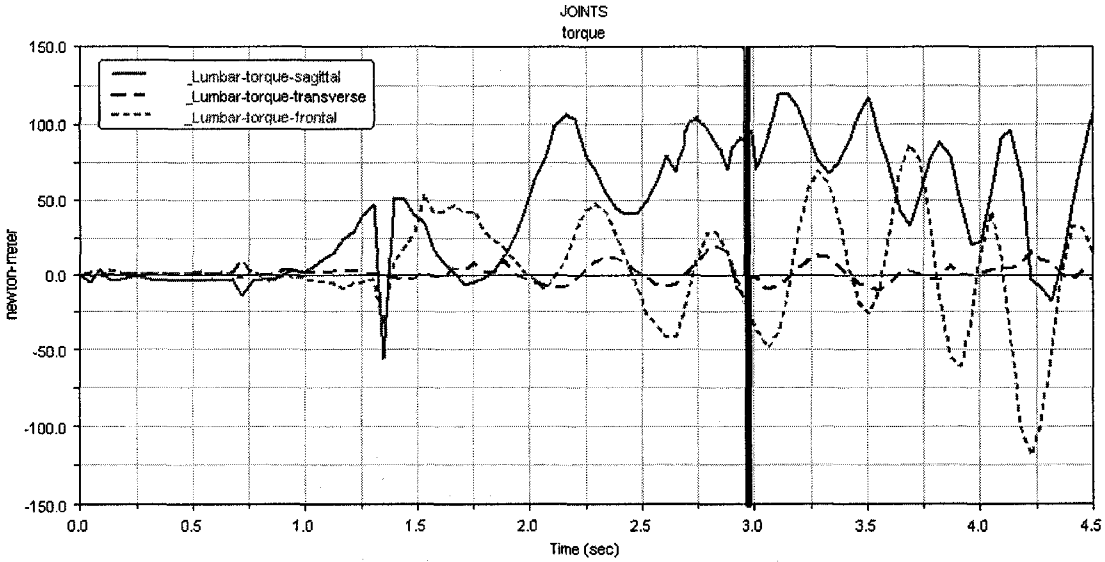


Figure 18 Lumbar sagittal, transverse and frontal torque-knee lifting method, 60 N hand load

The next graph presents the shoulder torque in three planes. The maximum torque appears in the frontal plane and the magnitude is 20 N-m.

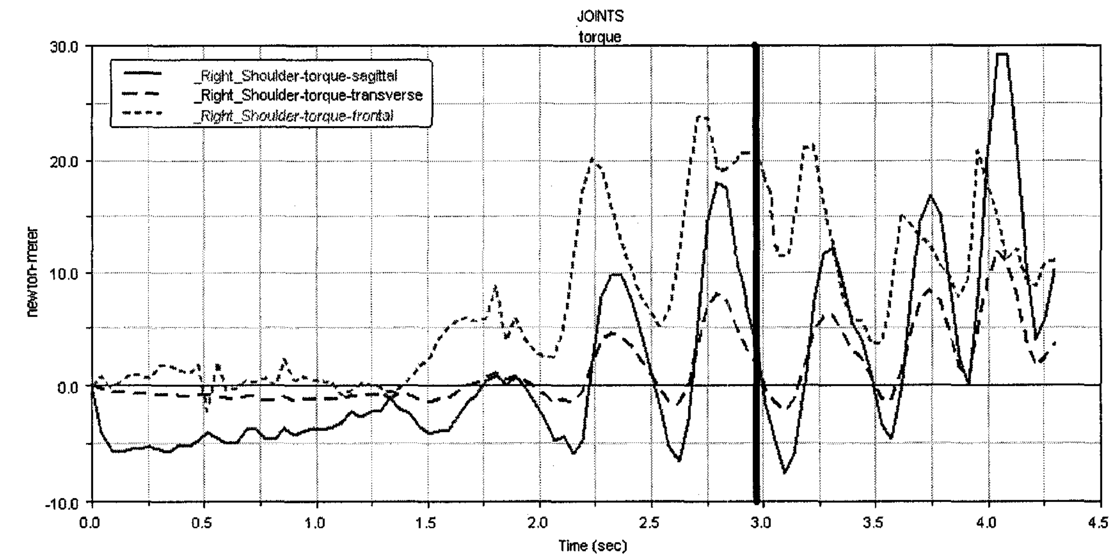


Figure 19 Sagittal, frontal and transverse torque at right shoulder, knee lifting method, 60 N hand load

Comparison of knee lifting, floor to waist level

The next table shows lumbar torques and forces and shoulder torques at the pick up moment for two different hand loads for the knee lifting method.

Table 14 Knee lifting method lifting to waist level, values at pickup moment

Force and torque	Lumbar compression, N	Lumbar torque, N-m sagittal, transverse, frontal → vector sum	Shoulder torque, N-m sagittal, transverse, frontal → vector sum
2 N	560	50, 5, 20 → 54.1	5, 2, 12 → 13.2
60 N	820	100, 20, 25 → 105	5, 3, 25 → 25.7

When the load increases, lumbar compression force, lumbar torques and shoulder torques all increase. The sagittal torque is the greatest component for the lumbar moment, while for shoulder torque the frontal torque is largest.

Results B: Hip lifting method, floor to waist level

The hip lifting method with waist destination is modeled in this section for 2 and 60 N hand loads.

Hip lifting, floor to waist level for 2 N hand load

Compression force, lumbar moments in all planes and shoulder torques are shown in following graphs. The picking up happens at 3.75 s. The vertical line in the middle shows the moment that the lifting task starts. The peak value at the picking up moment shows the greatest lumbar compression force.

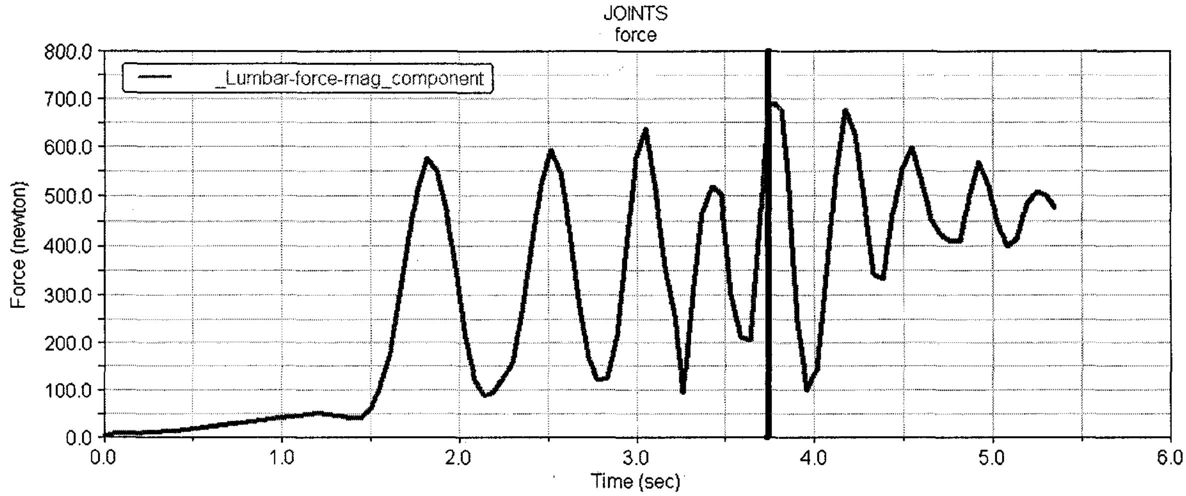


Figure 20 Lumbar compression force-hip lifting method, 2 N hand load

Lumbar sagittal torque after the vertical line is equal by 50 N-m. Compared to the knee lifting method, the sagittal torque does not change. The transverse torque is 10 N-m which is two times greater than transverse torque for knee lifting method and the same hand loading. The frontal torque increases 20%.

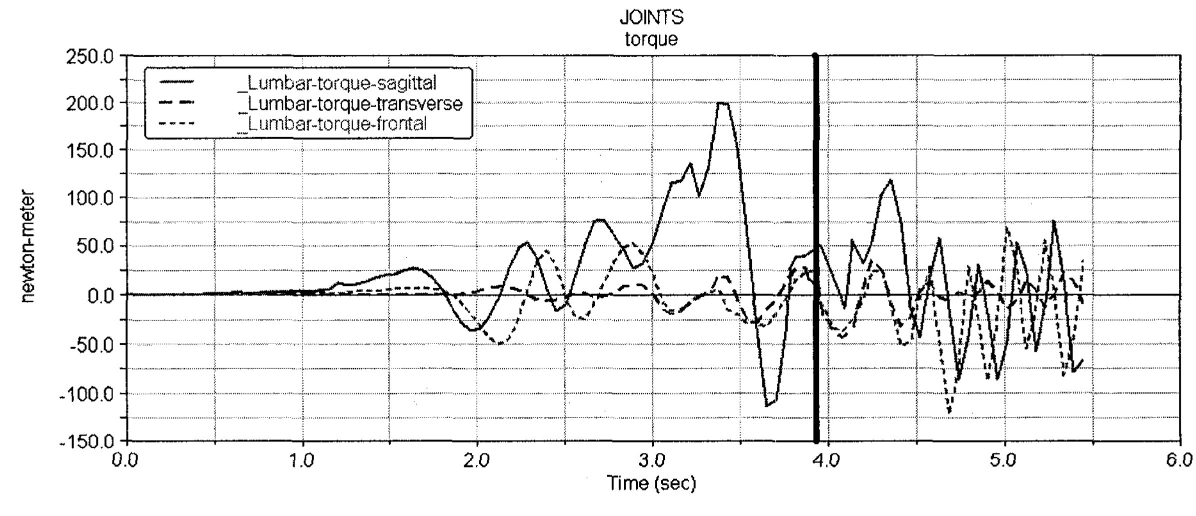


Figure 21 Lumbar sagittal, transverse and frontal torque, hip lifting method, 2 N hand load

Shoulder torques are plotted in the following graph.

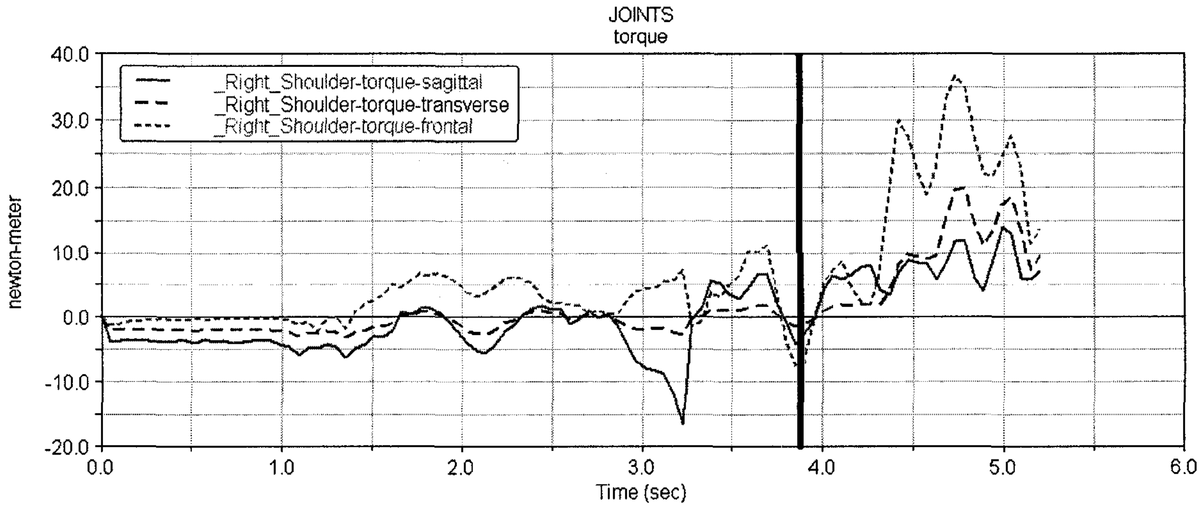


Figure 22 sagittal, frontal and transverse torque at right shoulder, hip lifting method, 2 N hand load

Hip lifting waist level for 60 N hand load

Compression force, lumbar moments in all planes and shoulder torques are shown in following graphs. The picking up happens at 3.7 seconds. The vertical line in the middle shows the moment that lifting task started. The peak value at the picking up moment shows the greatest lumbar compression force.

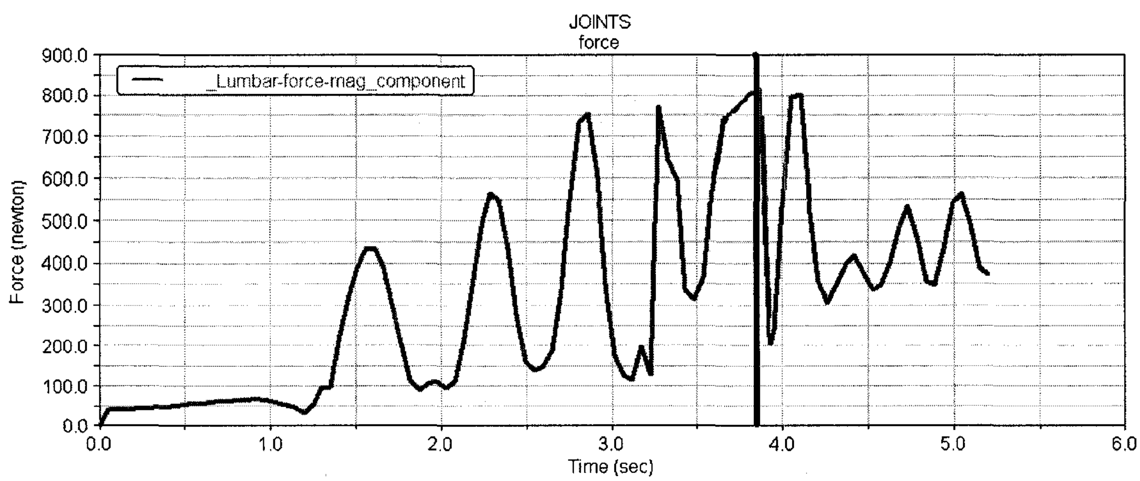


Figure 23 Lumbar compression force-hip lifting method, 60 N hand load

The sagittal torque at pick up moment is about 75 N-m. The transverse lumbar torque is about 30 N-m. Another peak appears at 0.5 second and is about 45 N-m in positive direction. The frontal lumbar torque is about 45 N-m.

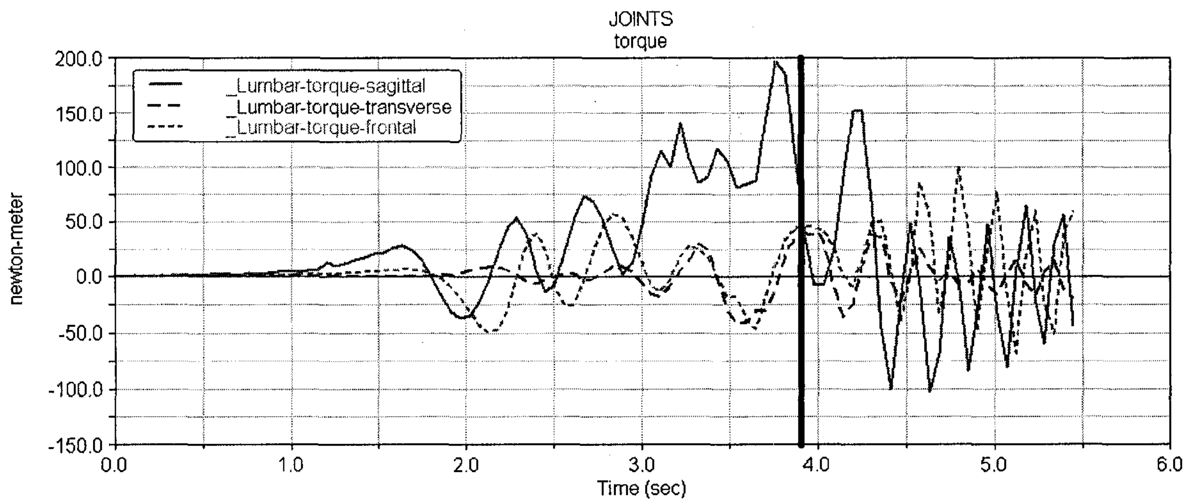


Figure 24 Lumbar sagittal, transverse and frontal torque-hip lifting method, 60 N hand load

The sagittal torque at pick up moment is about 10 N-m. The transverse torque is about 1 N-m. The frontal torque has the maximum value which is about 25 N-m.

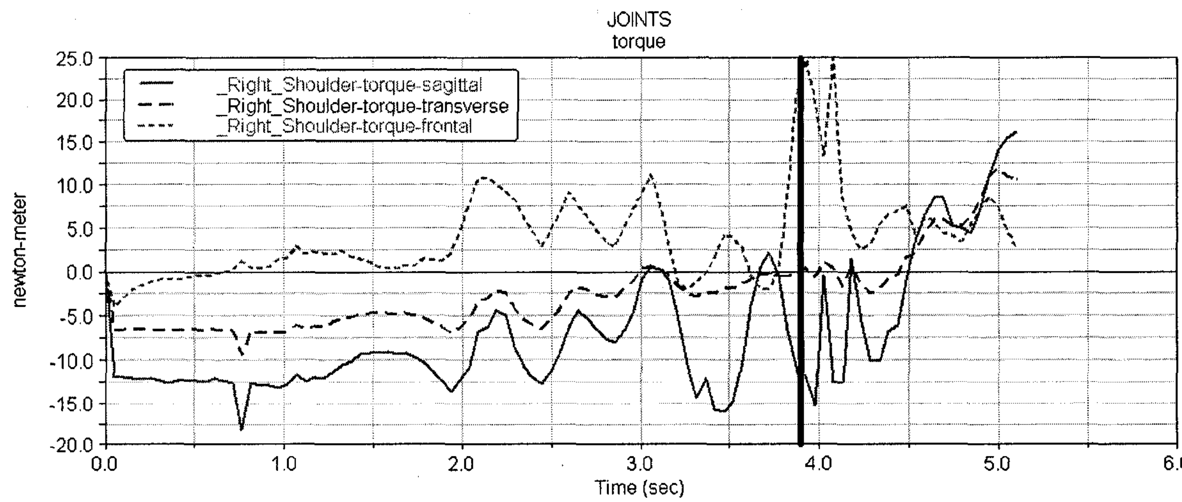


Figure 25 Sagittal, frontal and transverse torque at right shoulder, hip lifting method, 60N hand load

Comparison of knee lifting, floor to waist level

The next table shows lumbar torques and forces and shoulder torques at the pick up moment for two different hand loads for the knee lifting method.

Table 15 Hip lifting method lifting to waist level, values at pickup moment

Force and torque	Lumbar compression, N	Lumbar torque, N-m sagittal, transverse, frontal → vector sum	Shoulder torque, N-m sagittal, transverse, frontal → vector sum
2 N	680	50, 10, 25 → 56.8	3, 1, 8 → 8.6
60 N	800	75, 30, 45 → 92.4	10, 1, 20 → 22.3

When the load increases, lumbar compression force, lumbar torques and shoulder torques all increase. The sagittal torque is the greatest component for the lumbar moment, while for shoulder torque the frontal torque is largest.

Result C -Knee lifting destination level above the shoulders

The knee lifting method for destination above the shoulders in this section. Two different hand loads are used. A 2 N hand load is used as a light load for lifting and 60 N is chosen to represent heavy hand loading. Having higher destination level in this lifting task, the subject chooses a higher acceleration at pickup moment.

Knee lifting above the shoulder level for 2 N hand load

Compression force, lumbar moments in all three planes and shoulder torques are shown in following graphs. The picking up happens at 3 seconds. In this movement, the subject performs the lifting task at a higher speed and the box is located 5 cm farther from the tip of the feet compared to the situation where the box was lifted to the waist level.

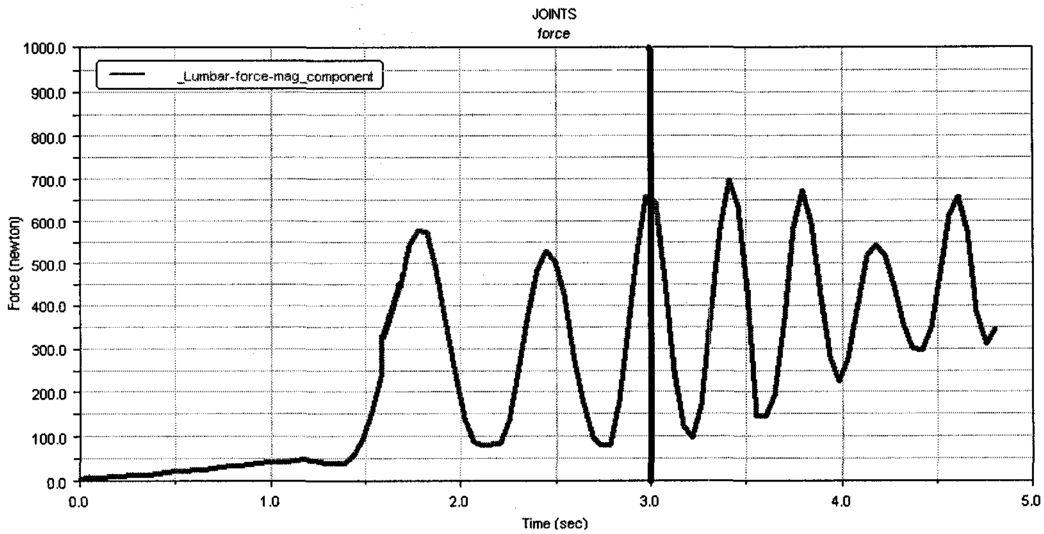


Figure 26 Lumbar compression force, knee lifting method, 2 N hand load

The second graph shows a larger peak after picking up moment for sagittal lumbar torque. It might be caused by an unusual movement during the capturing data. The lumbar sagittal torque is 75 N-m when lifting task starts but the maximum value at the middle posture is almost 110 N-m. The peak value for transverse torque is 10 N-m. For the lumbar frontal torque, the torque is about 15 N-m at the lifting moment.

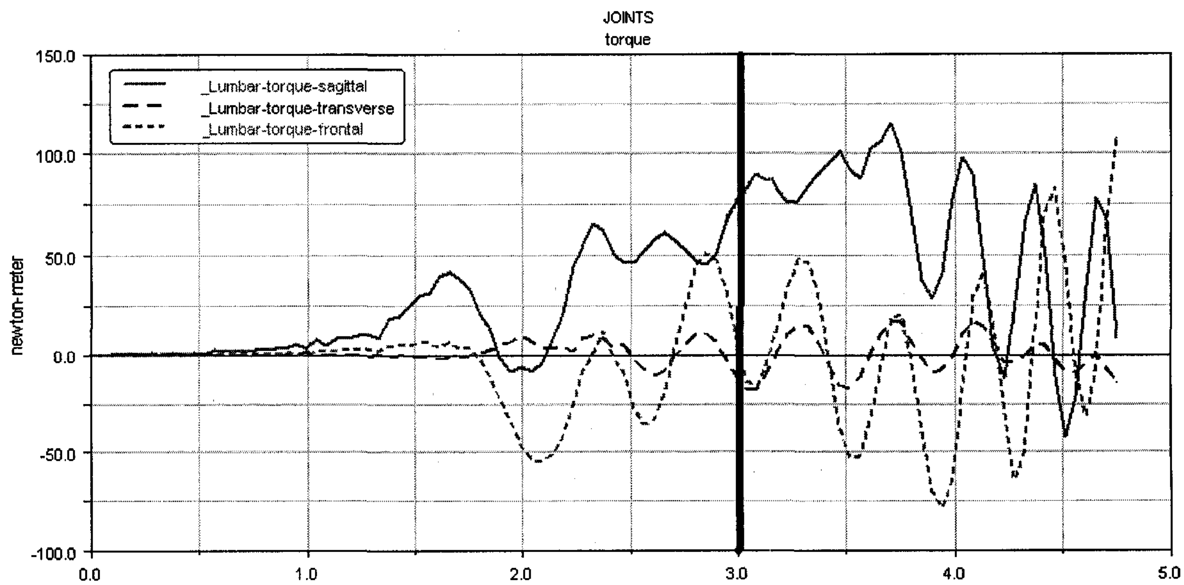


Figure 27 Lumbar sagittal, transverse and frontal torque, knee lifting method, 2 N hand load

The sagittal torque at pick up moment around the shoulder joint is about 10 N-m. The transverse torque is almost zero. The frontal torque has a value about 8 N-m.

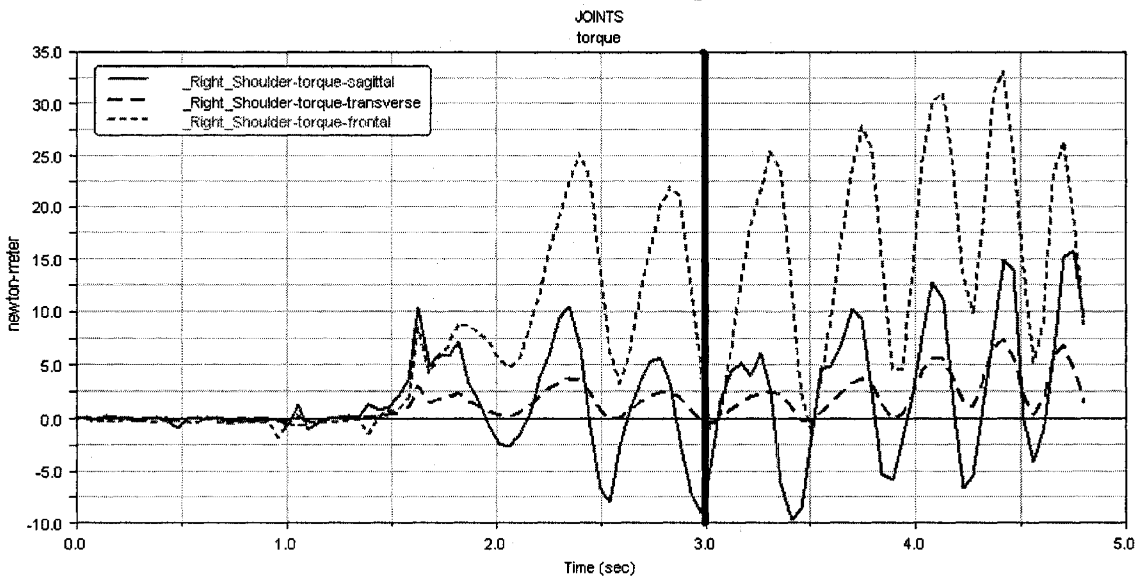


Figure 28 sagittal, frontal and transverse torque, knee lifting method at right shoulder, 2 N hand load

Knee lifting destination above shoulder level for 60 N hand load

Compression force lumbar moments in three planes and shoulder torques are shown in following graphs. The picking up happens at 2.70 seconds.

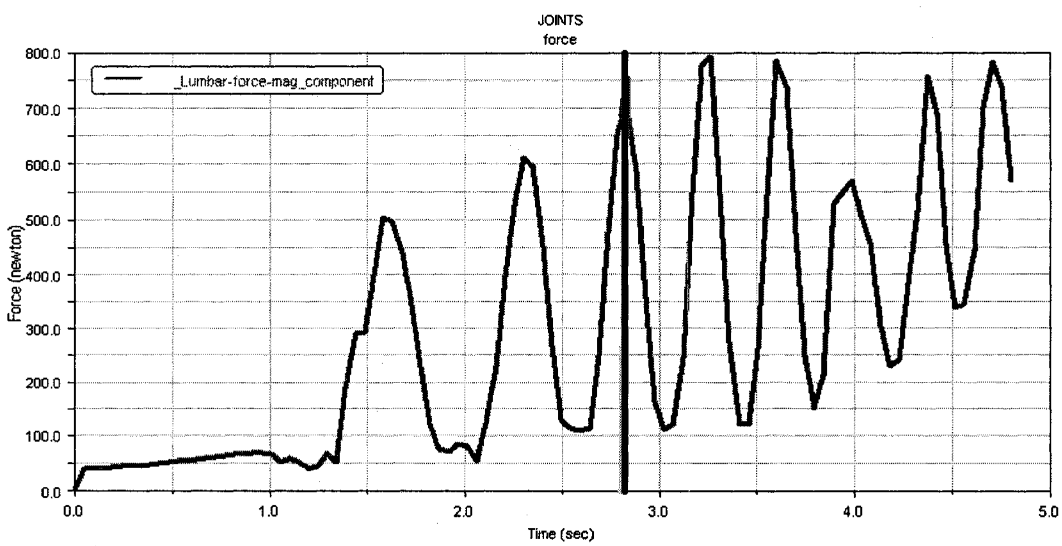


Figure 29 Lumbar compression force, knee lifting method, 60 N hand load

The sagittal torque at pick up moment is about 80 N-m. The transverse torque is 10 N-m and the frontal torque has a value about 15 N-m.

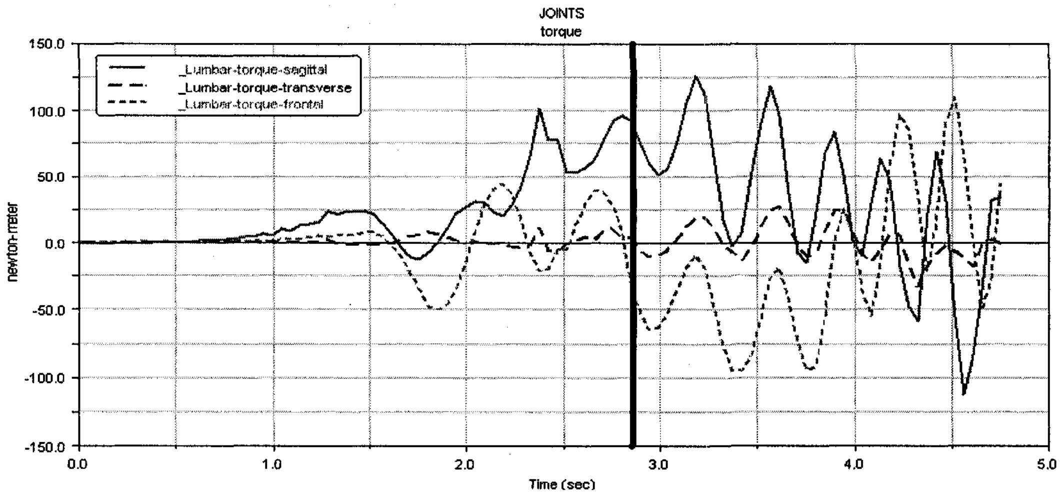


Figure 30 Lumbar sagittal, transverse and frontal torque, knee lifting method, 60 N hand load

The sagittal torque at pick up moment around the shoulder joint is about 10 N-m. The transverse torque is almost zero. The frontal torque has a value about 20 N-m, which is the only torque magnitude that significantly has changed comparing to the last loading.

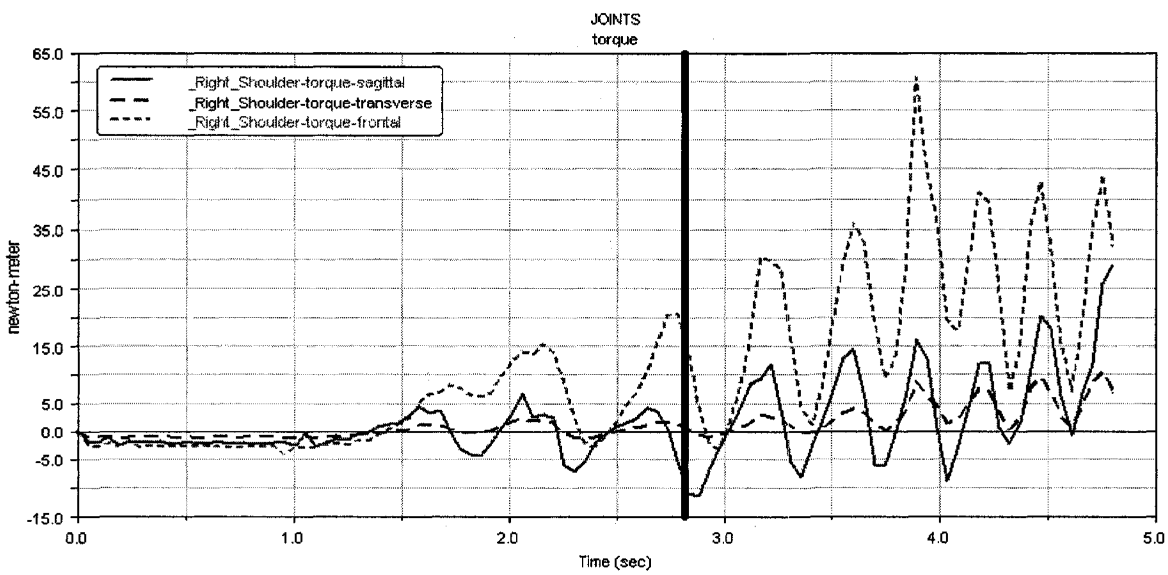


Figure 31 Sagittal, frontal and transverse torque at right shoulder, knee lifting method, 60 N hand load

Comparison of knee lifting, destination above the shoulder

The next table shows lumbar torques and forces and shoulder torques at the pick up moment for two different hand loads for the knee lifting method.

Table 16 Knee lifting method lifting to shoulder level, values at pickup moment

Force and torque	Lumbar compression, N	Lumbar torque, N-m sagittal, transverse, frontal → vector sum	Shoulder torque, N-m sagittal, transverse, frontal → vector sum
2 N	650	70, 10, 15 → 72.3	1, 1, 10 → 10.1
60 N	750	80, 10, 40 → 90	12, 2, 18 → 21.7

When the load increases, lumbar compression force, lumbar torques and shoulder torques all increase. The sagittal torque is the greatest component for the lumbar moment, while for shoulder torque the frontal torque is largest.

Result D – Hip lifting destination level above the shoulders

The hip lifting method for destination above the shoulders in this section. Two different hand loads are used. A 2 N hand load is used as a light load for lifting and 60 N is chosen to represent heavy hand loading.

Hip lifting above shoulder level for 2 N hand load

Lumbar compression force and lumbar and shoulder torque in three planes are shown in following graphs. The picking up happens at 4.6 seconds. The vertical line in the graph indicates this moment. The peak value at 4.6 seconds is not the greatest value. Surprisingly, two greater peaks appear before the lifting task start. Rapid movement and marker dislocation especially at spine area causes this kind of errors.

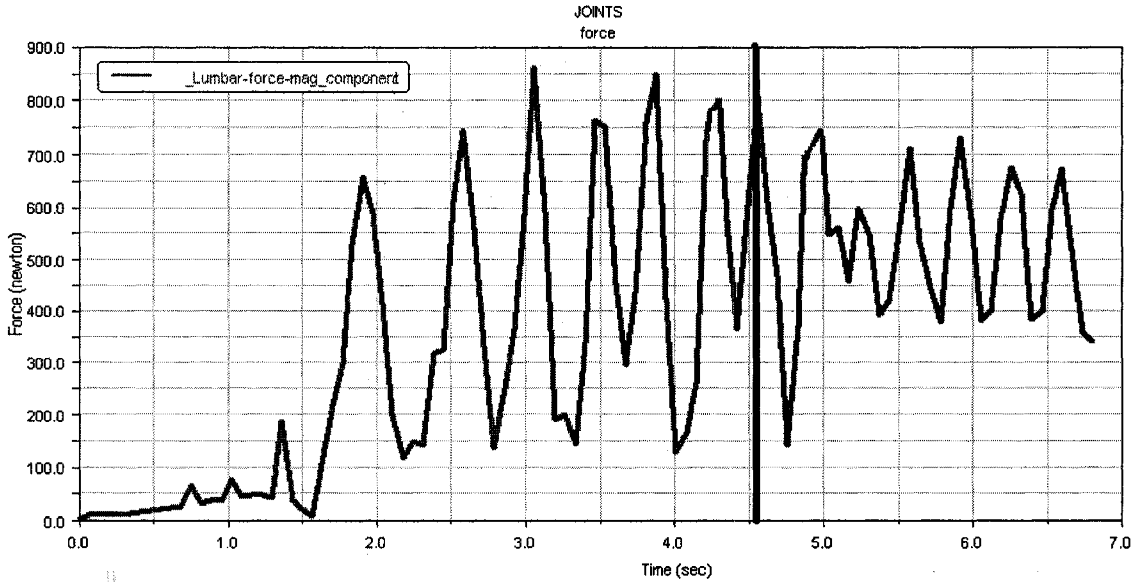


Figure 32 Lumbar compression force, hip lifting method, 2 N hand load

Lumbar torques in sagittal, transverse and frontal planes are presented in the following figure. In sagittal plane, two peaks appear almost at 0.5 second before and after the first second that evidently shows an abnormal trend in graph behavior.

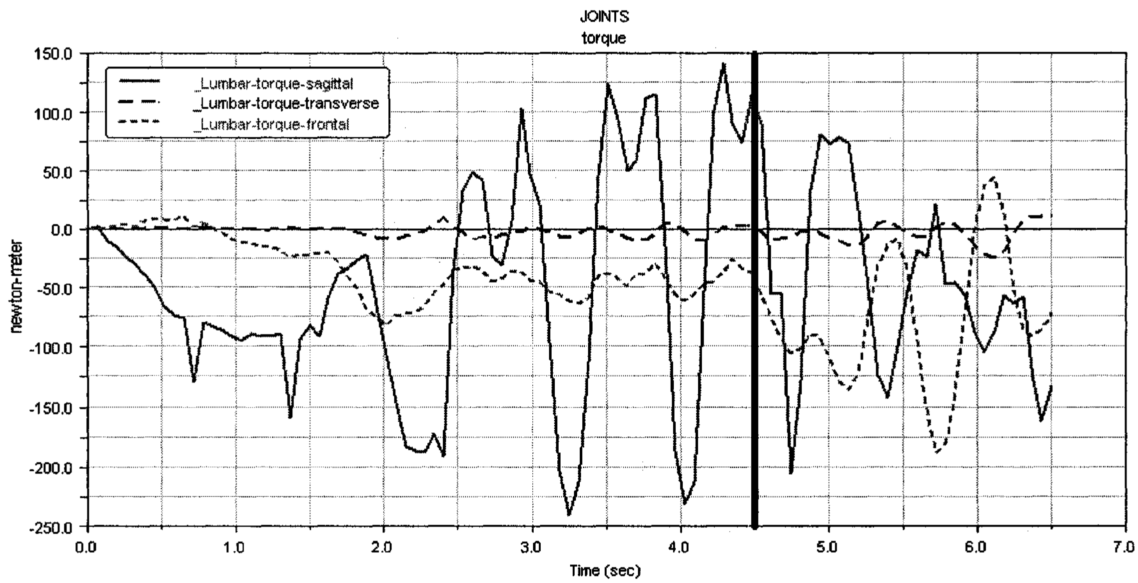


Figure 33 Lumbar sagittal, transverse and frontal torque, hip lifting method, 2 N hand load

These peak values occur at the same times as in lumbar compression force graph. The lumbar sagittal torque at picking up moment is 110 N-m. As seen before the transverse torque has the smallest value among lumbar torques, which in this case is almost zero. The frontal torque does not show a clear torque at peaking up moment.

Next graph presents the shoulder torques. The sagittal torque increases by increasing the elbow flexion. The frontal torque has the greatest value in shoulder torques as seen before. Transverse torque has almost a uniform trend and the value at the picking up moment is near zero.

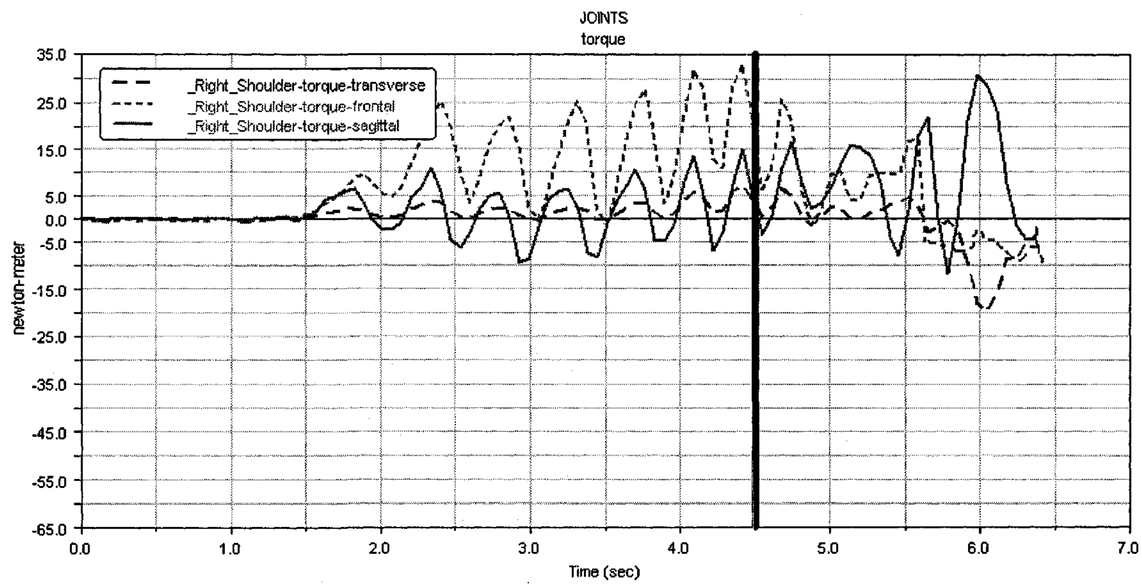


Figure 34 Sagittal, frontal and transverse torque at right shoulder, hip lifting method, 2 N hand load

Hip lifting destination above shoulder level for 60 N hand load

Lumbar compression force and lumbar and shoulder torque in three planes are shown in following graphs. The picking up happens at 4.65 seconds. The vertical line in the graph indicates this moment. Lumbar compression force is shown in the following graph. At the moment which lifting task starts, the graph shows a high peak (850 N) that decreases gradually and by end of the task reaches 450 N.

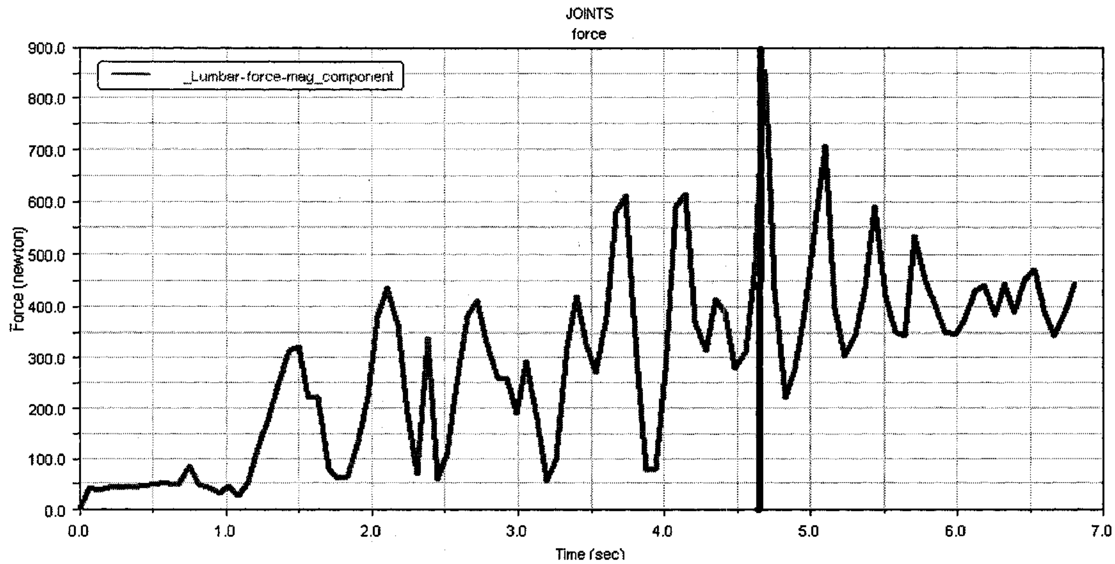


Figure 35 Lumbar compression force, hip lifting method, 60 N hand load

Next graph presents the lumbar torques in three planes. The sagittal torque right after the pick up moment is about 130 N-m. The transverse torque is 20 N-m and the frontal torque has a value about 30 N-m. Again, it is noticed that frontal torque does not show any clear peak at picking up moment.

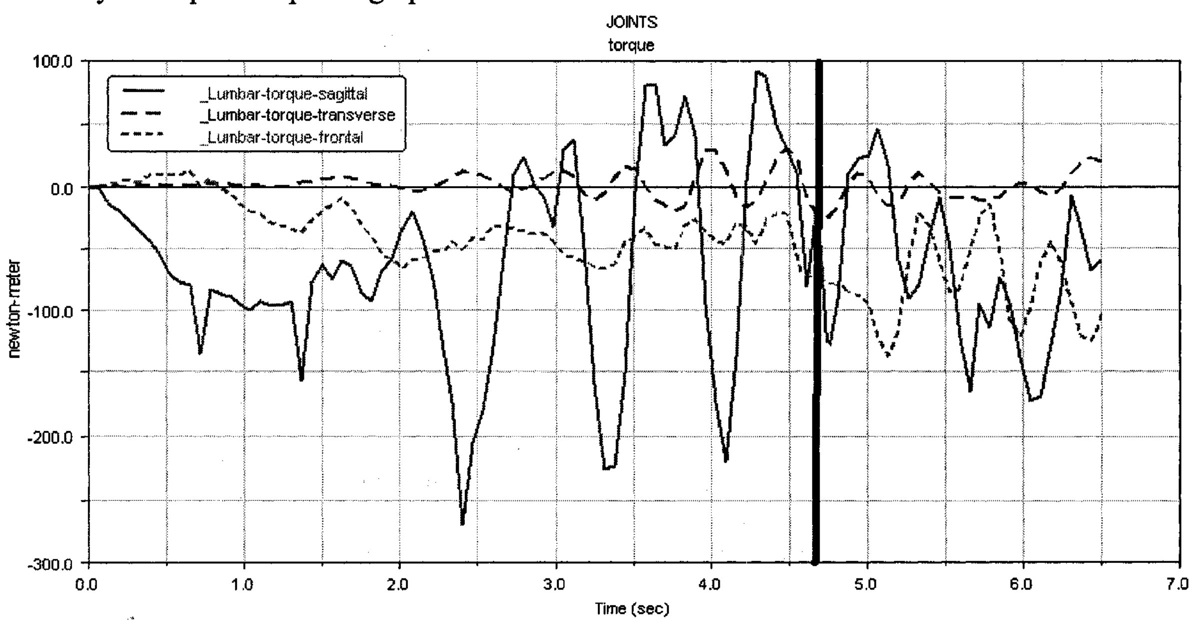


Figure 36 Lumbar sagittal, transverse and frontal torque, hip lifting method, 60 N hand load

Shoulder torques at peak up moment are 15, 8 and 2 N-m respectively in frontal, sagittal and transverse planes.

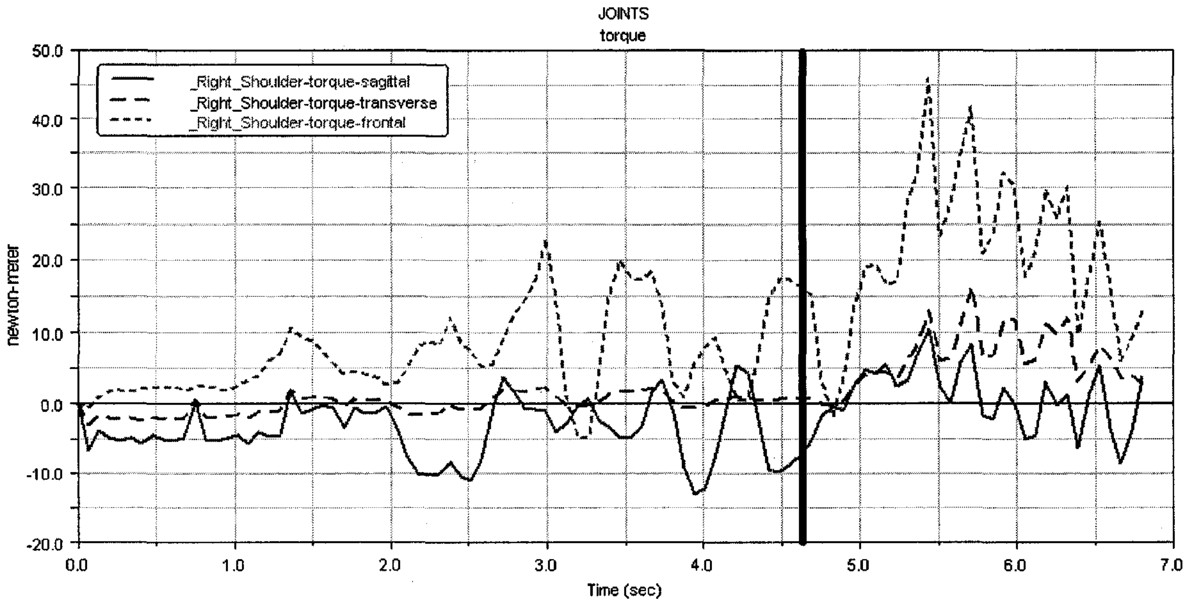


Figure 37 Sagittal, frontal and transverse torque at right shoulder, hip lifting method, 60 N hand load

Following table presents the result for hip lifting method and the destination level above the shoulder for three different hand loading. This movement performs at a higher speed comparing to the lifting task with destination at the waist level, which help the subject to provide enough force to accomplish a longer lifting task.

Comparison of hip lifting, destination above the shoulder

The next table shows lumbar torques and forces and shoulder torques at the pick up moment for two different hand loads for the knee lifting method.

Table 17 Hip lifting method lifting to shoulder level, values at pickup moment

Force and torque	Lumbar compression, N	Lumbar torque, N-m sagittal, transverse, frontal → vector sum	Shoulder torque, N-m sagittal, transverse, frontal → vector sum
2 N	800	110, 5, 30 → 114.1	3, 3, 10 → 10.8
60 N	860	130, 20, 30 → 134.9	8, 3, 15 → 17.2

When the load increases, lumbar compression force, lumbar torques and shoulder torques all increase. The sagittal torque is the greatest component for the lumbar moment, while for shoulder torque the frontal torque is largest.

For the lumbar compression force, when the weight increases from 2 to 60 N lumbar compression force increases 7.5%. For the lumbar torque, by increasing the weight from 2 to 60 N the sagittal torque increases 18%, the transeverse torque 300% and at the total lumbar torque 18%. Overall shoulder torque shows a 59% increase.

3.4.3 Biomechanical analysis using 3DSSPP

3DSSPP is a static strength prediction program that calculates the internal body forces at different body postures. To model the mannequin in this software joint angles need to be specified in the horizontal and vertical planes for the upper arm and forearm, upper and lower leg and back. The posture can be symmetric or asymmetric. In order to model the lifting task, three postures are selected: the start of the lift at the picking up moment, the end of the lift and about halfway in between. The required joint angle inputs for these postures were obtained from LifeMOD. The hand location in the posture prediction section provides the exact location for the hand especially at the moment that lifting task starts. The box dimensions are 40*18*32 cm. A 1 N vertical force is applied to each hand as a light weight and 30 N to each hand to simulate the heavy weight. Anthropometric data for the subject in this experiment are as follows.

Table 18 Anthropometric data for the subject

Gender	Height	Weight
Female	163 cm	48 kg

Joint angles in the sagittal and transverse planes in LifeMOD are used for modeling the body in 3DSSPP. Joint angles in the sagittal plane in LifeMOD represent the horizontal angles in 3DSSPP and data in the transverse plane in LifeMOD indicate the joint angles in the vertical plane in 3DSSPP. Because of the differences in definition of the origin for joint angels in LifeMOD and 3DSSPP, it is necessary to convert the joint angles obtained from LifeMOD to a new set that can be used by 3DSSPP. For example, –100 degrees for back flexion in LifeMOD is equal to 10 degrees for back flexion in 3DSSPP.

The following six graphs show the LifeMOD joint angles in the sagittal and transverse planes for 2 and 30 N hand loads using either the knee lifting method or the hip lifting method. The vertical lines show the angles at the beginning of the lift, at the end of the lift and about halfway in between.

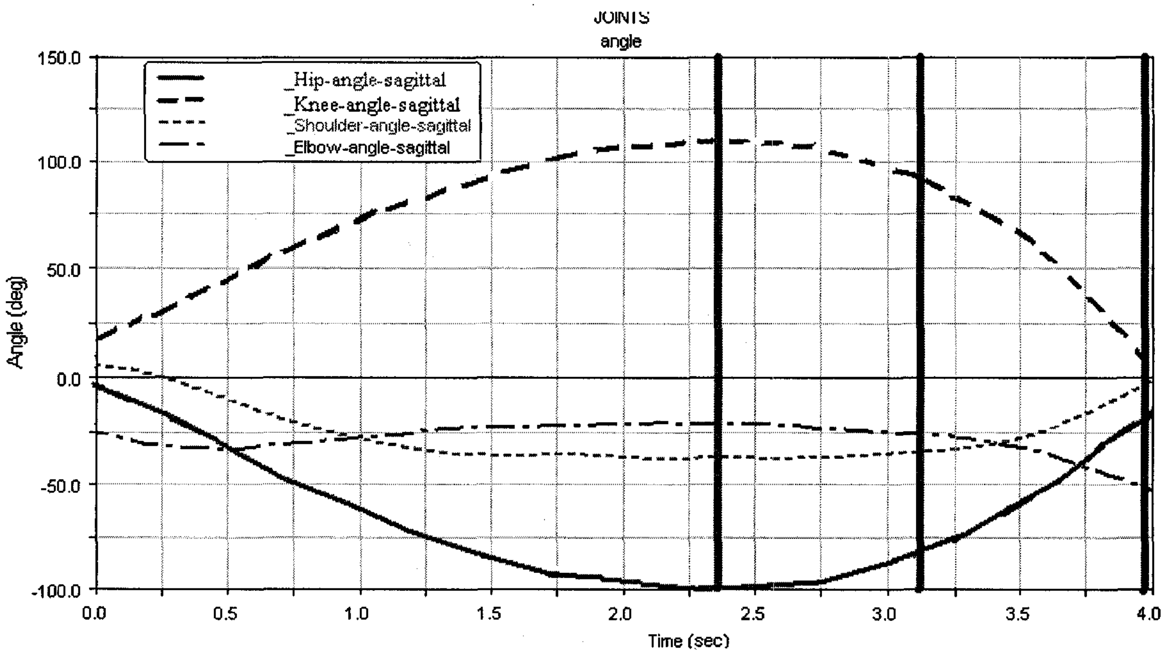


Figure 38 Joint angles in sagittal plane, knee-lifting method, 2 N hand load

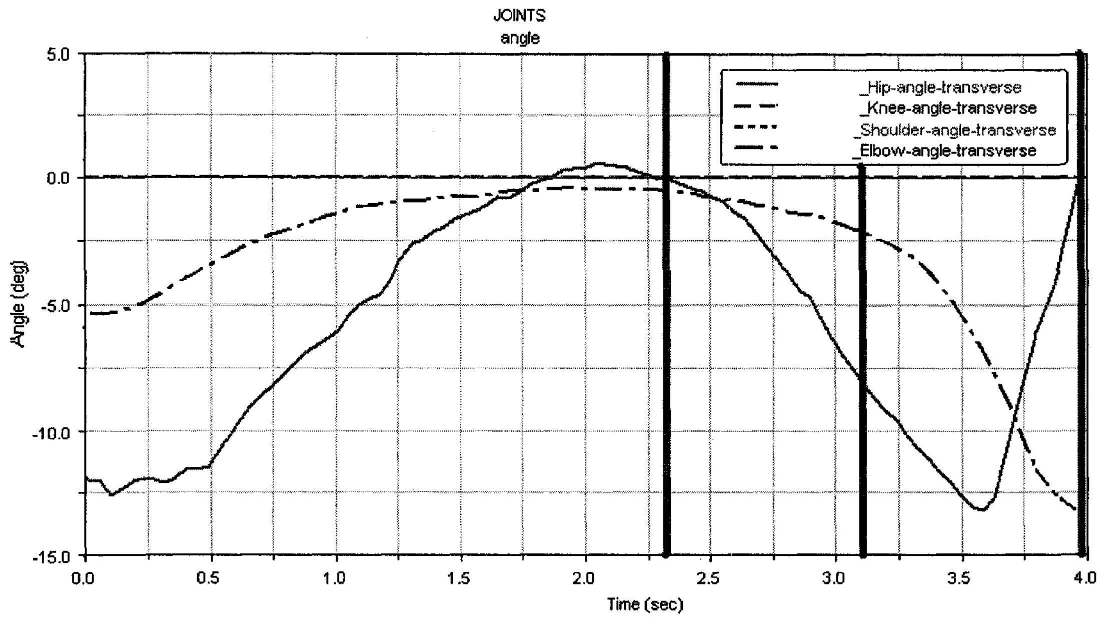


Figure 39 Joint angles in transverse plane, knee lifting method, 2 N hand load

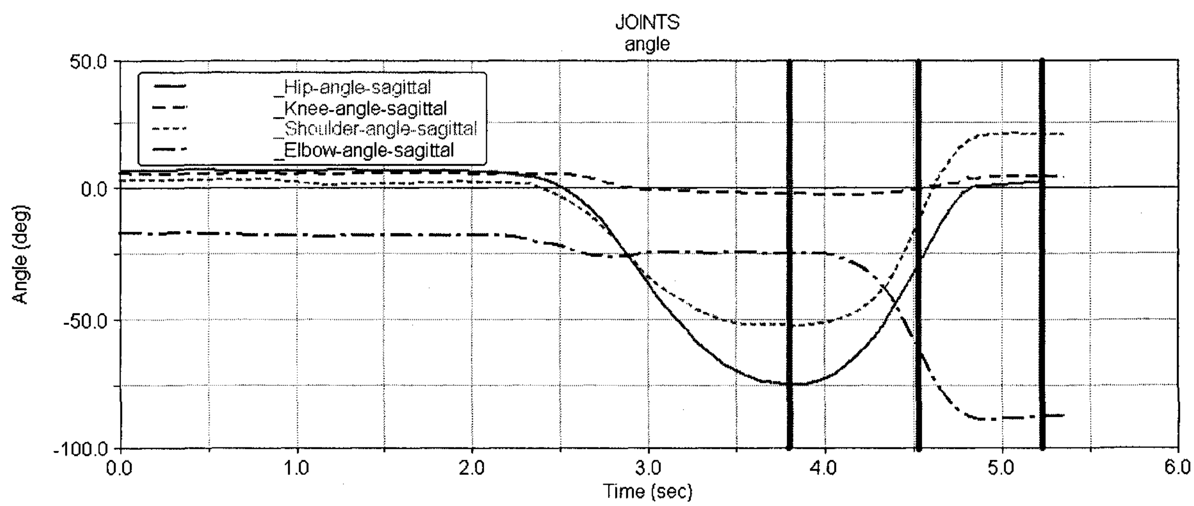


Figure 40 Joint angles in sagittal plane, hip lifting method, 2 N hand load

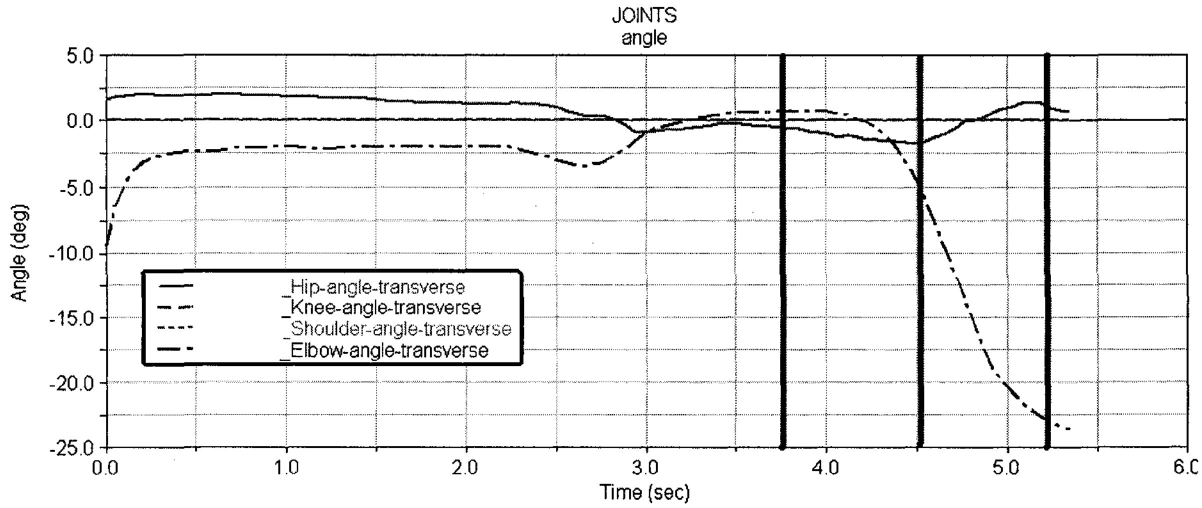


Figure 41 Joint angles in transverse plane, hip lifting method, 2 N hand load

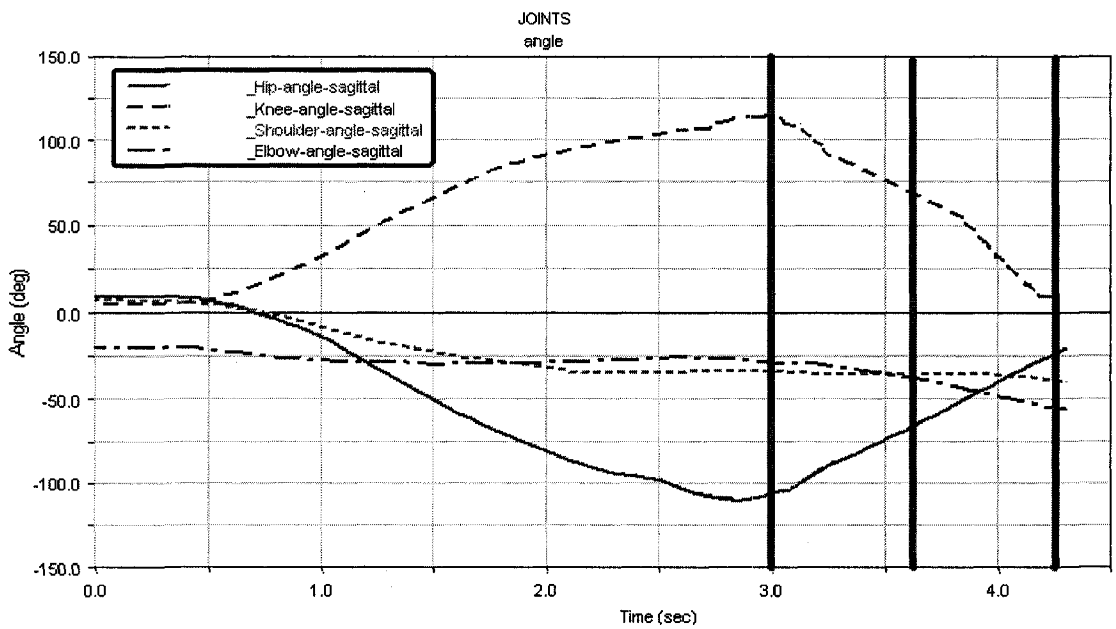


Figure 42 Joint angles in sagittal plane, knee-lifting method, 60 N hand load

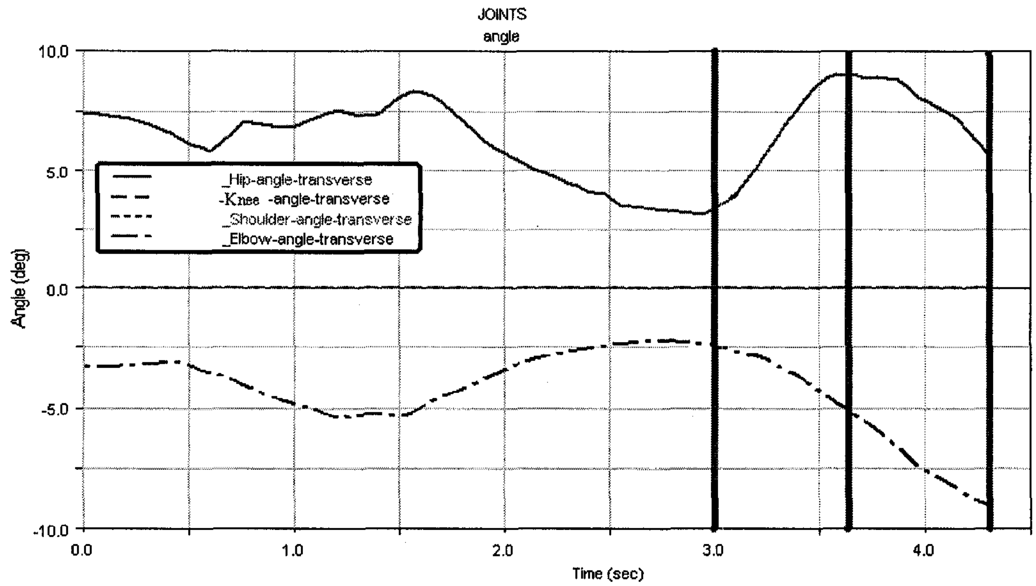


Figure 43 Joint angles in transverse plane, knee lifting method, 60 N hand load

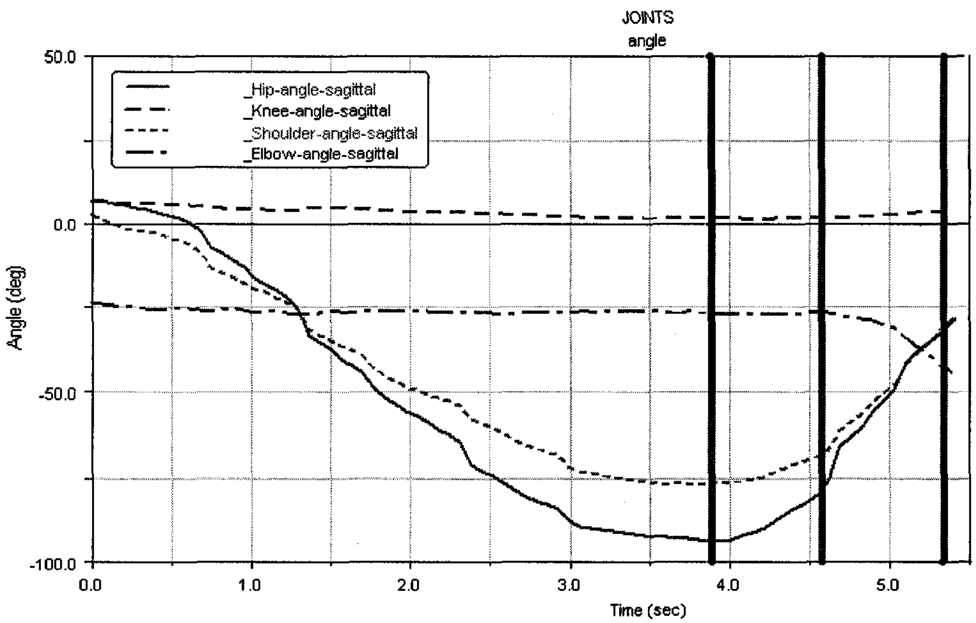


Figure 44 Joint angles in sagittal plane, hip lifting method, 60 N hand load

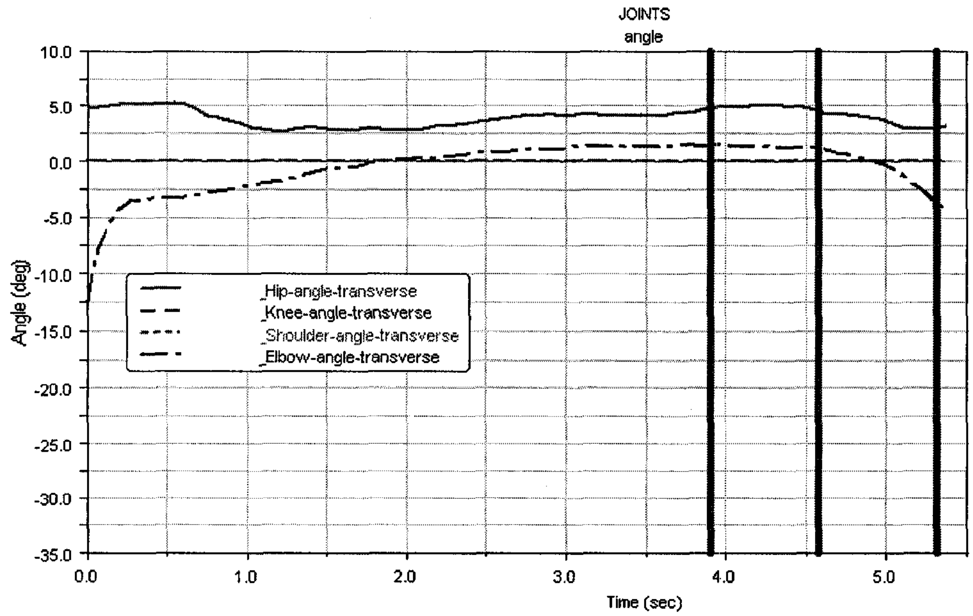


Figure 45 Joint angles in transverse plane, hip lifting method, 60 N hand load

The following tables show the LifeMOD joint angles for elbow, shoulder, knee and hip in two planes, sagittal and transverse, for the knee and hip lifting methods and for the three marked postures. Note that the ending posture is the same for knee lifting and hip lifting. The total hand force of 2 and 60 N is divided equally over both hands.

Table 19 Joints angles at starting posture, picking up moment

		Elbow		Shoulder		Knee		Hip	
Force/hand		1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee Lifting	Sagittal	20	25	35	30	115	120	100	100
	Transverse	0	2.5	0	0	0	0	0	3
Hip Lifting	Sagittal	25	25	50	75	0	0	75	85
	Transverse	2	2	0	0	0	0	0	5

Table 20 Joint angles at middle posture

		Elbow		Shoulder		Knee		Hip	
Force/hand		1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee Lifting	Sagittal	25	30	30	30	80	60	80	60
	Transverse	2	5	0	0	0	0	5	8
Hip Lifting	Sagittal	75	30	25	60	0	0	25	80
	Transverse	5	2	0	0	0	0	2	4.5

Table 21 Joints angles for ending posture

		Elbow		Shoulder		Knee		Hip	
Force/hand		1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee Lifting	Sagittal	65	50	15	30	0	0	10	20
	Transverse	12	8	0	0	0	0	5	6
Hip Lifting	Sagittal	75	50	18	25	0	0	10	25
	Transverse	20	3	0	0	0	0	2	5

Using above sets of joint angles three postures are modeled in 3DSSPP to simulate the lifting task. Joint forces and moments are calculated for each static posture by 3DSSPP.

The figure below shows the initial posture for the knee and hip lifting methods. 3DSSPP verifies if the centre of pressure is located between the feet, in which case the posture is balanced and warns if the posture is not balanced. It was sometimes necessary to make small adjustments to the posture to ensure proper balance.

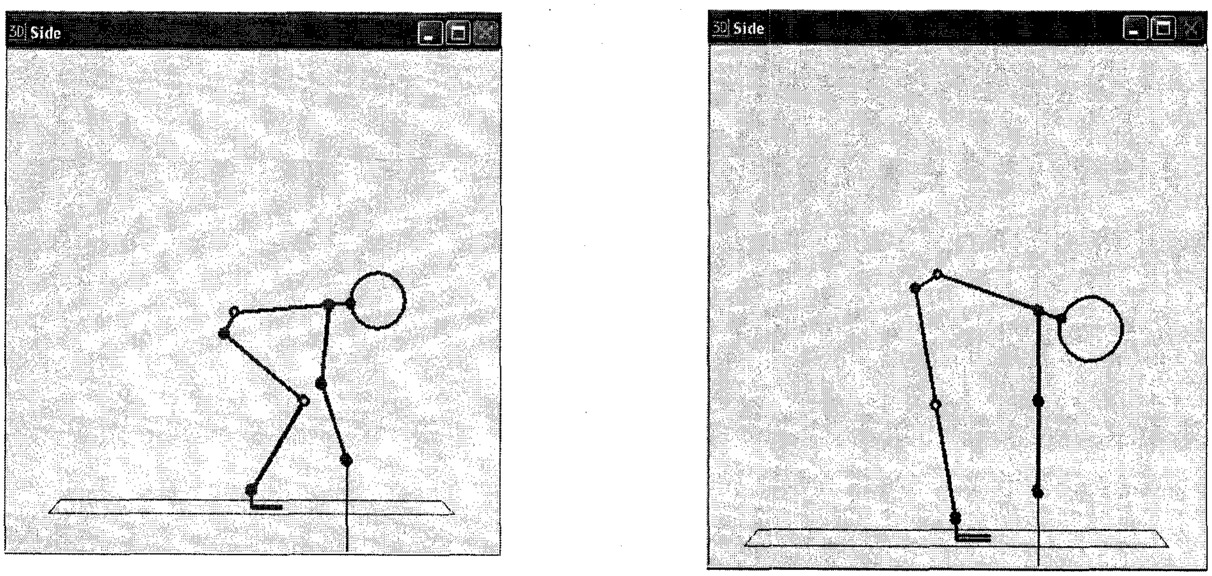


Figure 46 Initial posture for knee and hip lifting method

The following table compares joint forces and torques results in the lumbar and shoulder regions for two lifting methods for weights of 2 and 60 N, or 1 N and 30 N per hand.

Table 22 Force and torque comparison at initial posture

	Compression force at L5/S1, N		Shear force at L5/S1, N		L5/S1 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee lifting	1250	2015	206	247	74.8	99.5	0.8	3.7
Hip lifting	1829	2128	349	406	119.8	141.3	0	0

The results show higher compression, shear force and moment at L5/S1 for hip lifting compared to the knee lifting method in the static posture. The shoulder torque is almost zero in hip lifting method because of the vertical arm position distance.

By increasing the hand load from 2 N to 60 N, the lumbar compression force increases by 61% in knee lifting and 16% in hip lifting. The hip lifting method shows less sensitivity to increasing the load. The results show that the shear force at L5/S1 has higher values in hip lifting which increases by 16% for heavy load.

The following figure shows the middle posture with the hands about 80 cm above the ground for knee and hip lifting.

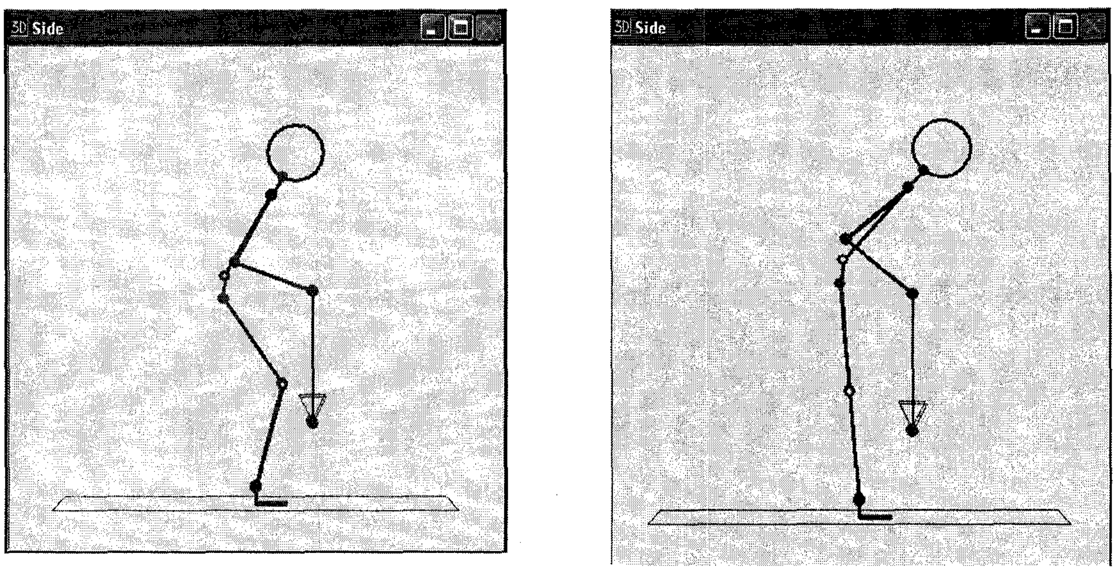


Figure 47 Middle posture for knee and hip lifting method

The following table shows the joint forces and moments at the middle posture for different hand loads.

Table 23 Force and torque comparison at middle posture

	Compression force at L5/S1, N		Shear force at L5/S1, N		L5/S1 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee lifting	845	1209	158	195	37.5	55.3	2.1	10.4
Hip lifting	934	1224	169	212	43.5	58.2	1.9	2.8

For different hand loading, the result shows that hip lifting applies more force to lumbar part. As before, the shear force is higher in hip lifting method and the shoulder torque shows a lower magnitude. Lumbar compression force increases 43% in knee lifting and 31% in hip lifting when hand loads increase from 1 N to 30 N which shows less load sensitivity in hip lifting method.

The next figure shows the body in a holding position. This posture is the same for both lifting methods.

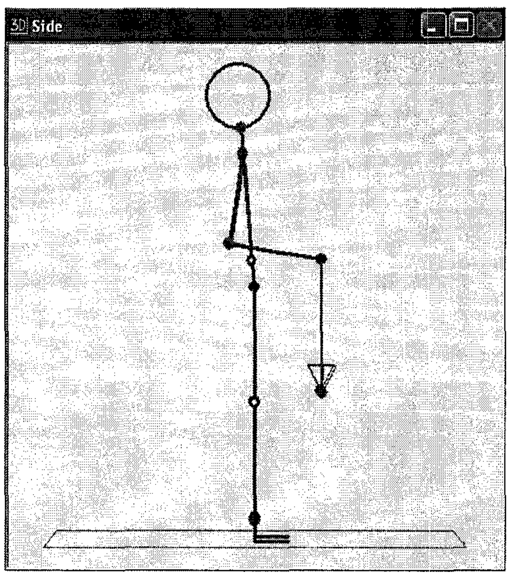


Figure 48 Holding posture

The table below compares the forces and torques at this position.

Table 24 Force and torque comparison for holding position

	Compression force at L5/S1, N		Shear force at L5/S1, N		L5/S1 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Holding position	340	667	197	229	3.8	20.7	1.6	10.2

Compression force in lumbar decreases significantly compared to the previous postures, but L5/S1 shear force and shoulder torque are almost the same compared to the middle posture. The lumbar moment decreases sharply.

For heavy load, the L5/S1 moment decreases by 62% from middle posture to the holding posture for knee lifting and 64% for hip lifting. Total L5/S1 compression force is 340 N for 2 N load handling and 667 for 60 N, which shows a 96% increase.

In the final posture the hands are above the shoulders in front of the face, as shown in the figure below.

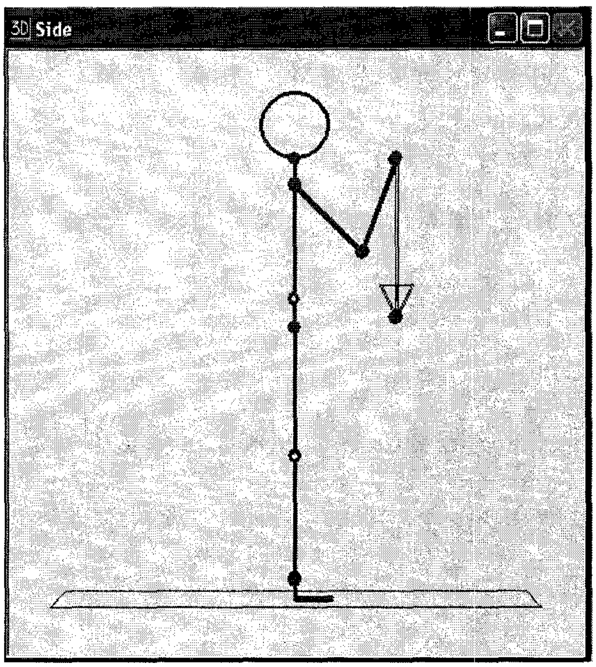


Figure 49 Hands higher than shoulder position

The following table shows the joint forces and torques for the two hand loads.

Table 25 Force and torque comparison for hand above the shoulder position

	Compression force at L5/S1, N		Shear force at L5/S1, N		L5/S1 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Hand above shoulder position	407	890	142	178	6.0	36.9	12.4	18.3

By increasing the overall load from 2 N to 60 N, the lumbar compression force increases 119%. The shear force shows a total increase of 25.3%. Lumbar moment and shoulder moment increases 515% and 48% respectively.

To find out how force and torque in the lumbar spine change during the lifting task, plots have been prepared to show the change from one posture to the next, starting from the picking up moment and ending with the hands above the shoulder. The L5/S1 shear, moment and compression force are shown in the three following figures. In each graph, both knee lifting and hip lifting methods for the two different hand loads are plotted.

As the figure below shows, the maximum shear force in the four postures in lumbar area occurs at the picking up moment. It decreases to the middle posture and after that increases for the holding posture. At the posture with the hands above the shoulder, shear force has the lowest magnitude. At the beginning of the lift shear force is higher in hip lifting for both hand loads.

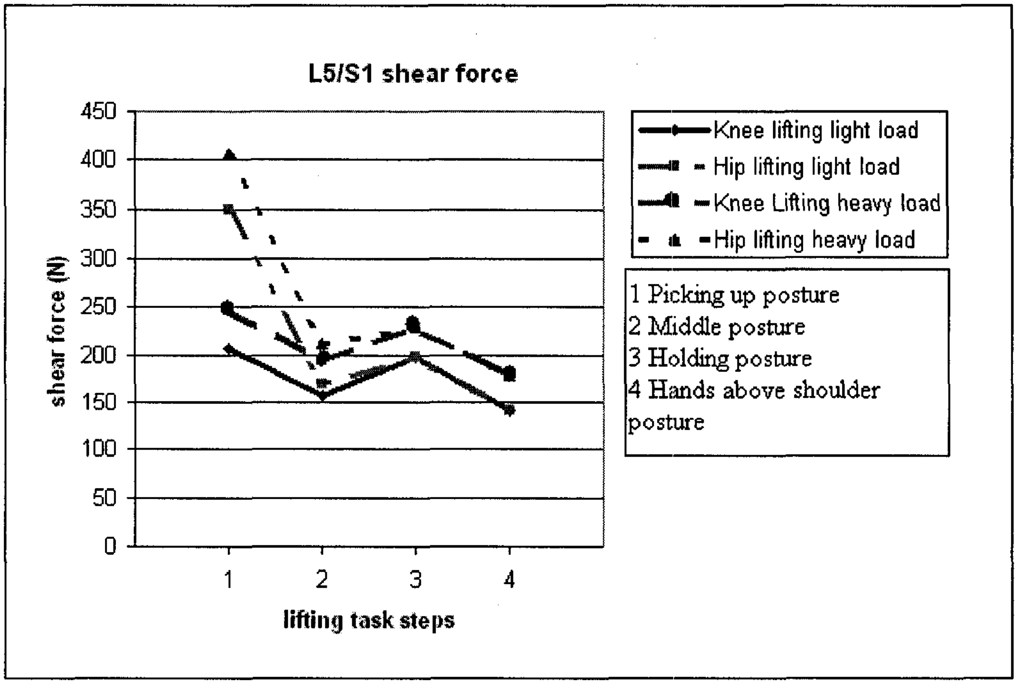


Figure 50 L5/S1 shear force

The next figure shows the L5/S1 moment during the lifting task. Knee lifting causes a higher moment in L5/S1 in the initial posture. The moment decreases from the initial posture to the holding posture and after that increases to the final posture with destination above the shoulder, where the moment is still much lower than at the beginning.

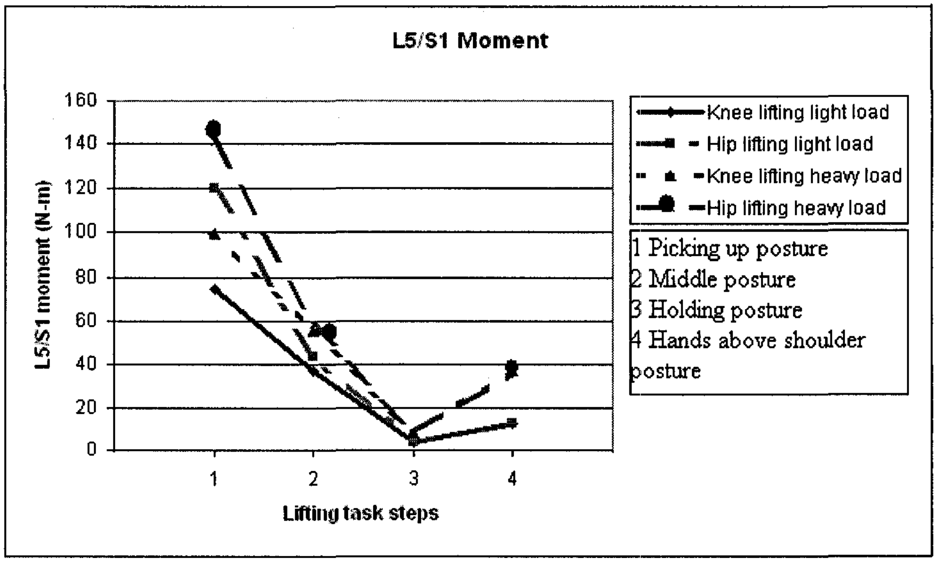


Figure 51 L5/S1 moment

As the L5/S1 compression force graph in the figure below shows, knee lifting applies more force especially during heavy load lifting to the lumbar area at the starting point. Hip lifting for heavy load shows lower compression force before middle point. Raising the load above the shoulders provides higher compression in the lumbar area compared to the holding posture. The increase is more noticeable for the heavy hand load.

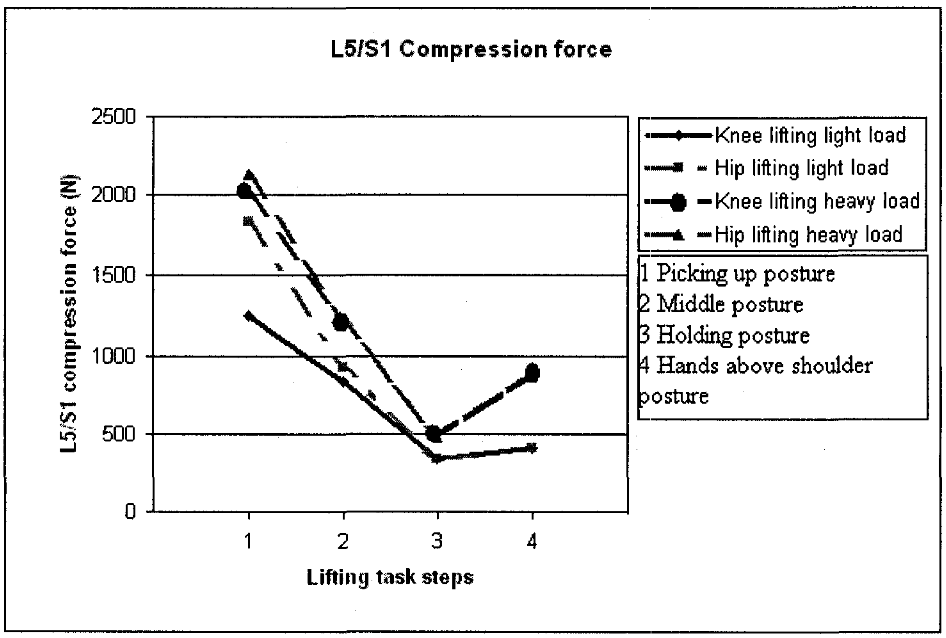


Figure 52 L5/S1 compression force

As the study of the static postures of the lifting task using the 3DSSPP software shows, the initial posture is the riskiest posture in the lifting task for both lifting methods, because lumbar moment, compression force and shear force are maximum. Lumbar forces and moment increase and L5/S1 shear force decreases when the destination height changes from holding posture to hand above shoulder posture.

3.4.4 Biomechanical analysis using CATIA

CATIA is the second software selected to study the static postures during the lifting task in this study. The anthropometric data and postures/joint angles used in

3DSSPP were also used in CATIA. Those data can thus be found in the previous section. However, it was not always possible to generate the identical posture because CATIA has limitations in maximum joint angles.

Two following figures show the hip lifting and knee lifting at initial posture. The hand location is almost at the same level in both figures.

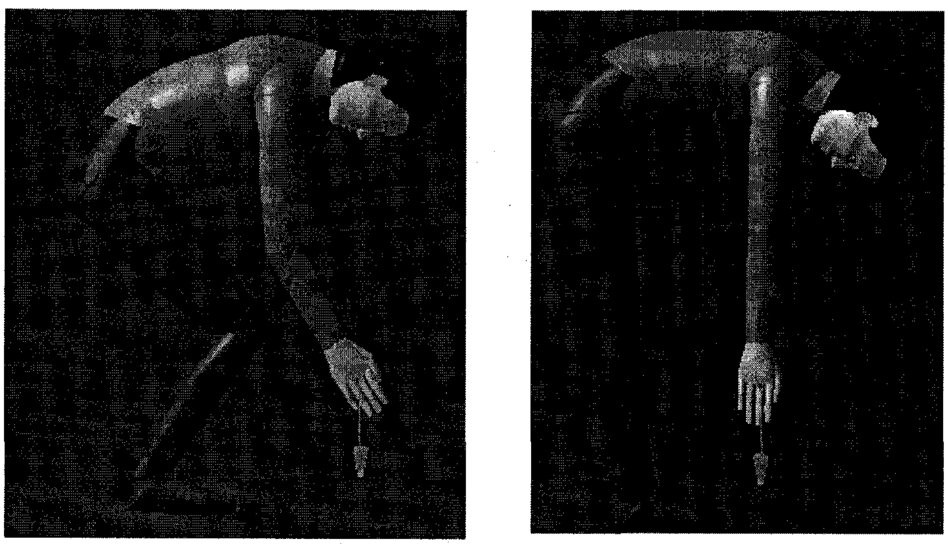


Figure 53 Initial posture for knee lifting and hip lifting methods

While 3DSSPP calculates the loading of the lower back at L5/S1, CATIA calculates the compression and shear forces and moment at L4/L5. The following table presents the lumbar force and torque, and shoulder torque for the initial posture.

Table 26 Force and torque comparison for picking up moment

	Compression force at L4/L5, N		Shear force at L4/L5, N		L4/L5 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee lifting	1037	1522	107	123	53	83	0	5.0
Hip lifting	1012	1303	151	187	59	73	0	3.1

Compression force in L4/L5 is higher for knee lifting but shear force in lumbar and lumbar 3D moment are higher in hip lifting method in light load lifting.

The same procedure is applied for the heavy load and the same trend in term of lumbar force obtained. For this hand loading the lumbar moment has a bigger value for knee lifting comparing to the hip lifting method. The compression force increases by 46% in knee lifting method and by 28% for hip lifting when hand loading increases from 2 N to 60 N. In knee lifting method higher moment applied to the shoulder joint.

The following figure shows the middle postures for both lifting methods.

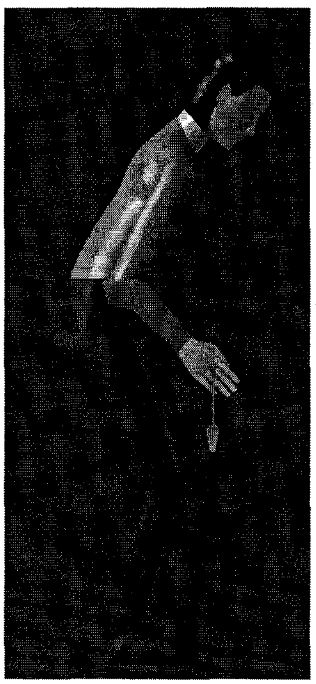


Figure 54 Middle posture for knee lifting and hip lifting methods

Force and moment in lumbar region are calculated in heavy hand loading and light hand loading for knee-lifting and hip-lifting methods. The results are presented in table 27.

Table 27 Force and torque comparison for middle posture

	Compression force at L4/L5, N		Shear force at L4/L5, N		L4/L5 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Knee lifting	817	1126	61	82	36	53	1.1	3.7
Hip lifting	684	1118	65	183	28	53	1.0	2.5

Knee lifting method causes a higher lumbar compression force than hip lifting. L4/L5 moment is the slightly higher in the knee lifting method for light hand load. Shear force is higher in hip lifting, as observed in initial posture.

The figure below shows the holding posture. In this position, the subject holds the box at the waist level. For the heavy load, the trunk is straight upward but for the heavy hand loading the trunk leans slightly backward.

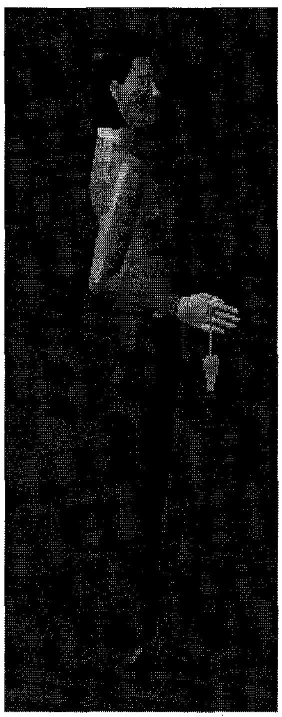


Figure 55 Holding position, hands at waist level

The following table compares forces and torques for different hand loads at the holding position.

Table 28 Force and torque comparison for holding position

	Compression force at L4/L5, N		Shear force at L4/L5, N		L4/L5 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Holding position	271	328	15	58	0	0	1	6.5

When the hand load changes from 2 to 60 N, L4/L5 compression increases by 21% and shear force by 287%. The lumbar moment is zero. The shoulder moment increases by 550% by increasing the hand load.

The figure below shows the posture when hands are above shoulder level. In this posture, the body is straight and leans back somewhat when holding the heavy load.

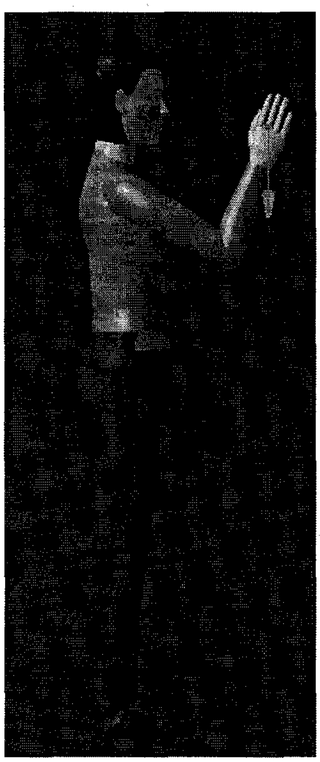


Figure 56 Hands higher than shoulder level

Table 29 shows the force and torque comparison when the hands are higher than the shoulder.

Table 29 Force and torque comparison for hand above the shoulder position

	Compression force at L4/L5, N		Shear force at L4/L5, N		L4/L5 moment, N-m		Shoulder moment, N-m	
Force/hand	1 N	30 N	1 N	30 N	1 N	30 N	1 N	30 N
Hand above the shoulder position	438	885	30	67	10	33	5.8	16.7

In this posture, lumbar compression force increases by 102% by increasing the load. Similarly, lumbar shear force increases 123% and lumbar moment by 230%.

To compare the loading in the four different postures, three graphs are plotted. These plots present the shear force, bending moment and compression force at L4/L5. In each graph knee lifting and hip lifting methods for both light and heavy hand loading are presented.

The first graph in this series, figure 57, presents the lumbar shear force at L4/L5.

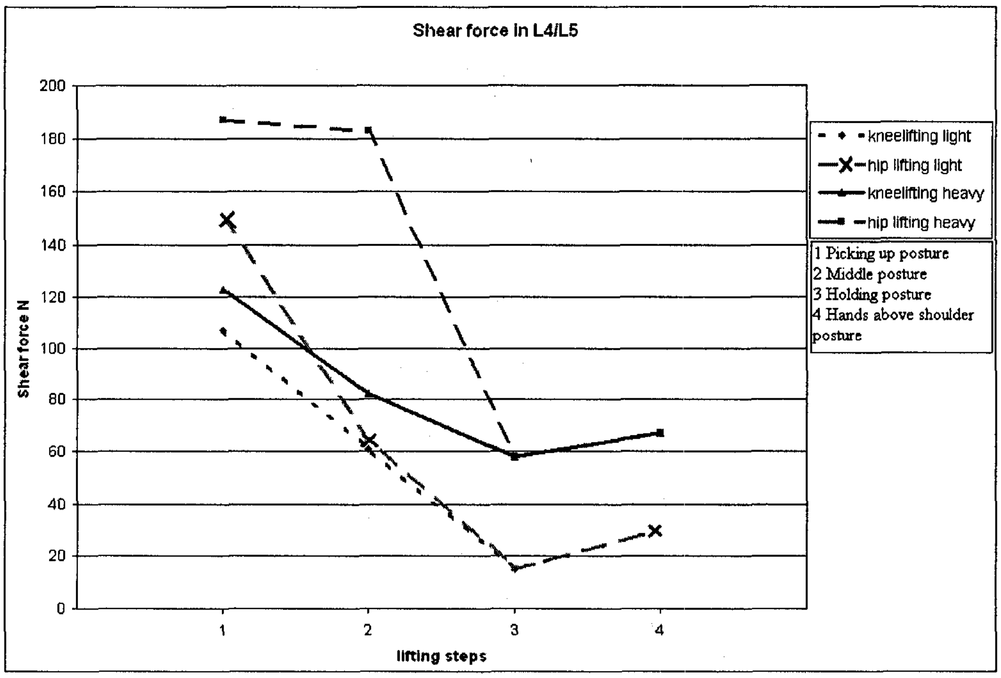


Figure 57 L4/L5 shear force

Hip lifting method results in higher shear force in back. The initial posture is the most critical one, as it has a higher shear force than the other postures. A higher destination level increases the lumbar shear force.

The following graph shows the lumbar moment for different postures.

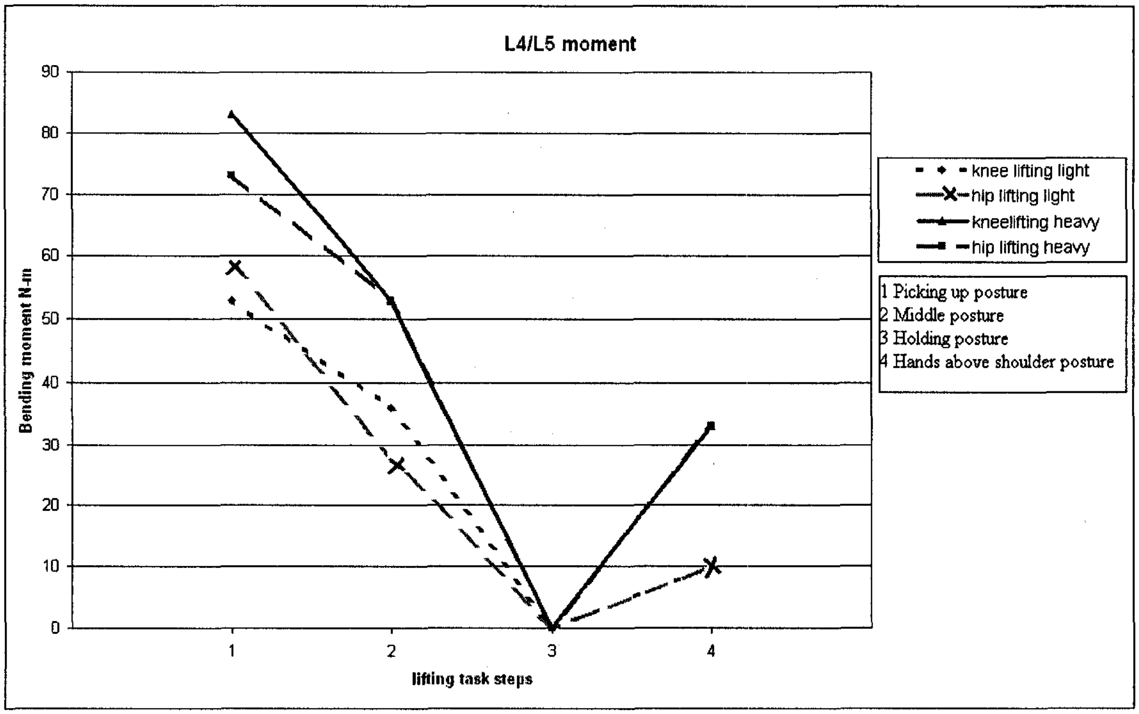


Figure 58 L4/L5 moment

For the lumbar moment, CATIA shows that the initial posture is still the riskiest posture, because it has the highest moment. The lumbar moment reaches zero in the holding position at waist level. After that point, the lumbar moment increases for higher destination level.

The following figure shows the compression force at L4/L5.

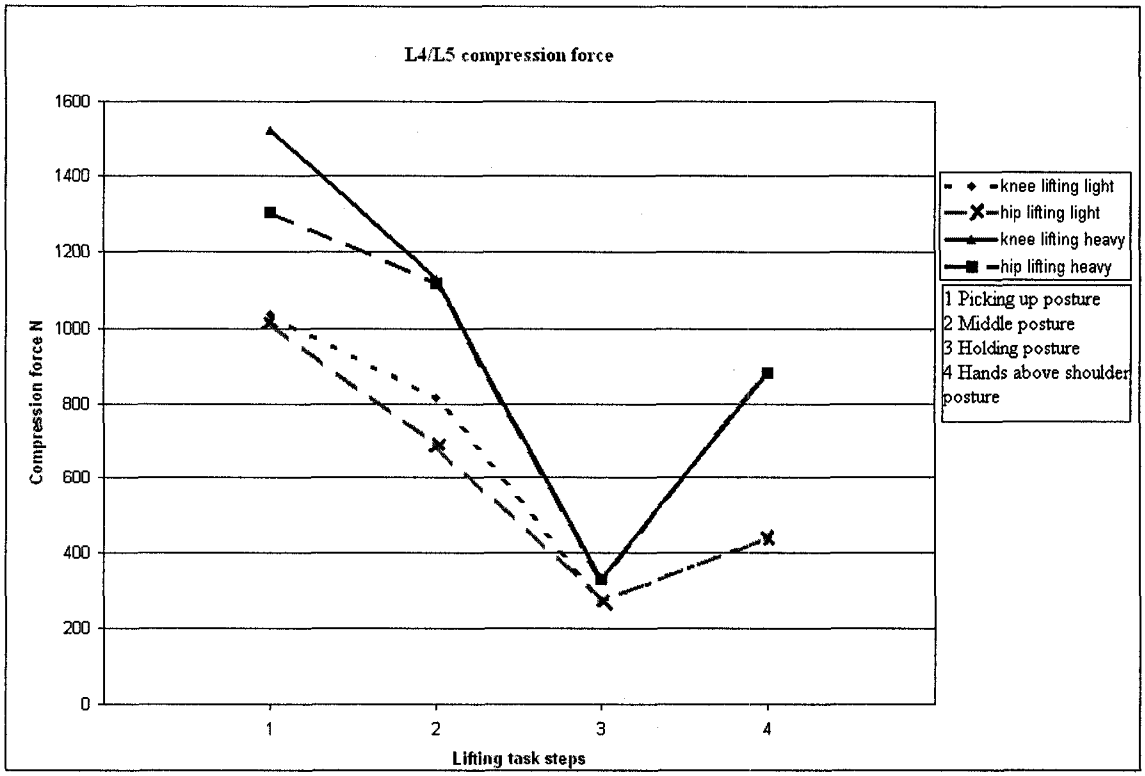


Figure 59 L4/L5 compression force

For lumbar compression force, CATIA shows higher compression force in the initial posture compared to the other postures. In the first posture, knee-lifting method shows higher compression force magnitude.

As a summary, the initial posture always has higher loading than the other postures for the same hand load.

3.4.5 Comparison of results from LifeMOD, 3DSSPP and CATIA

The comparison between these three softwares can be defined as comparing the dynamic and static analysis of the lifting task. The postures analyzed using the different softwares were similar. The small differences in postures were due to the different ways the postures are created in these sofwares. Also, 3DSSPP and CATIA use slightly different locations to calculate the lumbar loading, namely L5/S1 for 3DSSPP and L4/L5 for CATIA, while LifeMOD does not specify where the lumbar load is calculated.

All investigated softwares shows higher or almost equal shoulder torque in knee lifting compared to the hip lifting method. For destinations higher than shoulder level, the initial acceleration increases to provide the adequate force for longer distance displacement. The vertical acceleration levels were derived from the 3D coordinate data of the wrists. The difference in acceleration is more significant for the heavy load. The task duration is shorter in squat lifting, but the initial acceleration is almost 10 times higher in hip lifting.

The study showed the positive effects of knee lifting in terms of lower lumbar moment and compression force. Dynamic and static analysis shows lower compression force at the pick up moment for the knee lifting method. The shear force is higher in hip lifting method.

Because the initial posture has the highest loads, that posture is used to compare the lumbar loads. The following table shows the changes in lumbar torque between the two lifting methods for heavy and light load, rapid and slow lifting, static (3DSSPP and CATIA) and dynamic (LifeMOD) analyses.

Table 30 Lumbar moment, comparing different situations

Lumbar moment	Knee to hip lifting, 2 N	Knee to hip lifting, 60 N	2 to 60 N, knee lifting method	2 to 60 N, hip lifting method
3DSSPP, L5/S1	60% increase	42% increase	32% increase	18% increase
CATIA, L4/L5	11% increase	12% decreases	57% increase	24% decrease
LifeMOD Rapid	58% increase	49% increase	25% increase	18% increase
LifeMOD Slow	5% increase	6% decrease	94% increase	61% increase

Similarly, the next table compares changes in lumbar compression for the conditions studied.

Table 31 Lumbar compression force, comparing different situations

Lumbar compression	Knee to hip lifting, 2 N	Knee to hip lifting, 60 N	2 to 60 N, knee lifting method	2 to 60 N, hip lifting method
3DSSPP, L5/S1	46% increase	5% increase	61% increase	16% increase
CATIA, L4/L5	2.4% decrease	14% decrease	46% increase	29% increase
LifeMOD Rapid	23% increase	15% increase	15% increase	7.5% increase
LifeMOD Slow	21% increase	2.5% decrease	46% increase	18% increase

For slow dynamic analysis, the difference between the two lifting methods is less compared to rapid lifting. The hip lifting method shows less sensitivity to increasing the load. Differences between the two lifting methods are more significant for light weight compared to heavy load lifting.

When comparing the actual values of the lumbar loading the following observation can be made:

- 3DSSPP always calculates the highest lumbar compression force and moment.
- The static (3DSSPP) compression force is 1.9-2.7 times the dynamic (LifeMOD) one.
- The variation in lumbar moment using the different analysis methods is less for knee lifting (48% for 2 N, 27% for 60 N) than for hip lifting (111% for 2 N, 94% for 60 N).
- Both compression force and lumbar moment for rapid lifting are higher than for slow lifting except for lifting 60 N using knee lifting.
- For the same lifting method, lumbar compression force and moment are always higher for the 60 N hand load compared to the 2 N hand load.
- 3DSSPP and LifeMOD show that compression force and lumbar moment are always larger for hip lifting than for knee lifting.

The fact that LifeMOD, 3DSSPP and CATIA calculate different lumbar loads for similar postures is probably because the anatomical structures are modeled differently.

The very high compression force calculated by 3DSSPP is possibly due to higher muscle cocontraction.

3.5 Kinematic analysis of lifting and lowering

Three male subjects performed the lifting and lowering task using two hands. The load is a recycling box 50x40x35 cm loaded with paper for a total weight of 13 kg. The experimental setup was already shown in Figure 11. This load is lifted from ground level to 113 cm height, which is the dumpster height that is used as the emptying container for the paper-recycling box. The subject is free to choose the lifting method and body posture during the lifting and lowering of the box. The subject starts standing straight, then bends down to pick up the recycling box from the floor. Next, the subject lifts the box, places it on the 113 cm high bar and holds it there for about 3 seconds. Finally, the subject picks up the box again, lowers it to the floor and stands up with empty hands. The objective of this study is to study the individual variability in choosing the posture when performing the lifting task. The anthropometric data for three subjects are presented in the following table.

Table 32 Anthropometric data for three male subjects

Subject	Height, cm	Weight, kg
Subject1	189	80
Subject2	173	74
Subject3	166	70

The shoulder and hip joint angles are presented in two planes to show flexion and abduction. For the shoulder, the sagittal plane angle indicates shoulder flexion and the frontal plane angle shoulder abduction. For the elbow, knee and ankle the joint angle presented in the sagittal plane indicates flexion or extension. The joint angles for the left and right sides are very similar. Therefore, only joint angles of the right side are shown.

3.5.1 Subject1

Subject 1 chose the knee lifting method for lifting the box. Shoulder and hip angles in two planes and elbow, knee and ankle in one plane are presented in the following graphs. The first graph presents the arm angles and the second one the hip, knee and ankle angles.

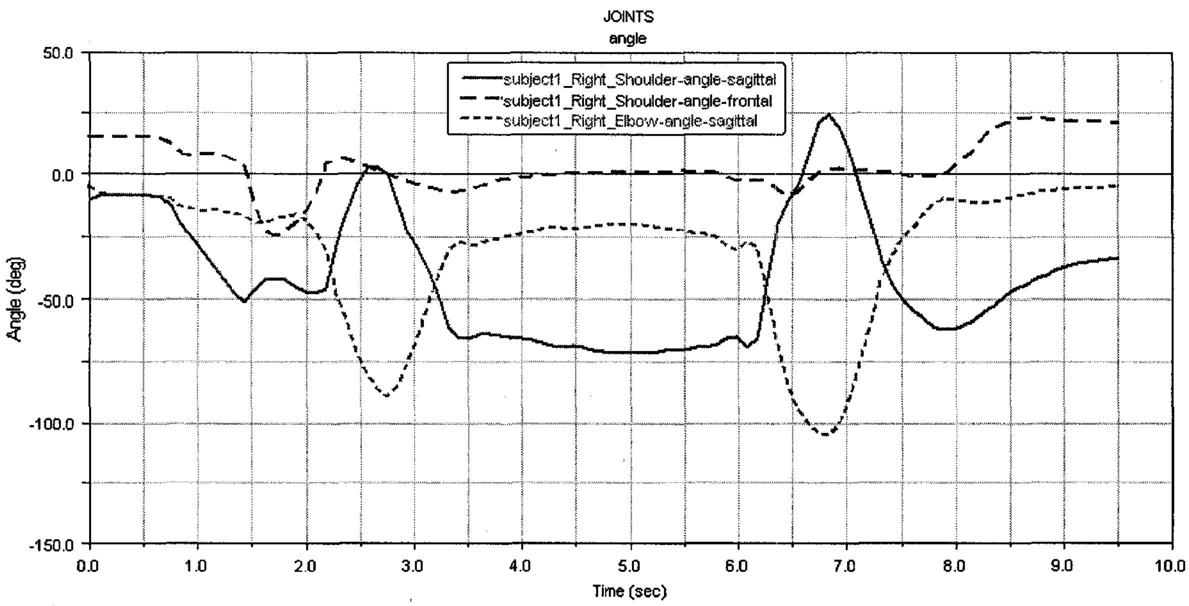


Figure 60 Arm angles, subject1

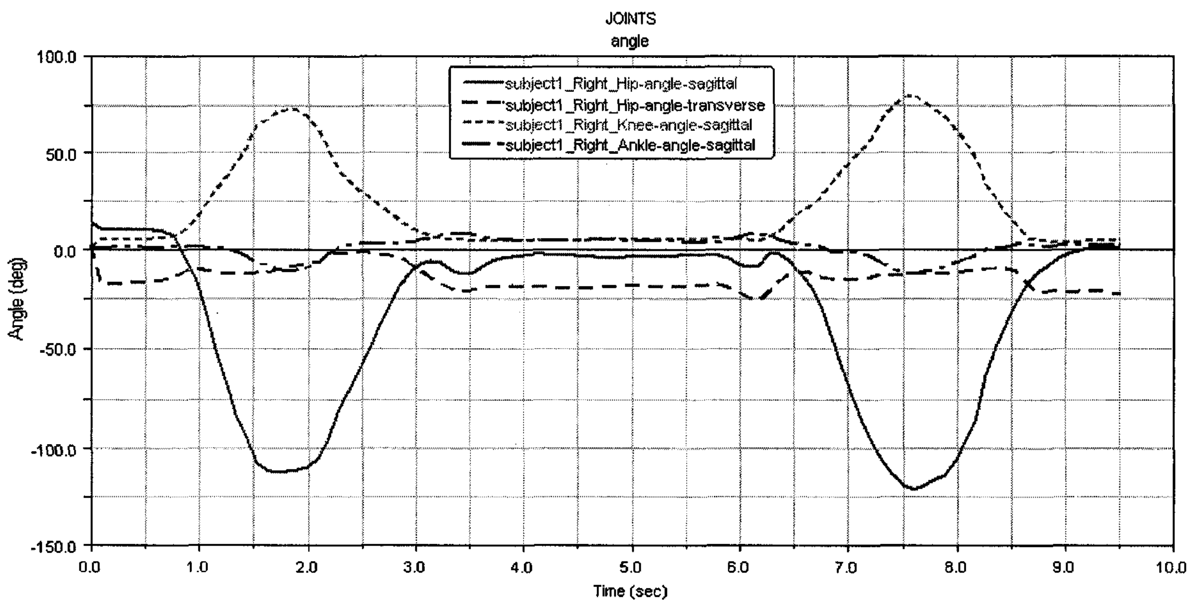


Figure 61 Leg angles, subject1

3.5.2 Subject2

Subject 2 chose the knee lifting method for lifting the box. Shoulder and hip angles in two planes and elbow, knee and ankle in one plane are presented in the following graphs. Figure 62 presents the arm angles and figure 63 the hip, knee and ankle angles.

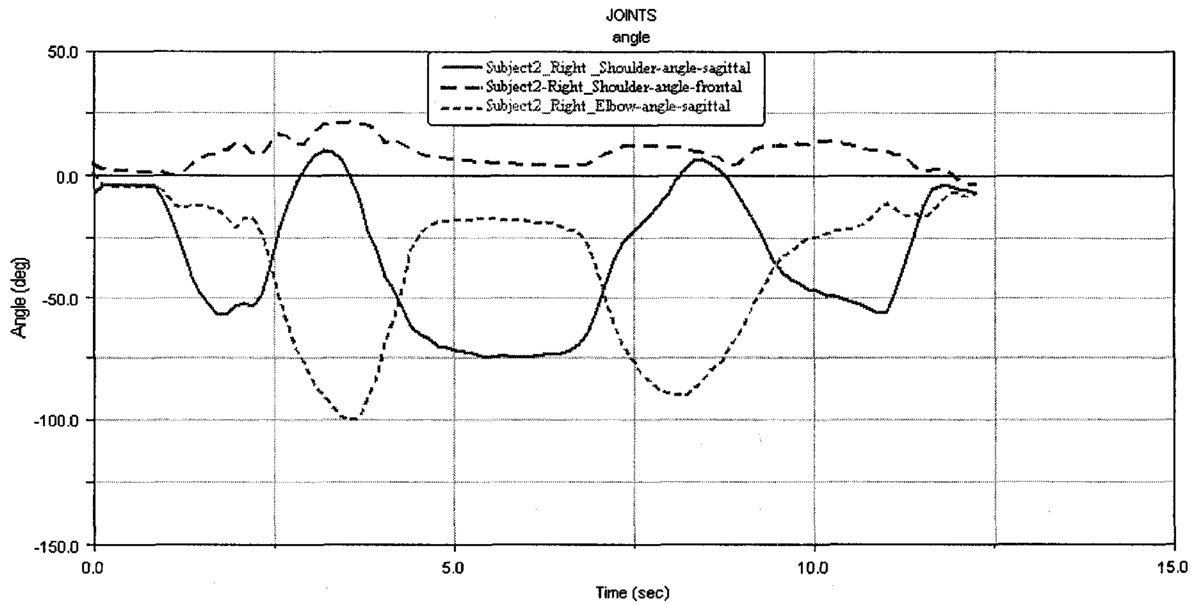


Figure 62 Arm angles, subject2

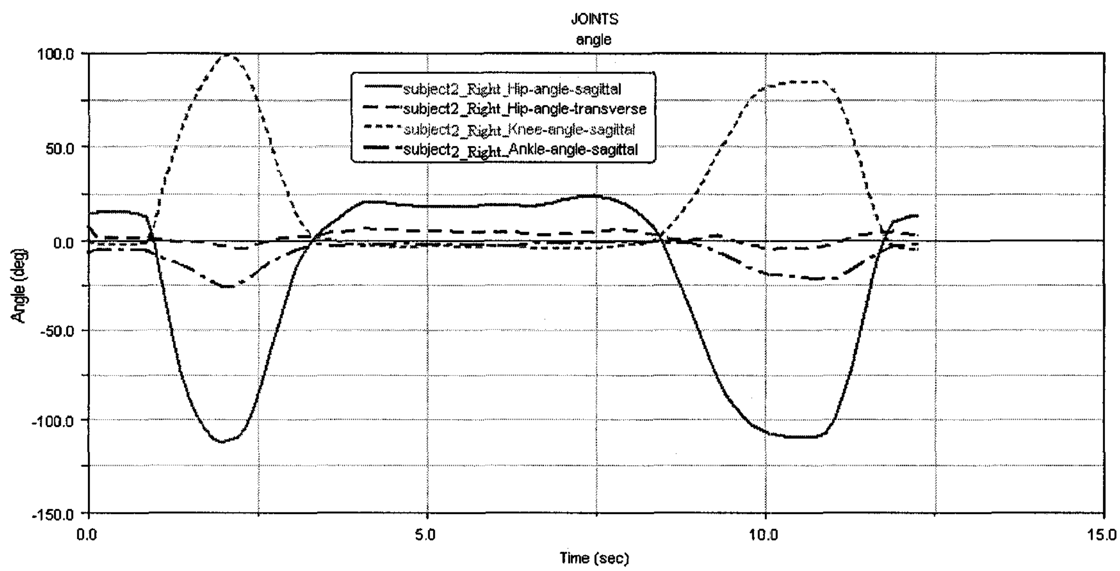


Figure 63 Leg angles, subject2

3.5.3 Subject3

Subject 3 chose the knee lifting method for lifting the box. Shoulder and hip angles in two planes and elbow, knee and ankle in one plane are presented in the following graphs. The first graph presents the arm angles and the second one hip, knee and ankle angles.

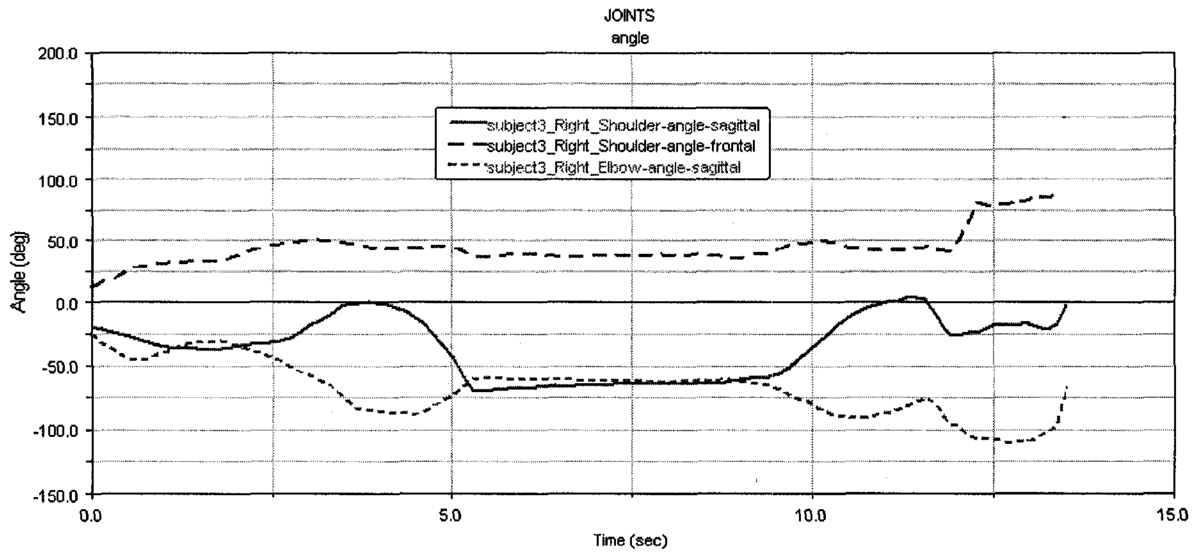


Figure 64 Arm angles, subject3

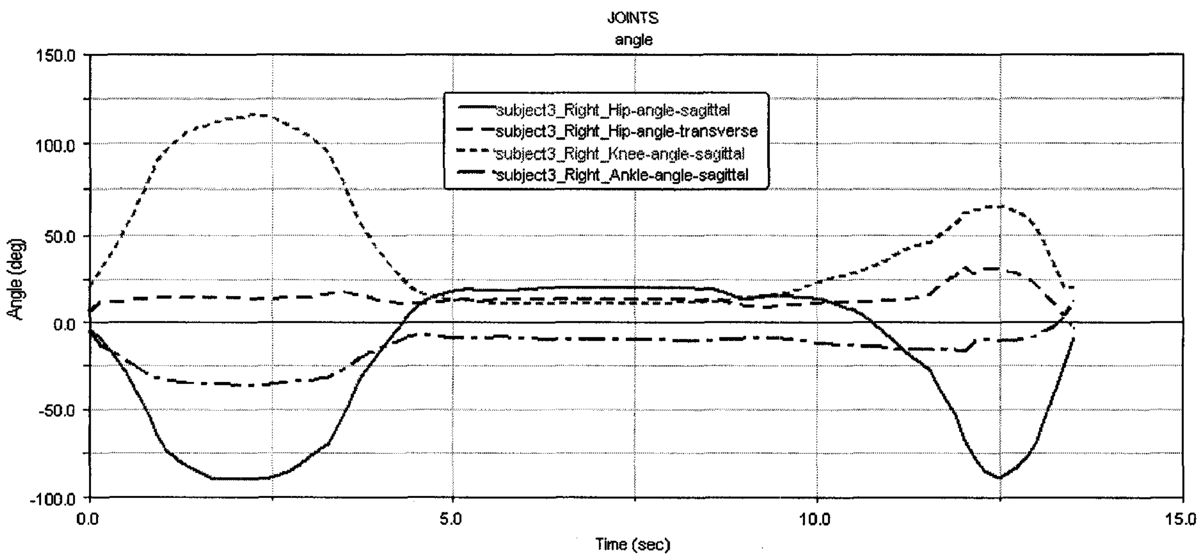


Figure 65 Leg angles, subject3

3.5.4 Comparison of joint angle ranges

All subjects chose the knee lifting method. Following table presents the joint angle ranges for all three subjects.

Table 33 Joint angle range for different subjects

		Subject1 tall	Subject2 average	Subject3 short
Shoulder	Sagittal	-75 to 25°	-75 to 5°	-75 to 0°
	Frontal	-25 to 25°	-20 to 0°	-50 to 0°
Elbow		-105 to 0°	-100 to 0°	-80 to -25°
Hip	Sagittal	-122 to 10°	-100 to 25°	-100 to 20°
	Transverse	-25 to 0°	-5 to 5°	-20 to 0°
Knee		0 to 77°	5 to 110°	10 to 120°
Ankle		-5 to 5°	-25 to 0°	-30 to 0°

Compared to the average and short subject, the tall subject has a decreased range for the knee and ankle and an increase range in the shoulder. All subjects have the similar range for the hip. The tall and average subjects fully extend their elbow while the short subject maintains the elbow in the flexed position. Above table shows that different subjects assume different postures when performing the same task.

4 Conclusion and future work

This research analyzes selected lifting tasks during manual paper recycling. Various ergonomic checklists are used to estimate the hazard level of the lifting task. 3DSSPP and CATIA are used to study the body forces in static postures and LifeMOD is used to create the motion and analyzes the internal body forces by considering body part acceleration and momentums. An OptiTrack motion capture system and software were used to determine 3D coordinates during the lifting task. Weights of 2 and 60 N were lifted from ground level to different heights by a female subject. A weight of 130 N was lifted from ground level to 113 cm by male subjects. The subjects used the knee lifting or hip lifting method.

The checklists show many hazardous postures and awkward positions during the task. Waist position, neck flexion and lumbar bending under heavy load are the most repeated postures that provide this hazard evaluation. The WISHA lifting analysis shows no hazard for any of the lifting tasks since the lifted load is lower than the load limit. The NIOSH lifting equation shows caution for the posture where 130 N is lifted higher than shoulders. The REBA final scores indicate a medium to high risk level at the starting and ending positions of all lifts except for the lowest weight. The Liberty Mutual MMH tables show that about 75% of male and female workers are able to perform the selected tasks.

The kinetic analysis using LifeMOD shows that knee lifting results in a higher back compression force compared to hip lifting. Knee lifting shows lower values for lumbar torque but shoulder torque is less in hip lifting method in most postures. For the destination level above the shoulder, the lumbar forces and torques are higher. This results show the effect of speed and acceleration. When the destination of the lifting task changes from waist level to shoulder level, acceleration at the picking up moment is 100 times higher (10^{-7} m/s^2 for waist level destination and 10^{-5} m/s^2 for shoulder level destination).

The 3DSSPP analysis shows that compression and shear forces and lumbar moment are higher in hip lifting method in initial posture. CATIA calculates a higher compression force for knee lifting and a higher shear force and moment for hip lifting. Both 3DSSPP and CATIA show higher shoulder torque using knee lifting compared to the hip lifting. The hip lifting method shows less sensitivity to increasing the load.

LifeMOD, 3DSSPP and CATIA calculate different lumbar loads for similar postures and hand loads. This means that no reliable estimate of the actual load can be obtained.

4.1 Future work

The following are some suggestions for future work:

1. Use more different subjects to cover a wider range of the population
2. Study other lifting methods including non-symmetric lifting
4. Study the forces and moment of the knee, hip and wrists.
5. Develop a human body model in other biomechanical softwares, define the joint and muscle properties and use it to study the dynamic behavior while a subject performs a certain task.

5 References

Adams, M.A. and Hutton, W.C. (1982) Prolapsed intervertebral disc: a hyper-flexion injury. *Spine* **7**, pp. 184–191.

Adams, M.A. and Hutton, W.C. (1985) Has the lumbar spine a margin of safety in forward bending? *Clinical Biomechanics* **1**, pp. 3-6.

Adams, M.A. McNally, A., Chinn, D., Dolan, P. (1994) Posture and the compressive strength of the lumbar spine. *Clinical Biomechanics* **9**, pp. 5-14.

Aghazadeh, F., Lu, H., Morrissey, S.J. (1993) Determination of the maximum acceptable weights of lifting and lowering using the direct estimation method, *Human Factors and Ergonomics Society Annual Meeting Proceedings* **37**, pp. 735-738.

Aims, A., Dowsan, D., Wright, V. (1980) Analysis of elbow forces due to high speed forearm movement. *Journal of Biomechanics* **13**, pp. 825-831.

An, H., Englehardt, J., Fleming, L., Bean, J. (1999). Occupational health and safety amongst municipal solid waste workers in Florida. *Waste Management & Research* **17**(5), pp. 369-377.

Anderson, C.K. (1983) A biomechanical model of the lumbosacral joint for lifting activities. PhD dissertation, University of Michigan.

Anderson, C.K. and Chaffin, D.B. (1986) A biomedichanical evaluation of five lifting techniques. *Applied Ergonomics* **17**(1), pp. 2-8.

Andrews, D.M., Norman, R.W., Wells, R.P. (1996) Accuracy and repeatability of low back spine compression force estimates from self-reports of body posture during load handling. *International Journal of Industrial Ergonomics* **18**, pp. 251-260.

Anjos, L.A., Ferreira, J.A., Damião, J.J. (2007) Heart rate and energy expenditure during garbage collection in Rio de Janeiro, Brazil. *Cadernos de Saúde Pública* **23** (11), pp. 2749-2755.

Braune, W., & Fischer, O. (1889) Uber den Schwerpunkt des menschlichen Korpers [On the centre of gravity of the human body]. *Abhandlungen der Mathematisch Physische Klasse der Konigl. Sachsischen Gesellschaft der Wissenschaften* **15**, pp. 561-572.

Brinckmann, P.,Biggemann, M., Hilweg, D. (1988) Fatigue fracture of human lumbar vertebrae. *Clinical Biomechanics* **3** (Suppl.1) pp. 1-23.

Bureau of Labor Statistics (2004) *Census of Fatal Occupational Injuries Summary, 2004.* http://stats.bls.gov/news.release/cfoi.nr0.htm

Chaffin, D.B. (1967) *The development of the prediction model for the metabolic energy expended during arm activity.* PhD thesis, University of Michigan.

Chaffin, D.B. (1969) A computerized biomechanical model developed and use in study gross body action. *Journal of Biomechanics* **2**, pp. 429-441.

Chaffin, D.B. and Baker, W.H. (1970) A biomechanical model for analysis of symmetric sagittal plane lifting. *Iinstitute of Industrial Engineers Transactions* **2**, pp.16-27.

Chaffin, D.B., Gallay, L., Woolley, C., Kuciemba, S. (1986) An evaluation of the effect of a training program on worker lifting postures. *International Journal of Industrial Ergonomics* **1**(2), pp.127-136.

Center of Disease Control and Prevention (2007), *Fatal Occupational Injuries - United States,* http://www.cdc.gov/MMWR/preview/mmwrhtml

Cloutier, E. (1994) The effect of age on safety and work practices among domestic trash collectors in Quebec. *Safety Science* **17**, pp. 291-308.

Coury, B.G., and Drury, C.G. (1982) Optimum handle position in a box holding task. *Ergonomics* **25**, pp. 645-662.

Davis, K.G. (1996) The Effect of lifting vs. lowering on spinal loading. *Human Factors and Ergonomics Society Annual Meeting Proceedings* **40**, pp. 599-603.

Dolan, P., Earley, M., Adams, M.A. (1994) Bending and compressive stresses acting on the lumbar spine during lifting activities. *Journal of Biomechanics* **27**(10), pp.1237-48.

Doriot N. and Wang X. (2006) Effects of age and gender on maximum voluntary range of motion of the upper body joints. *Ergonomics* **49**(3), pp. 269-281.

Eppes, S. (2004) *Washington state ergonomics tool: predictive validity in the waste industry*, M.Sc. thesis, Texas A&M University, Texas.

Escobar, C.P. (2006) *Sensitivity analysis of object ergonomic assessment tools,* Industrial and System Engineering Department, Alabama University, Alabama.

Fathallah, F.A., Marras, W. S., Parnianpour, M. (1998) An assessment of complex spinal loads during lifting tasks. *Spine* **23**(6), pp. 706-716.

Faria, M.P. and Silva A.M.(1986) Análise de acidentes do trabalho ocorridos durante parte do ano de 1983 na Grande Belo Horizonte (MG). *Revista Brasileira de Saúde Ocupacional* **14**, pp. 26-32.

Freivalds, A. (1984) Computer aided strength prediction using the articulated total body model. *Computers and Industrial Engineering* **8**(2), pp.107-118.

Frymoyer, J.W, and Cats-Baril, W. (1987) Prediction of low back pain disability. *Clinical Orthopaedics and Related Research* **221**, pp. 89-98.

Garg, A.D. and Herrin, G.D. (1979) Stoop or squat: a biomechanical and metabolic evaluation. *Institute of Industrial Engineers Transactions* 11, pp. 293-302.

Hignett, S. and McAtamney, L. (2000) Rapid entire body assessment (REBA). *Applied Ergonomics* **31**, pp.201-205.

Hsiang, S., Brogmus, G.,Courtney, T., Courtny, T.K.(1997) Low back pain (LBP) and lifting technique - A review *International Journal of Industrial Ergonomics* **19**, pp. 59-74.

Imrie, D. (1983) *Goodbye backache. The practical way to a pain-free and healthy back.* Newcastle Publishing Ltd, Toronto. Ontario.

Karwowski , W. (1996) Maximum safe weight of lift: A new paradigm for setting design limits in manual lifting tasks based on the psychophysical approach. *Human Factors and Ergonomics Society Annual Meeting Proceedings* **40**, pp. 614-618.

Koda, S. and Ohara, H. (1999) Preventive effects on low back pain and occupational injuries by providing the participatory occupational safety and health program. *Journal of Occupational Health* **41**, pp.160-165.

Kuijer, P.P.F.M. and Frings-Dresen, M.H.W. (2004) World at work: Refuse collectors. *Occupational and Environmental Medicine* **61**, pp. 282-286.

Kumar, S. (1984) The physiological cost of three different methods of lifting in sagittal and lateral planes. *Ergonomics* **19**, pp. 59-74.

Liberty Mutual (2008) *Liberty Mutual Manual Material Handling Tables.* http://libertymmhtables.libertymutual.com/CM_LMTablesWeb/

Maeda, S. and Morioka, S., (1998) Measurement of whole body vibration exposure from garbage trucks. *Journal of Sound and Vibration* **215**(4), pp. 959-964.

Marras, W.S., Lavender, S.A., Leurgans S.E. (1993) The role of dynamic three dimensional trunk motion in occupational related lower back disorders: the effects of workplace factors, trunk position and trunk motion characteristics on risk of injury. *Spine* **18**, pp. 617-628.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Fathallah, F.A., Ferguson, S.A., Allread, W.G., Rajulu, S.L..(1995) Biomechanical risk factors for occupational related low back disorders. *Ergonomics* **38**, pp. 377-410.

McConville, J.T., Robinette, K.M., Churchil, T.D. (1981) *An antropometric data base for commercial design applications (Phase I).* Final report NSF/BNS-81001 (PB81-211070). Washington, D.C.

McHugh, A.R. (2006) Workers get a lift, *Work Safe Magazine* March–April 2006, pp. 14-15.

Nachemson, A. (1981) Disc pressure measurement. *Spine* **6**, pp. 93-97.

NIOSH ALERT (1997), Preventing worker injuries and deaths from moving refuse collection vehicles, *NIOSH.*

NIOSH (1994) *Applications manual for the revised NIOSH lifting equation.* http://www.cdc.gov/niosh/docs/94-110/.

NIOSH (2008) program portfolio, http://www.cdc.gov/niosh/programs/pps/risks.html

Patel, A. and Ogle, A. (2000) Diagnosis and management of acute low back pain, *American Family Physician* **61**, pp. 1779-1786.

Riihimaki, H. (1991) Low-back pain, its origin and risk indicators. *Scandinavian Journal of Work, Environment and Health* **17**, pp. 81-90.

Robazzi, M., Moriya, T., Favero, M., Lavrador, M., Luis, M. (1997) Garbage collectors: Occupational accidents and coefficients of frequency and severity per accident. *Annals of Agricultural and Environmental Medicine* **4**, pp. 91-96.

Schmidt, H., Kettler , A. , Heuer, F., Ulrich, S. , Lutz, C. , Wilke, H. (2007) Intradiscal pressure, shear strain, and fiber strain in the intervertebral disc under combined loading. *Spine* **32**(7), pp. 748-755.

Schultz , A.B. and Anderson, G.B.J. (1982) Analysis and measurement of lumbar trunk loads in tasks involving bend and twist. *Journal of Biomechanics* **15**, pp. 669-675.

Sedgwick, A.W. and Gormley, J.T. (1997) Training for lifting; an unresolved ergonomic issue? *Applied Ergonomics* **29**(5), pp. 395-398.

Sharp, A.M., Rice J.V., Nindle, C.B., Mello, P.R. (1995) Maximum acceptable Load for lifting and carrying in two person teams. *Human Factor and Ergonomics Society Annual Meeting* **39**, pp. 640-644.

Snook, S.H., Campanelli, R.A., Hart, J.W. (1978) A study of three preventive approaches to low back injury. *Journal of Occupational Medicine* **20**, pp. 478-481.

Steffen, T., Baramki, H.G., Rubin, R.K., Antoniou, J., Beckman L. (1996) *Multi-localized Intradiscal Pressure Measurements in the Cadaveric Lumbar Spine.* McGill University, Orthopedic Research Laboratory.

Toussaint, H.M., Van Baar, C.E., Van Langen, P.P., De Looze, M.P., Van Dieen, J.H. (1992) Coordination of the leg muscles in leg lift and back lift. *Journal of Biomechanics* **25**, pp. 1279-1289.

Troup, J.D.G. (1977) Dynamic factors in the analysis of stoop and crouch lifting methods: a methodological approach to the development of safe materials handling standards. *Orthopedic Clinics of North America* **8**, pp. 201–209.

Troup, J.D.G., Leskinen, T., Stalhammar, H., Kuorinka, I. (1983) A comparison of intra-abdominal pressure increases, hip torque and lumbar vertebral compression in different lifting techniques. *Human Factors* **25**(5), pp. 517-525.

Whitsett, C.E. (1962) *Some dynamic response characteristics of weightless man.* MS thesis. Wright Patterson Air Force Base, Ohio. U.S. Air Force Institute of Technology.

WISHA (2008), Washington State Department of Labor & Industries, http://personal.health.usf.edu/tbernard/HollowHills/WISHA_WMSD_Checklist.pdf and http://personal.health.usf.edu/tbernard/HollowHills/WISHA_Lifting.pdf

Zhang, X., Nussbaum, M., Chaffin, D. (2000) Back lift versus leg lift: an index and visualization of dynamic lifting strategies. *Journal of Biomechanics* **33**, pp. 777-782.